Fringe cracks: Key structures for the interpretation of the progressive Alleghanian deformation of the Appalachian plateau

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ABSTRACT

Vertical joints in Devonian clastic sedimentary rocks of the Finger Lakes area of New York State are ornamented with arrays of fringe cracks that reveal the complex deformational history of the Appalachian plateau detachment sheet during the Alleghanian orogeny. Three types of fringe cracks were mapped: gradual twist hackles, abrupt twist hackles, and kinks. Gradual twist hackles are curviplanar en echelon fringe cracks that propagate with an overall vertical direction within the bed hosting the parent crack and are found in all clastic lithologies of the detachment sheet. Abrupt twist hackles propagate as planar features in thick shale beds above or below the siltstone beds hosting parent joints. Kinks propagate horizontally as planar surfaces from the tips of parent joints in siltstone beds. The breakdown of the parent joint into either gradual or abrupt twist hackles depends on the orientation and magnitude of the remote stress field, internal fluid pressure, and the elastic properties of the bed. The twist angle of gradual twist hackles is larger in coarser clastic beds, indicating that stress and internal pressure are more important parameters than elastic properties in controlling breakdown. Assuming that the vertical stress axis (S_v) equals 78 MPa at 3 km burial depth, the difference in twist angle between sandstone and shale beds is used to estimate the maximum horizontal stress difference in the shale beds as $S_H - S_h \approx 2.5$ MPa when $S_H - S_h \approx 12$ MPa in sandstone beds.

The twist angle of the fringe cracks and the abutting relationships of parent joints give an indication of the overall change in stress field orientation within the detachment sheet during Alleghanian tectonics. These parent joints indicate a regional clockwise stress rotation of Alleghanian age concordant with the twist angle of fringe cracks throughout the western part of the study area. A counterclockwise twist angle in the eastern portion indicates a local stress attributed to drag where no salt was available to detach the eastern edge of the plateau sheet. The clockwise change in stress orientation is consistent with the rotation in stress orientation found in the anthracite belt of the Pennsylvania Valley and Ridge, but is opposite to the sense of rotation in the southwestern portion of the detachment sheet (western Pennsylvania and West Virginia). The two regional rotation domains are separated by the Juniata culmination.

INTRODUCTION

In outcrops of the anthracite belt in eastern Pennsylvania, gradual twist hackles, a set of fringe cracks growing in an en echelon arrangement following breakdown of a parent joint into smoothly curving segments (Fig. 1), all propagated to a plane rotated clockwise from the parent joint in map view (Fischer et al., 1991). There is the possibility that these clockwise twist hackles are further evidence for the clockwise sense of change in stress orientation attributed to progressive Alleghanian deformation within both the northeastern Appalachian plateau (e.g., Engelder and Geiser, 1980) and the Appalachian Valley and Ridge east of the Susquehanna River (e.g., Nickelsen, 1979; Gray and Mitra, 1993). The question for us is whether fringe cracks are organized across a geologic province to the extent that they provide a structural record of the tectonic history of a region.

One purpose of this paper is to document the areal distribution of fringe cracks in Devonian clastic rocks of the Appalachian plateau detachment sheet in New York State. Very few parent joints within the detachment sheet are bounded by fringe cracks. However, those parent joints with fringe cracks leave behind a record that is of great value in deciphering the tectonic history of the Appalachian plateau detachment sheet during the Alleghanian orogeny.

Fringe Cracks

Twist Hackles. Early descriptions of joint surfaces divided them into a planar portion, a rim of conchoidal fractures, and a fringe (Woodworth, 1896). With the evolution of terminology over time, these three parts of a joint surface are now described as the main joint face, with its characteristic plumose structure, conchoidal ridges (rib marks of Kulander and Dean, 1985), and the fringe, with its en echelon fringe cracks (Hodgson, 1961a, 1961b). The boundary between the main joint face and its fringe cracks may be either an abrupt transition known as a shoulder or a smoothly curving transition. Later descriptions of fringe cracks implicitly recognized the genetic similarity between the abrupt and smooth transitions by referring to both types of en echelon cracks as twist hackles (Kulander and Dean, 1985). The fringe is called a gradual twist hackle (Fig. 1) if individual cracks emerge from the tip line of the parent joint face in a smooth, uninterrupted manner, whereas the fringe is known as an abrupt twist hackle (Fig. 2) if a series of planar en echelon cracks abut the joint tip line (Kulander et al., 1979, 1990; Kulander and Dean, 1995). Other names for these structures include hackle zone, hackle marks, dilatant fringe cracks, fingers, and fracture lances (for review of terminology, see Purslow, 1986; Kulander and Dean, 1995).

Gradual twist hackles result from a continuous breakdown of the parent joint, whereas abrupt twist hackles stem from a discontinuous breakdown. Pollard et al. (1982) provided a mechani-

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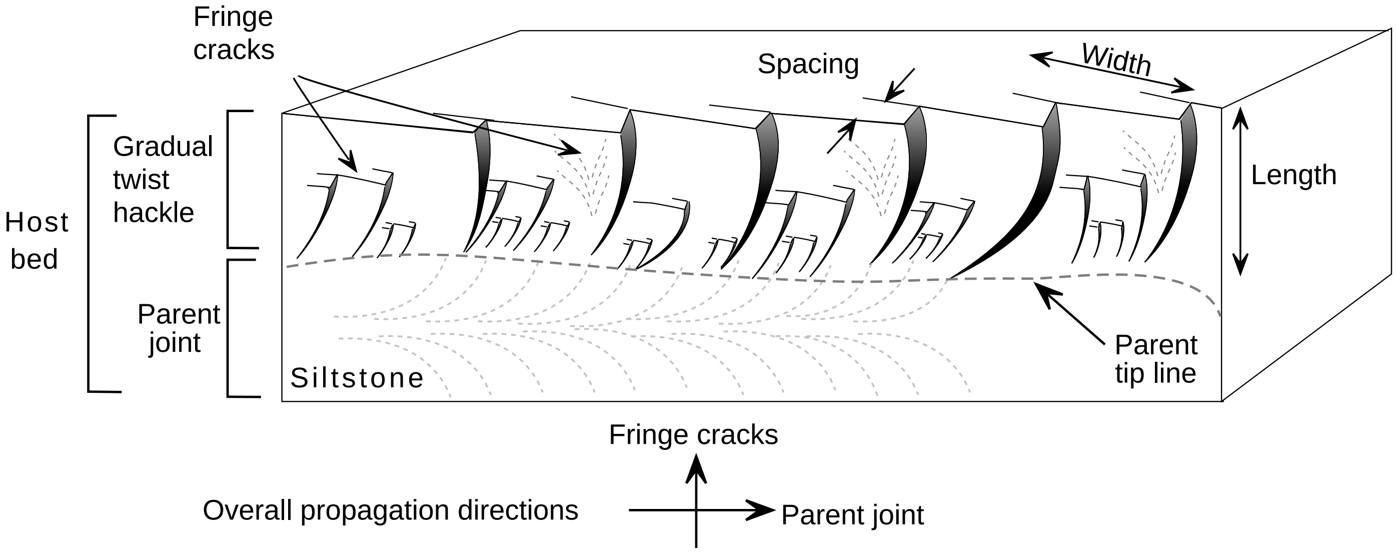


Figure 1. Schematic of a gradual twist hackle. The parent joint and twist hackle are carried within a single host bed. The number of fringe cracks decreases away from the parent joint. The spacing of the cracks changes from small at the tip line of the parent joint to large at the edge of the twist zone.

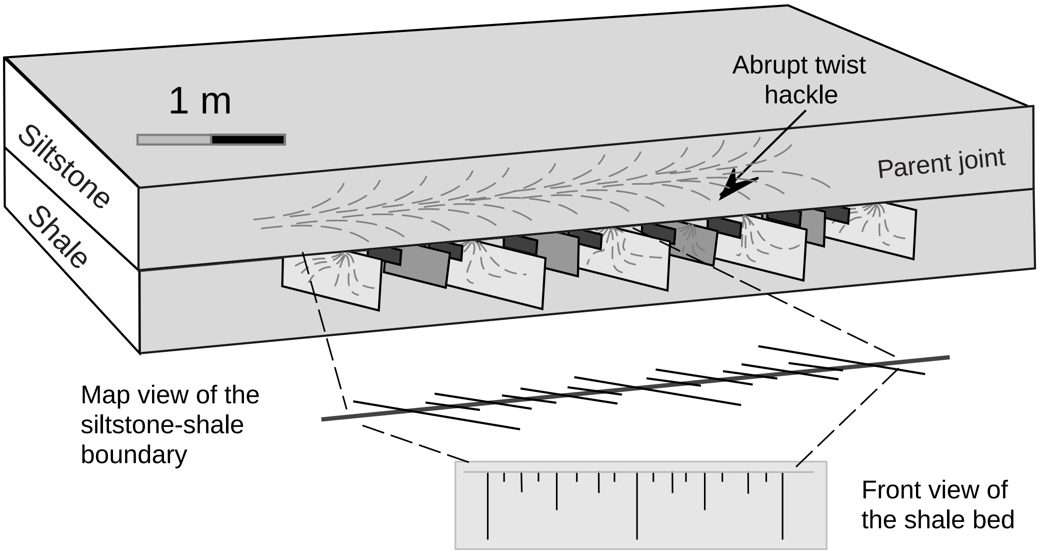


Figure 2. Schematic of an abrupt twist hackle. These fringe cracks can propagate downward or upward from a siltstone bed into adjacent beds. They have a characteristic sequence of large and small cracks, indicative of suppressed growth where crack stress shadows limit the growth of some cracks.

cal explanation for the two types of twist hackles and suggested that twist angle is a function of change in remote stress orientation, stress magnitude, and elastic properties. There is general agreement that the breakdown of the parent joint into fringe cracks is a consequence of a stress field with principal components that are neither orthogonal nor parallel to the tip line of the parent joint (e.g., Kulander et al., 1979; Pollard et al., 1982; Bankwitz and Bankwitz, 1984).

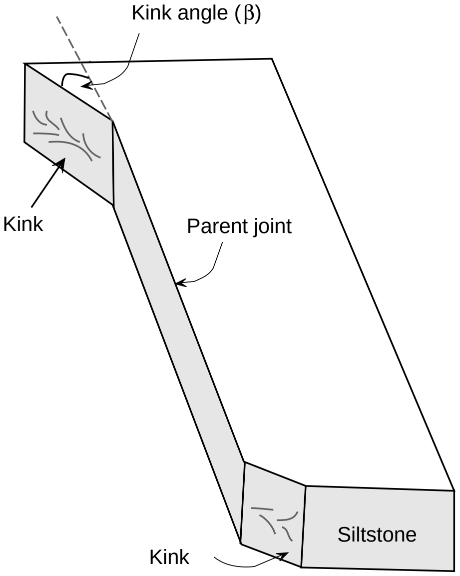


Figure 3. Schematic of two kinks propagating from the lateral tip lines of a parent joint. These fringe cracks form as the joint tip line is subjected to mixed mode I and II loading.

Kinks. The tip line of the parent joint can be decorated with a single fringe crack known as a tilt or kink (Fig. 3). A kink is a planar crack that propagates laterally at some angle from the edge of a parent joint (Cottrell and Rice, 1980). Such features are associated with systematic joints in Arches National Park, Utah (Cruikshank et al., 1991), and in the granites of the Sierra Nevada, California (Segall and Pollard, 1983). Kinks form after parent joints have been arrested. If the parent joint had not stopped prior to kink formation, there would have been a smooth curving or hooking of the crack path (Olson and Pollard, 1989).

In this paper the term fringe crack refers to any out-of-plane crack that emanates from the tip line of a parent joint (Fig. 4). The parent joint is typically a planar, persistent, long crack that often belongs to a systematic joint set. After propagating some distance, the parent joint may encounter a stress field with principal components that are neither parallel nor perpendicular to its plane. Depending on its orientation relative to the remote stress, the parent joint may break down at its tip line to form the en echelon cracks of a twist hackle (Pollard et al., 1982) or it may tilt or deviate from its path to form either a hook or kink (Cruikshank et al., 1991; Olson and Pollard, 1989). In this paper we apply the term fringe crack more broadly than Hodgson (1961a), who referred only to a twist hackle when using the term.

Conditions for Development of Fringe Cracks

Joint propagation occurs in response to three principal loading modes (e.g., Lawn, 1993) that represent the configuration of the stresses at the joint tip line (Fig. 5A). If a joint propagates in its plane driven by a tensile stress perpendicular to that plane, it propagates under mode I, or opening mode, loading. As long as the tensile stress remains normal to the joint, long planar joints form without breakdown at the tip line. In addition to mode I loading, the joint plane may be subject to a shear traction. This condition is known as mixed-mode loading. If the shear couple is directed parallel to propagation direction and normal to the tip line, the additional loading is mode II; if the shear couple is perpendicular to the propagation direction and parallel to the tip line, the additional loading is mode III. The application of shear tractions near the joint tip line forces the joint to deviate, following a path determined by the sense and orientation of the shear couple. Hooks, abrupt kinks, and twist hackles are all manifestations of mixed-mode loading at the joint tip line.

Several criteria predict the joint path under mixed-mode loading (Broek, 1991; Lawn, 1993). For all these criteria, the joint follows the propagation path that minimizes the shear stresses acting on the joint tip and that maximizes the tensile

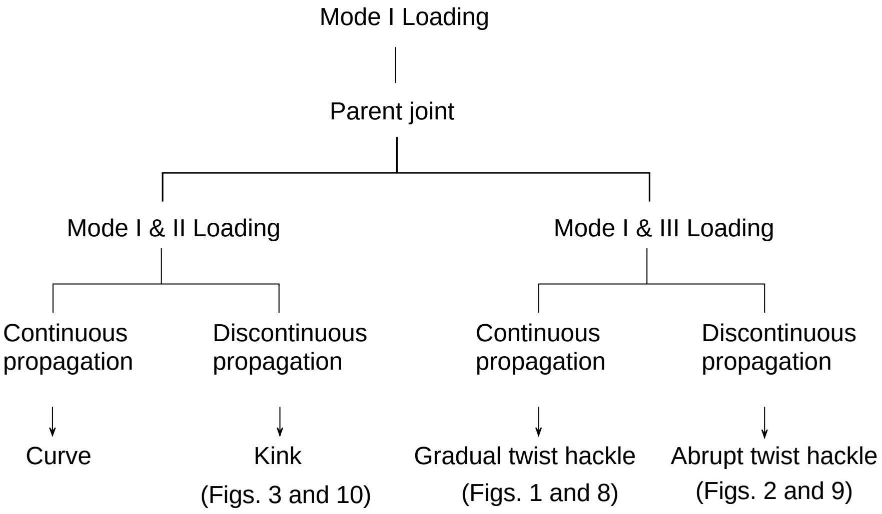


Figure 4. Flow chart indicating the loading conditions for a parent joint and four types of fringe cracks.

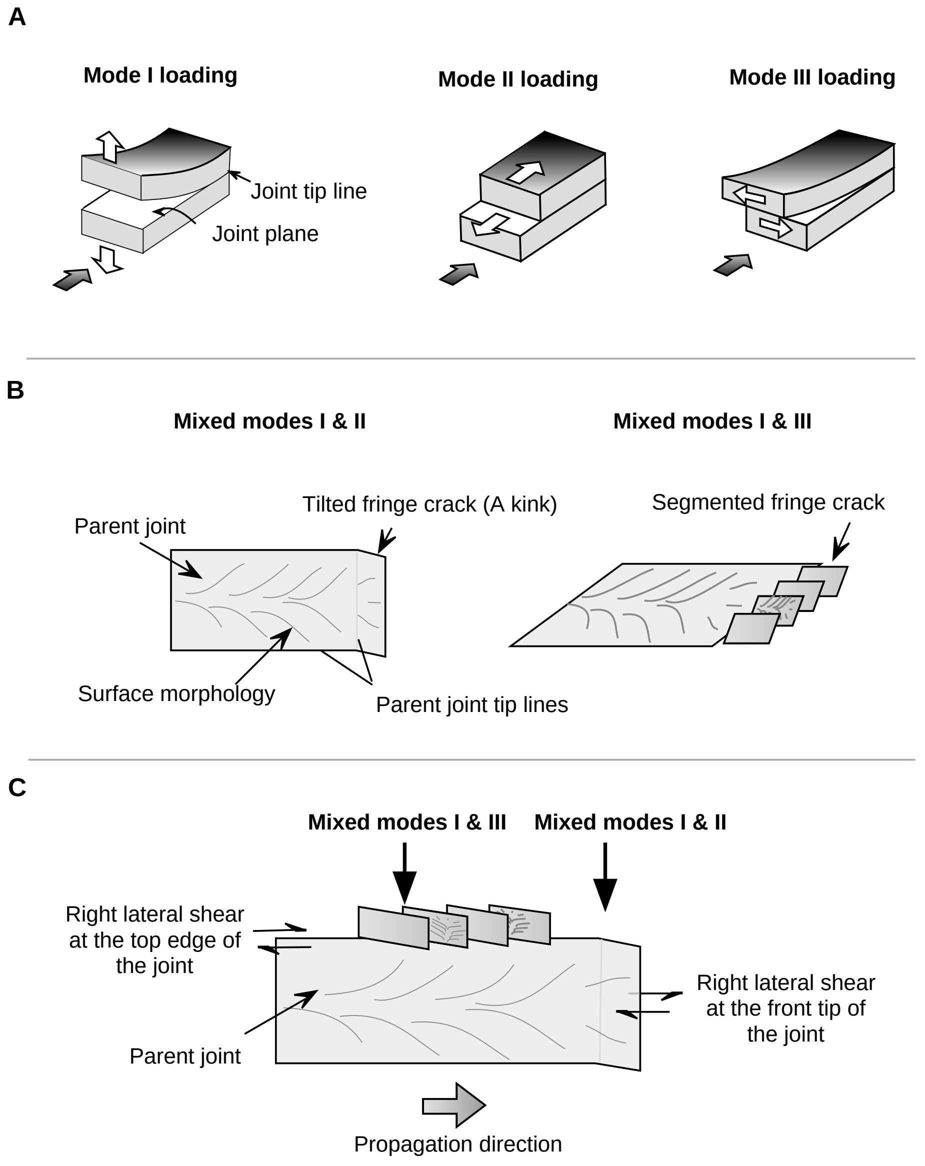


Figure 5. (A) Joint loading modes. The black arrows indicate the propagation direction of the crack tip, and the white arrows indicate the extension or shear. (B) Fringe crack geometries. The addition of mode II loading causes the joint to kink or curve, whereas the addition of mode III loading causes the joint front to break down into several smaller fringe crack segments. Here the tilted fringe crack is a kink. (C) The edge of a parent joint decorated with both twist hackles and a kink.

stress at the joint tip. The out-of-plane propagation at a joint tip is controlled by the orientation of the local stress field, which is not necessarily the same as the orientation of the remote stresses. Local stresses can arise through the interaction of neighboring cracks, elastic mismatches, or the interaction of a remote stress and the existing joint.

Kinks. Kinks form as the parent joint tilts to accommodate a component of mode II loading at the joint tip (e.g., Cottrell and Rice, 1980; He and Hutchinson, 1989). Kinks grow because the orientation of the remote stress field changed after initial joint propagation was arrested, and thus later subjected the parent joint to mixed-mode loading (Figs. 3 and 5, B and C). After initiation, kink growth is in the direction of the maximum horizontal stress; the kink angle, β, indicates the angular change in the orientation of the remote stress field. This condition reflects a temporal change in the orientation of the remote stress field (Engelder and Geiser, 1980). The tip line of a systematic joint may also curve smoothly out of plane because of local stress conditions such as the interaction between joints (Olson and Pollard, 1989) or the interaction of a joint with an inclusion (McConaughy and Engelder, 1999). This condition represents a spatial change in orientation of the local stress field.

Mixed-mode loading is the consequence of either a temporal rotation of remote stresses (Cooke and Pollard, 1996) or a spatial variation in the orientation of the local stress field around local structures (Muller and Pollard, 1977; Olson and Pollard, 1989). In this paper we focus on temporal changes in the remote stress-field orientation because it is this interpretation, not a spatial variation of local stress, that gives us an explanation for fringe cracks displaying the same sense of stress rotation over sizable regions of

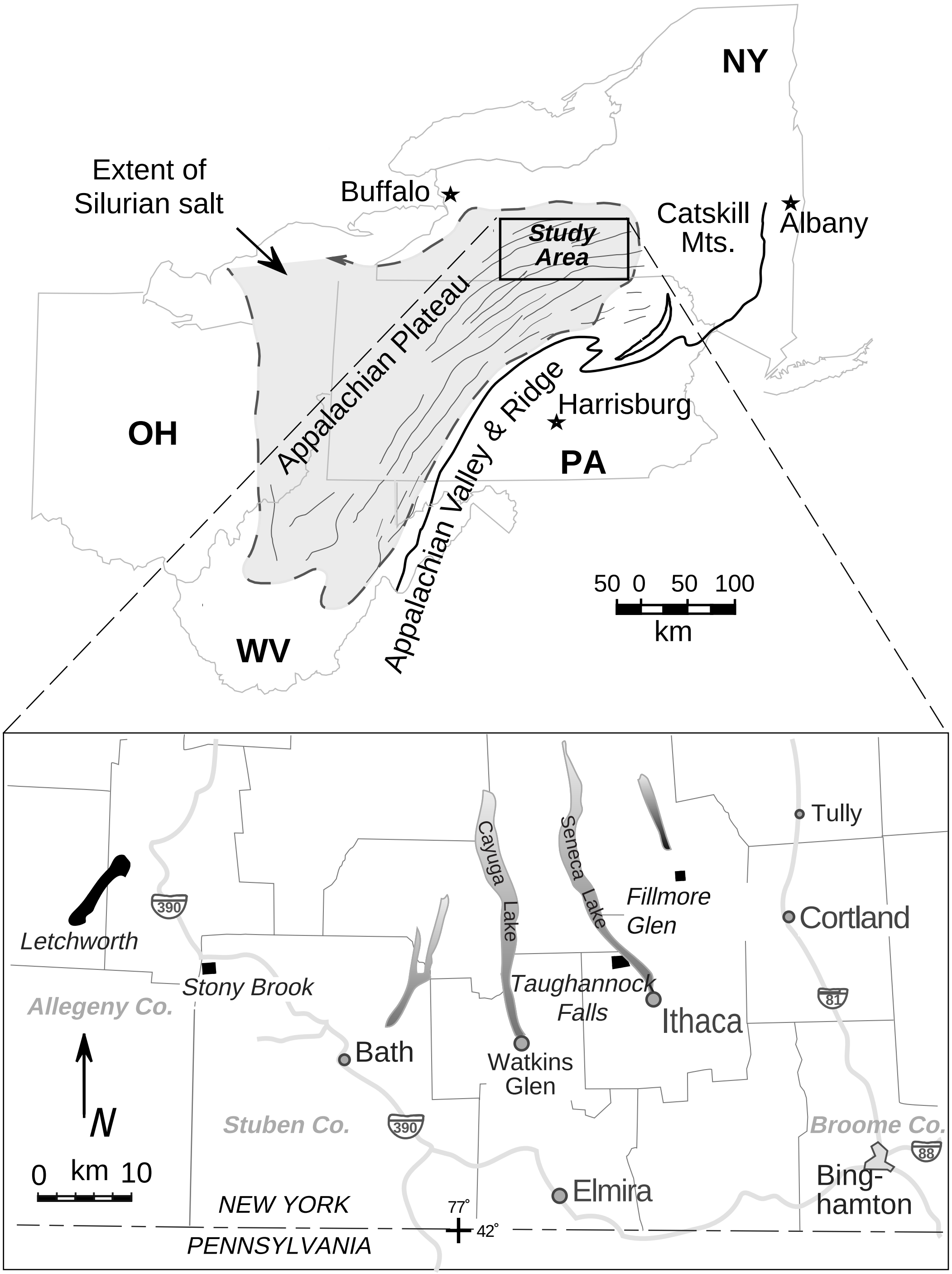


Figure 6. Location map of the Finger Lakes district in New York State. The extent of the Silurian salt is shaded and outlined by dashes in the states of New York (NY), Pennsylvania (PA), Ohio (OH), and West Virginia (WV).

the Appalachian plateau. Structures such as smoothly curving or hooking joint tips arising from the interaction of a joint and an inclusion are not discussed in this paper, although they are present in the study area (e.g., McConaughy and Engelder, 1998).

Twist Hackles. In addition to a single kinking or curving fringe crack, en echelon fringe cracks can also decorate the tip line of a parent joint in the form of twist hackles (Figs. 1, 2, and 5, B and C). Of several hypotheses that constitute the mechanical basis for explaining the local stress field that causes en echelon fringe cracks (Engelder et al., 1993), we prefer mixed-mode (I and III) loading induced by a rotation of the remote principal stress direction (Kulander et al., 1979; Pollard et al., 1982). This is a temporal rather than a spatial change in orientation of the stress field. After a rotation of the remote stress field, the joint follows a path that depends on several parameters, including the orientation and magnitude of the remote stresses, pore pressure, and the elastic modulus of the rock in which the joint propagates (Pollard et al., 1982). Stress and pore pressure are sometimes combined into one parameter called the stress ratio, *R*, which is the difference between the internal fluid pressure, P_i, on the joint face and the remote mean horizontal stress, divided by the remote horizontal shear stress:

$$R = \frac{2P_i + \sigma_1^r + \sigma_3^r}{\sigma_1^r - \sigma_3^r} \qquad (1)$$

$$P_i > -\sigma_1^r$$

where σ_i^r are the remote principal stresses with tensile stress taken as positive so that the maximum compressive principal stress is designated σ_3^r. For natural hydraulic fracturing, pore pressure and internal pressure are equal at the initiation of joint propagation (Engelder and Lacazette, 1990). As joints grow, the internal pressure may drop below the pore pressure outside the joint but it will remain open as long as the internal pressure in the joint exceeds the minimum compressive stress. The joint will recharge by flow down a pore pressure gradient (Engelder and Lacazette, 1990).

Because of the interaction of the remote stress field with the joint tip, en echelon fringe cracks propagate at an angle relative to the parent joint. The twist angle, β, is a function of the stress ratio, *R*, the angular change of the remote stress orientation, α, and Poisson's ratio, ν (Pollard et al., 1982):

$$\beta = 0.5\tan^{-1}\left[\frac{\sin 2\alpha}{(R + \cos 2\alpha)(0.5 - \nu)}\right] \cdot \qquad (2)$$

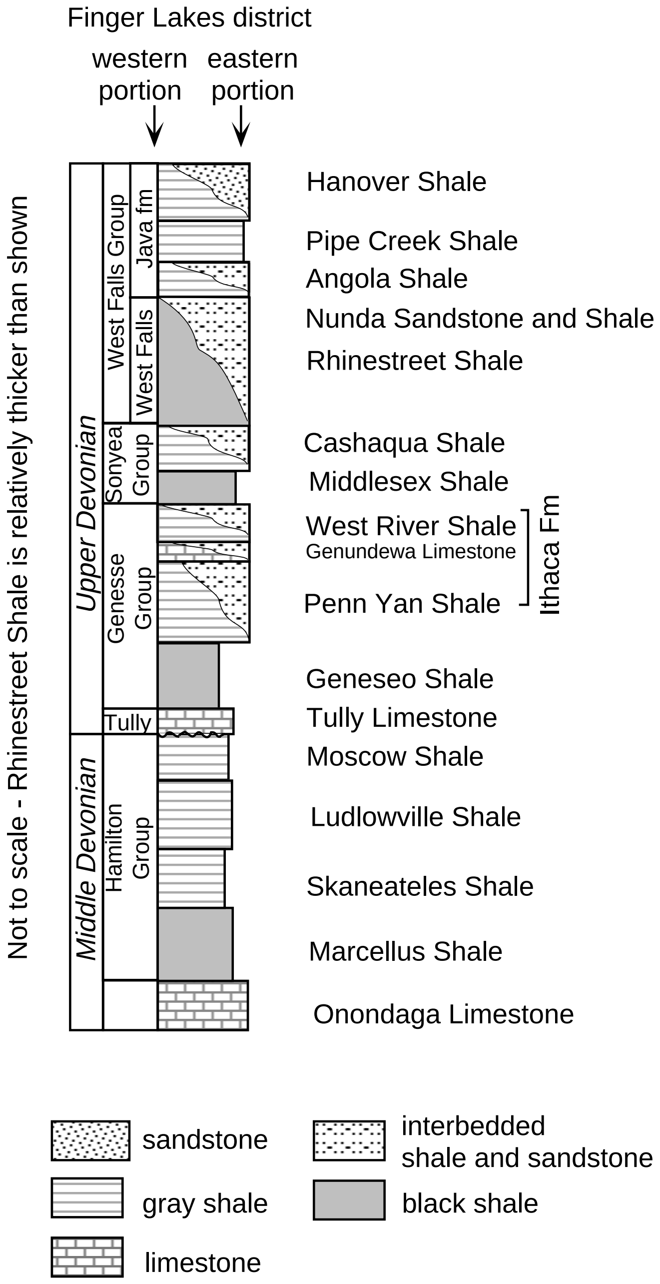


Figure 7. A simplified stratigraphic column of major rock units in the eastern and western portions of our study area in the Finger Lakes district of New York State (modified from Van Tyne, 1983). The facies become progressively coarser to the east as the proximal parts of the Catskill delta are approached. The unconformity at the base of the Tully Limestone extends up to the base of the Cashaqua shale in western New York.

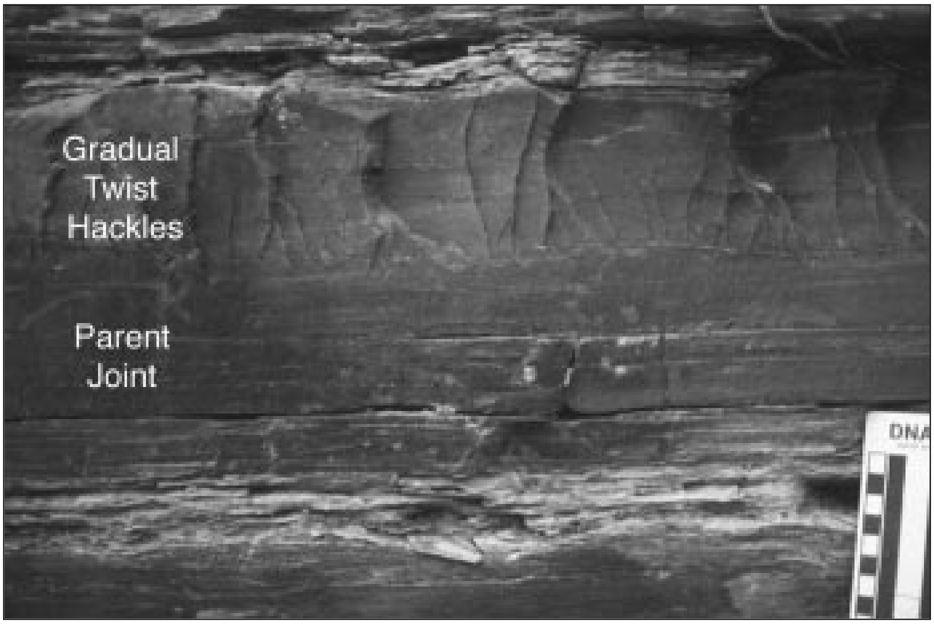


Figure 8. Gradual twist hackles. A parent joint and a twist hackle are carried within a single bed of siltstone of the Ithaca Formation at Taughannock Falls State Park, New York. Propagation direction for the twist hackle is upward. The sense of stress field rotation in this example is clockwise. The scale to the lower right is divided into centimeters.

Figure 9. Abrupt twist hackles. This set of fringe cracks propagated downward into a thick shale bed from a thinner siltstone bed hosting the parent joint at Taughannock Falls State Park, New York. These rocks are part of the Ithaca Formation. The sense of stress field rotation in this example is clockwise. The scale is a geologic compass with an 8 cm base.

For small α (i.e., $\alpha < \sim 10°$), fringe cracks form perpendicular to the rotated least compressive stress only when

$$R = \frac{0.5 + \nu}{0.5 - \nu} \cdot \qquad (3)$$

Otherwise, the twist angle, β, of the fringe crack relative to the parent joint will differ from the remote stress rotation angle, α. Here, a distinction should be made between the twist angle, β, and the kink angle, β, with β always equal to α in the latter case. The development of gradual twist hackles represents a continuous breakdown of the joint tip line, and indicates that $\alpha < \sim 10°$, and *R* is relatively large (Cottrell and Rice, 1980; Pollard et al., 1982). Abrupt twist hackles reflect a discontinuous breakdown of the parent joint and indicate either that $\alpha > \sim 10°$ or that $\alpha < \sim 10°$, and *R* is relatively small (Cottrell and Rice, 1980; Pollard et al., 1982).

GEOLOGICAL CONTEXT

This paper documents the spatial distribution and nature of fringe cracks within the northeastern portion of the Appalachian plateau detachment sheet (Fig. 6). This portion includes the Finger Lakes district of New York State, which extends from Broome County to Allegany County, and covers ~ 3000 km^2. The detachment sheet in this area consists of clastic sedimentary rocks of the Devonian Catskill delta shed from the Acadian highlands to the east (Ettensohn, 1985). The delta prograded from east to west, attaining its maximum thickness east of the study area. Clastic rocks of the delta complex consist of packages grading from black and gray shales through siltstone to sandstone. The clastic groups (Hamilton, Genesee, Sonyea, and West Falls Formations) are separated by three black shale formations (Genesee, Middlesex, and Rhinestreet Shales) that reflect reducing conditions at the time of deposition (Fig. 7). The Tully Limestone is an important marker bed at the base of the Genesee Group.

The detachment sheet was deformed into a series of low-amplitude folds mapped in outcrop (Wedel, 1932) and in the subsurface (Bradley and Pepper, 1938; Murphy, 1981). Folds of the detachment sheet are broad, persistent, and can be traced farther to the southwest in Pennsylvania and into West Virginia. In the study area the fold axes trend east-west in the eastern part and northeast-southwest in the western part. The detachment sheet contains layer-parallel shortening structures of Alleghanian age above a decollement within the Silurian Salina salt (Engelder, 1979; Murphy, 1981; Rodgers, 1970). Much of the layer-parallel shortening was accommodated by pressure solution and the formation of solution cleavage (Engelder and Geiser, 1979; Geiser and Engelder, 1983). The amount of slip on the decollement is as much as 22 km to the north-northwest as estimated at the Allegheny front (Engelder and Engelder, 1977). The extent of the detachment sheet is mapped by using strain markers such as deformed fossils and from subsurface data (Engelder and Engelder, 1977; Engelder, 1979; Engelder and Geiser, 1980; Beinkafner, 1983; Geiser, 1988; Hudak, 1992). The foreland limit of the detachment sheet and the region of folds in the post-Silurian rocks coincides with the limits of the Silurian salt (Frey, 1973).

Joints of Alleghanian age strike approximately normal to the axes of the folds within the detachment sheet (Parker, 1942; Ver Steeg, 1942; Nickelsen and Hough, 1967; Engelder and Geiser, 1980; Geiser and Engelder, 1983; Bahat, 1991; Lacazette and Engelder, 1992). These were first mapped as dip joints (i.e., parallel to the dip direction of bedding) by Sheldon (1912), who recognized that outcrops commonly contained dip joints in more than one orientation. Multiple sets of dip joints are particularly well developed in interlayered siltstone-shale beds, where the earlier dip joints favored siltstone beds. It is these dip joints, called cross-fold joints by Engelder and Geiser (1980), which are occasionally decorated with fringe cracks.

Tectonic Problem

In an analysis of the Bear Valley strip mine in the Appalachian Valley and Ridge, Nickelsen (1979) recognized a group of structures that were a manifestation of a clockwise rotation of maximum horizontal stress (S_H) during the Alleghanian orogeny. Engelder and Geiser (1980) recognized that jointing on the Appalachian plateau also reflected a clockwise rotation of the Alleghanian stress field. On the basis of rocks that had two distinct cleavages and outcrops commonly carrying two dip joint sets, Geiser and Engelder (1983) concluded that the Appalachian plateau was affected by two discrete tectonic phases: the Lackawanna and Main phases. However, outcrops in the anthracite coal district of the Appalachian Valley and Ridge of Pennsylvania, including the Bear Valley strip mine, indicate that the rotation of the Alleghanian stress field produced structures carrying a broad range of orientations. From these structures, Gray and Mitra (1993) concluded that the Alleghanian orogeny was a continuous series of structural events reflecting a gradual clockwise rotation in the Alleghanian stress field, rather than being punctuated by two tectonic phases as suggested

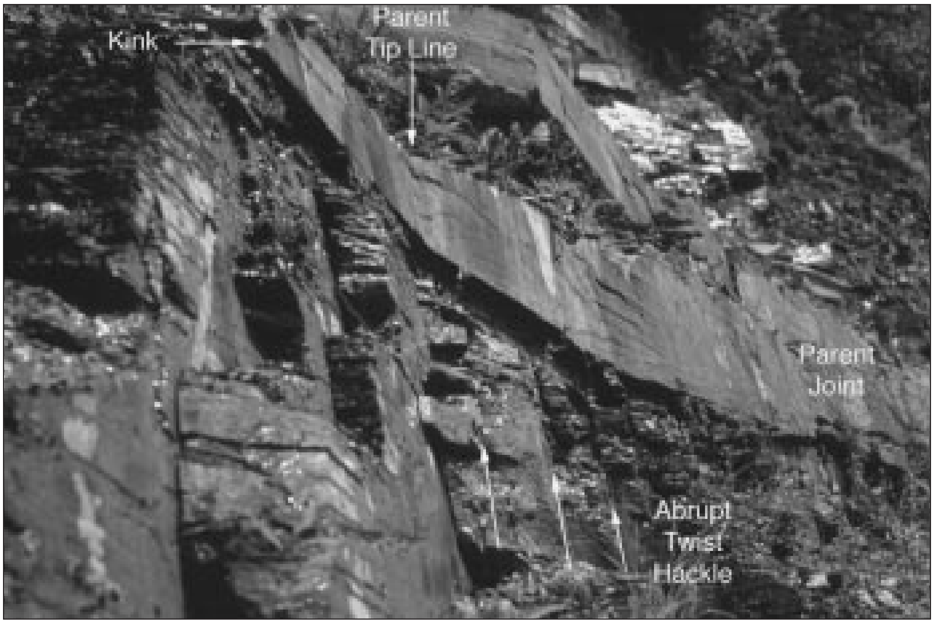


Figure 10. Kinks. This example of fringe cracks in a siltstone bed of the Ithaca Formation is found near Whitney Point, New York. The shale above and below the siltstone bed carries abrupt twist hackles. The sense of stress field rotation in this example is counterclockwise, both for the kink and the abrupt twist hackle. The parent joint is found in a bed roughly 20 cm thick.

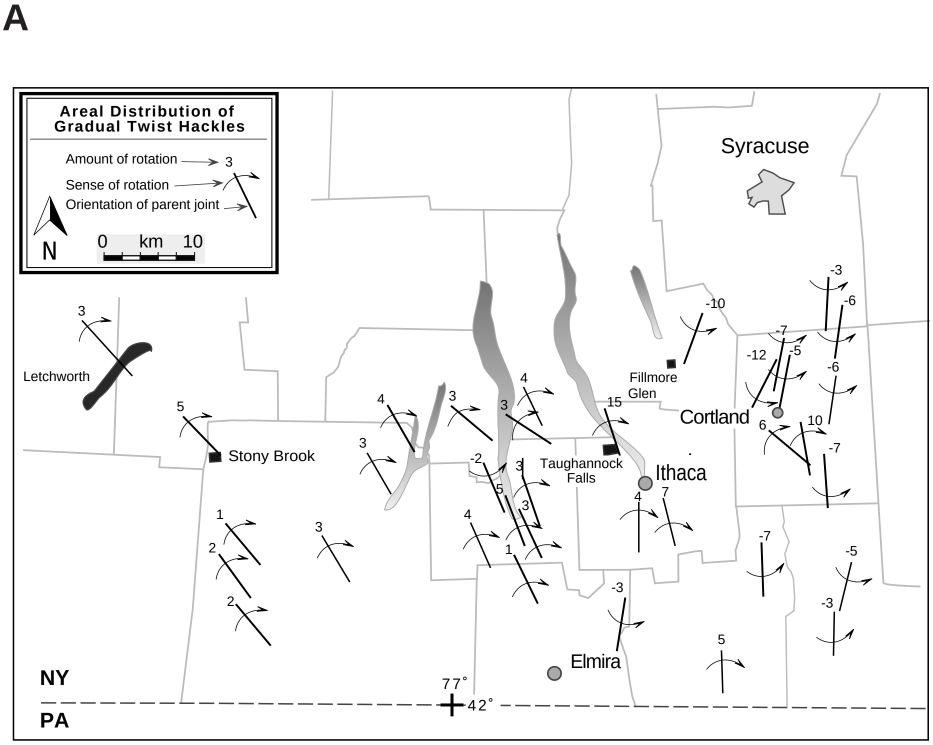


Figure 11. Areal distribution of fringe cracks. The amount of rotation shown is the average of all fringe crack sets at every station. CW—clockwise; CCW—counterclockwise.

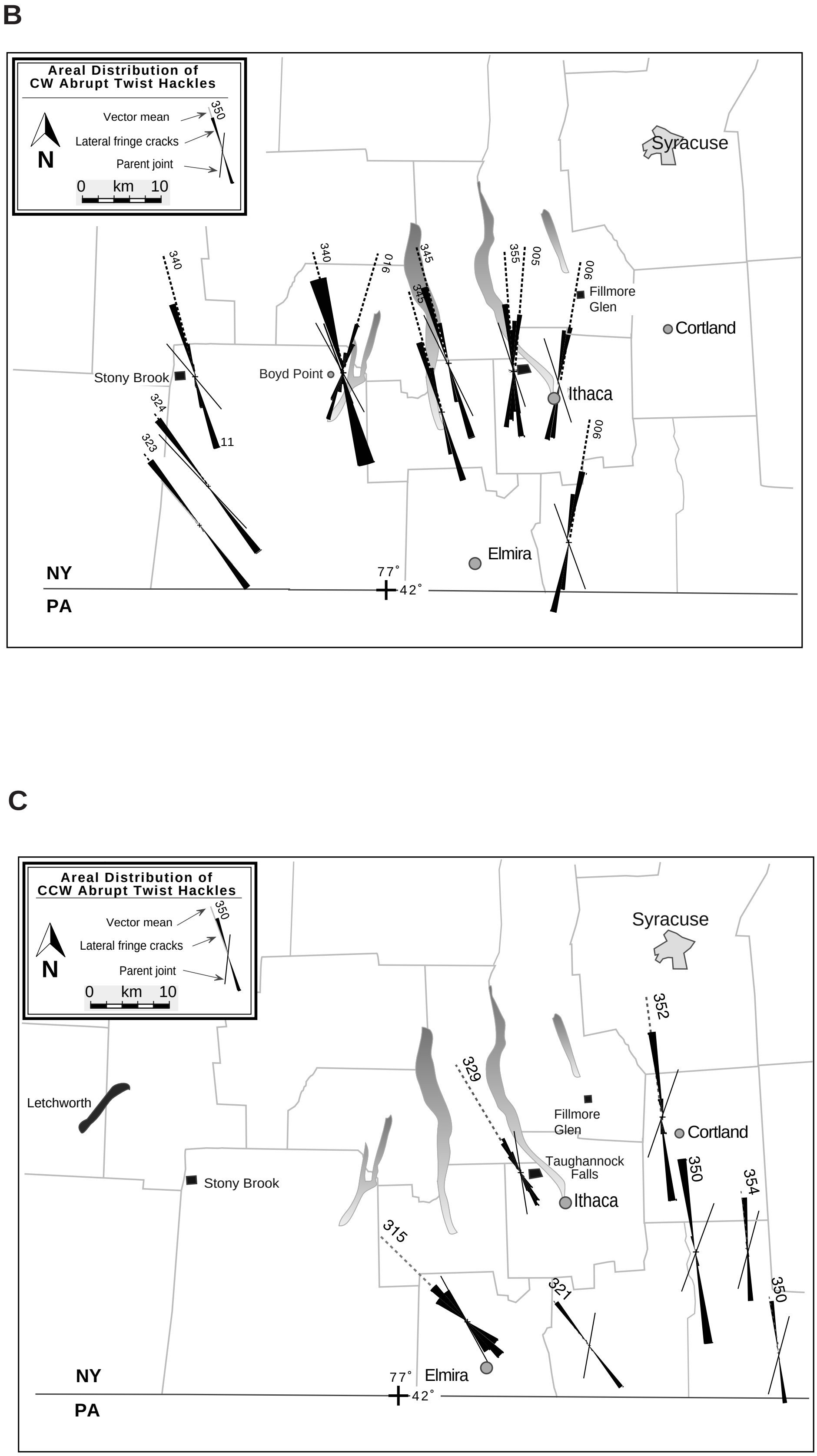


Figure 11. (*Continued*).

by Geiser and Engelder (1983). Bahat (1991) and Evans (1994) presented evidence for structures in more than two orientations suggesting that the northeastern portion of the Appalachian plateau detachment sheet was also deformed by a more continuous clockwise rotation of the Alleghanian stress field. If so, the tectonic evolution of the Appalachian plateau detachment sheet is consistent with that found in the Valley and Ridge.

FRINGE CRACKS OF THE DETACHMENT SHEET

Within the Appalachian plateau detachment sheet, we identify four types of fringe cracks (Fig. 4). Three of these types are discussed in this paper: gradual twist hackles, abrupt twist hackles, and kinks. We refer to the angle between the parent joint and the fringe crack as clockwise or counterclockwise, depending on the sense of rotation going from the parent to the fringe crack in map view. The fourth type is more difficult to recognize and is not discussed here.

Gradual Twist Hackles

On the Appalachian plateau, gradual twist hackles occur within the same bed and lithology that hosts the parent joint (Figs. 1 and 8). The surfaces of a gradual twist hackle occasionally show a plumose structure that indicates an overall vertical propagation direction. This surface morphology is often continuous with that of the parent joint, giving no indication that the tip line of the parent joint arrested before the gradual twist hackle propagated. Upon breakdown at the joint tip line, individual fringe cracks twist away from the parent as they realign normal to the local maximum tensile stress. Hence, the hackle is a series of en echelon fringe cracks that initiate from the plane of a parent joint and twist out of the plane by propagating normal (i.e., vertically) to the overall lateral propagation direction of the parent joint.

As fringe cracks grow, stress shadows develop to suppress the growth of adjacent cracks (Nemat-Nasser and Oranratnachai, 1979; Gross et al., 1995), giving rise to a characteristic pattern exhibited by gradual twist hackles (Figs. 1 and 8). The frequency of fringe cracks decreases with vertical distance away from the parent joint (Helgeson and Aydin, 1991). Gradual twist hackles can propagate downward, upward, or in both directions within the host bed. With very few exceptions, gradual twist hackles within the Appalachian plateau detachment sheet propagate toward the top of the bed after the parent joint passed through the lower portion of the stratum. Gradual twist hackles occur on both dip joints and on later systematic joints striking 070° within the study area and are equally common in sandstones, siltstones, and shales.

Abrupt Twist Hackles

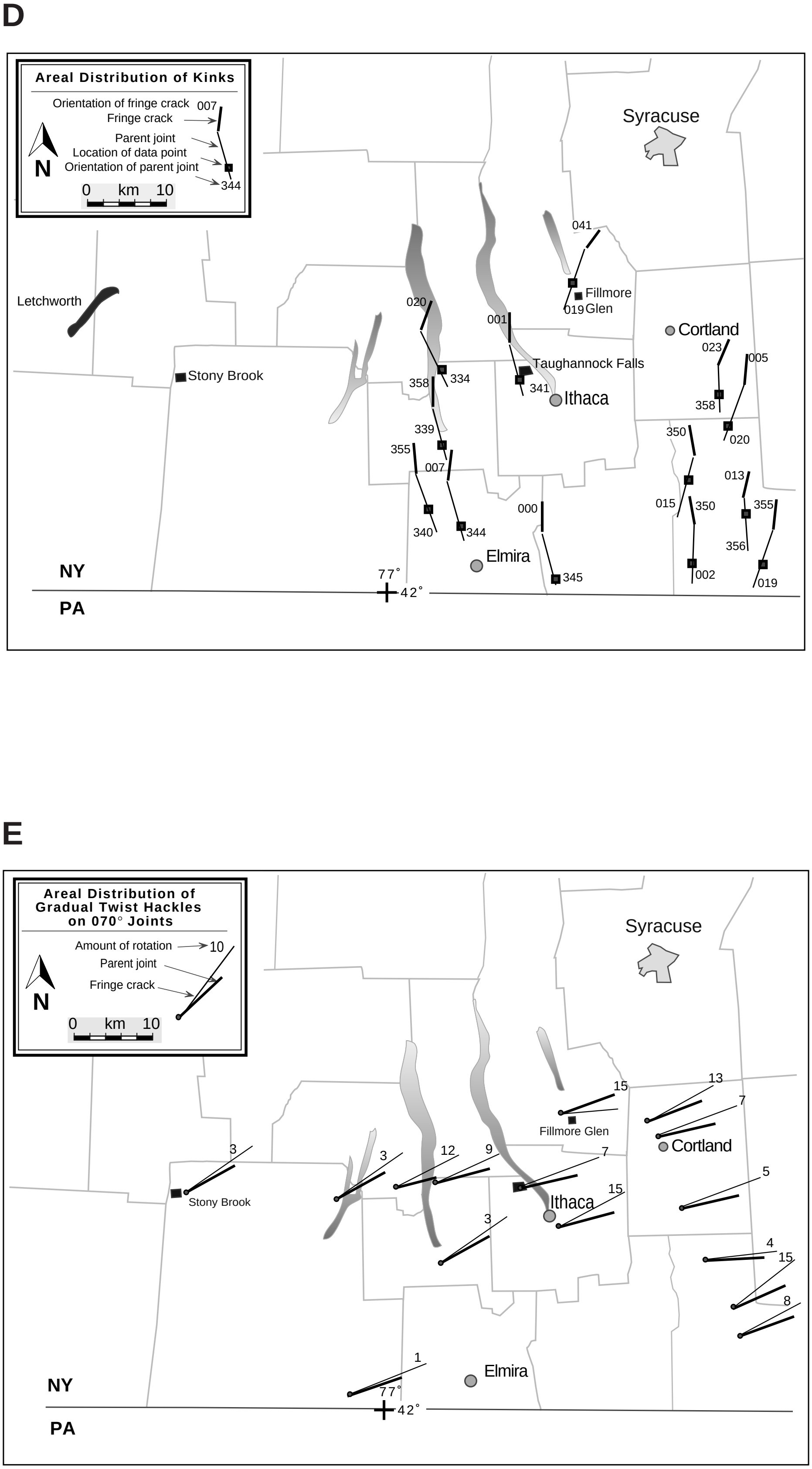
On the Appalachian plateau, abrupt twist hackles are commonly found in shale and initiate from the tip line of dip joints in siltstone beds that are typically less than 30 cm thick. Individual en echelon cracks that are planar and that emanate abruptly from the edge of a parent joint are known as abrupt twist hackles (Figs. 2 and 9). Because abrupt twist hackles abut the parent joint at a point, they appear in map view to grow across the edge of the parent joint. In contrast with gradual twist hackles that grow within the same bed as the parent joint, abrupt twist hackles are separated from parent joints by a bed boundary. These en echelon cracks are equally common propagating upward, downward, or in both directions from siltstone beds (cf. Helgeson and Aydin, 1991).

Fringe cracks rarely exceed one meter in length (i.e., the dimension parallel to propagation, which is vertical for twist hackles), and have a spacing that correlates well with the crack length. This spacing is governed by the stress shadows of the largest fringe cracks and forms the familiar pattern of suppressed growth found in gradual twist hackles. As a rule of thumb, spacing of the largest fringe cracks is about half their vertical dimension, whereas joint spacing in the parent beds is typically 30% larger than their vertical dimension (Loewy, 1995). Within an abrupt twist hackle, all the fringe cracks are usually parallel. However, in a few examples, smaller cracks tend to have a larger twist angle from the parent than the larger cracks.

Abrupt twist hackles are best developed in the Ithaca Formation of the Genesee Group. It is possible that the distinct shale and siltstone interlayering of the Ithaca Formation provides a favorable lithologic contrast for the initiation of the abrupt twist hackles. Field evidence indicates that siltstones are "fracturable" at an earlier time and shale at a later time, between which times a large stress rotation occurred (Engelder, 1985). A rotation of the remote stress field at some later time would produce the mixed-mode loading conditions necessary for the twist hackles to propagate in the adjacent shale beds.

Kinks

In the Appalachian plateau detachment sheet, kinks occur exclusively in siltstone beds. If two kinks occur with a parent joint, both show the same sense and magnitude of rotation relative to



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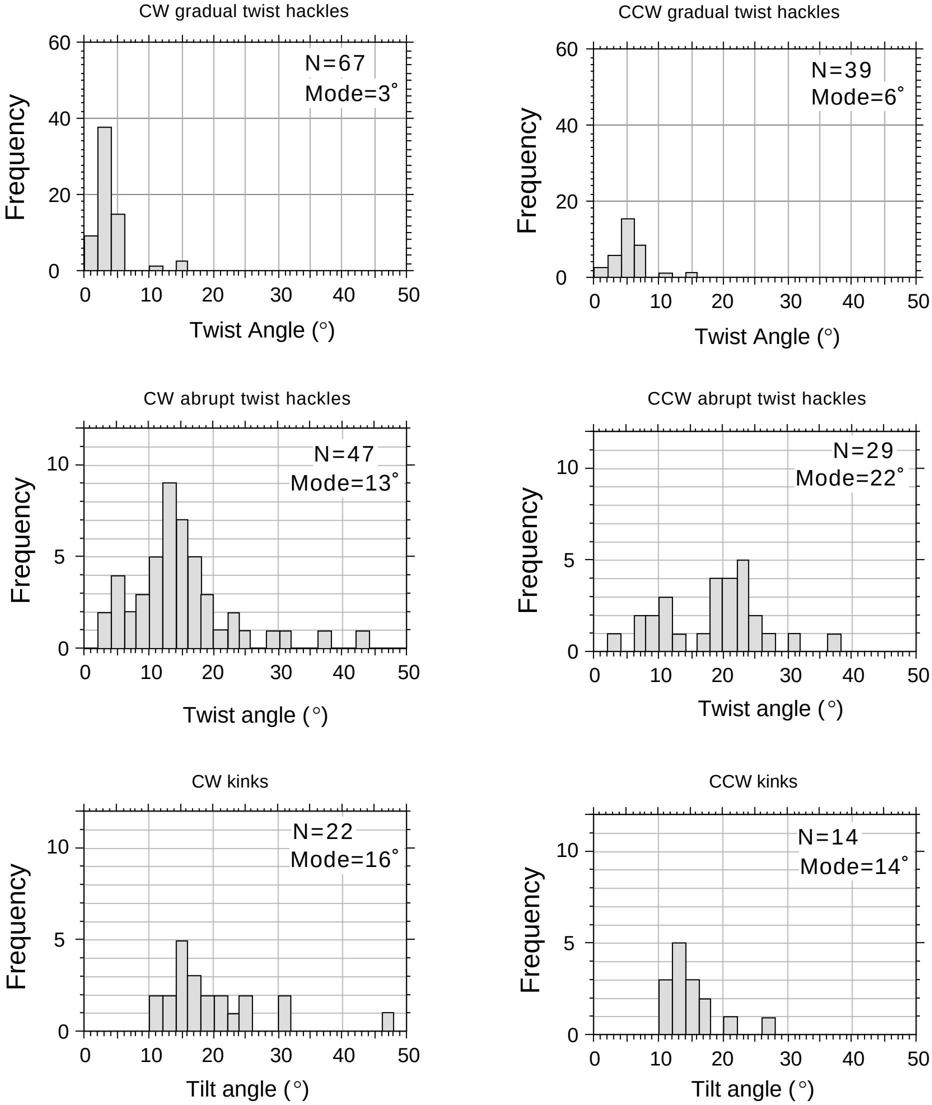


Figure 12. Histograms of the magnitude of clockwise (CW) and counterclockwise (CCW) rotations for gradual and abrupt twist hackles and kinks. The number of fringe sets and the statistical mode of orientation is shown inside each histogram. The amount of CCW rotation for twist hackles is larger than the CW rotation. Kinks have a more consistent orientation (mode is almost the same for CW and CCW rotations).

the parent (Figs. 3 and 10). Some parent joints with kinks are decorated with abrupt twist hackles in the adjacent shale beds. These flanking fringe cracks show the same sense of angular twist as the tilt of the lateral kinks. No evidence for slip was observed on any parent joint carrying kinks within the study area. Kinks occasionally show a surface morphology of plumes that are continuations of the plume morphology from the parent joint. This indicates that kinks occur as mode I cracks and the tilt in a crack path is driven by a shear traction superimposed on the parent joint after arrest following a finite amount of mode I propagation (Erdogan and Sih, 1963; Cottrell and Rice, 1980).

AREAL DISTRIBUTION OF FRINGE CRACKS AND PARENT JOINTS

Orientation of Fringe Cracks Relative to Parent Joints

More than 225 sets of fringe cracks were mapped in the northeastern portion of the Appalachian plateau detachment sheet within the Finger Lakes district of New York State. Although there are millions of joints throughout the detachment sheet, joints decorated with fringe cracks are rare. The number of joints decorated with fringe cracks within individual outcrops varies from one to more than several dozen. Figure 11 (A–E) shows the orientation and areal distribution of various types of fringe cracks and their parent joints. The maps plot the data from an outcrop by presenting the average strikes of all fringe cracks and their parent joints. Fringe cracks are found in rocks of all groups and most lithologies mentioned in Figure 7.

The general orientation of all fringe crack sets follows the systematic change in fold trend and strike of the parent joints from east to west through the detachment sheet. In general, depending on the type of fringe crack, the magnitude of the angle between parent joint and fringe cracks remains about the same across the area. However, there is a pattern to the sense of fringe crack rotation across the region. To the east of Ithaca, fringe cracks strike counterclockwise from the parent joints, to the west they strike clockwise from their parents, and in the vicinity of Ithaca, both senses of rotation are found. Because the loading conditions and timing of propagation are different for each fringe crack type, there are characteristic differences in twist or tilt angle. Kinks are concentrated in the eastern half of the study area and tend to strike within a few degrees of 002°, seemingly independent of orientation of the parent (Fig. 11D).

The angle of twist or tilt (β) of a fringe crack set changes according to the host rock, the type of the fringe crack, and the sense of rotation. The twist angles for clockwise twist hackles are generally smaller than for counterclockwise twist hackles (Fig. 12). Gradual twist hackles have small twist angles, with a mode at 3° for clockwise fringe cracks and 6° for counterclockwise fringe cracks. Abrupt twist hackles have larger twist angles, with a mode at 13° for clockwise fringe cracks and 22° for counterclockwise fringe cracks. Kinks have tilt angles with a mode of 16° for clockwise fringe cracks and 14° for counterclockwise fringe cracks.

The maximum twist angle (β) for gradual twist hackles varies according to the lithology hosting the parent joint. This is seen in a plot of the strike of fringe cracks versus the strike of parent joints (Fig. 13). In this plot, data for counterclockwise fringe cracks would plot below a line with a slope of one, whereas data for clockwise fringe cracks are plotted above this line. By drawing delimiting envelopes parallel to this line, we find the maximum twist angles in coarser beds. For example, twist hackles in shale layers have a maximum twist angle of 4°, whereas those in sandstone layers reach 10° for fringe cracks with a clockwise twist angle.

Sequence of Dip Joint Development

Throughout the detachment sheet, evidence for the timing of joint development includes curving or kinking of joints as the younger approaches the older or abrupt termination of younger joints against older joints (Fig. 14). Cases of unambiguous abutting are less common than mutual cross-cutting. Nevertheless, abutting between dip (i.e., parent) joints in the detachment sheet shows a consistent relationship from west to east where the later dip joints, particularly in the western portion of the study area, strike a few degrees clockwise from earlier dip joints (Fig. 15). Younger dip joint sets are defined by the horizontal clustering of data in Figure 15. Abutting dip joints cluster at strikes of 342°, 351°, and 003°, suggesting that younger dip joints have a consistent orientation throughout the region despite predecessors of widely varying orientation. The earliest dip joint set, a spectrum of joints in the range of 320°–330°, do not cluster. The same appears to be true of a dip joint set striking in the range of 006° to 021° in the easternmost portion of the study area. These data indicate that joints striking at 342° generally abut joints striking at 320°–330° and 351° joints generally abut 342° joints, and so forth. The exception to this general rule for a clockwise sequence of younger joints is found at the eastern edge of the study area, where 003° joints abut parent joints striking roughly 020°, indicating a counterclockwise sense of rotation of the stress field in this area with time. Based on these observations, the sequence of dip joint development in the detachment sheet is as follows, with parentheses indicating sets of joints clustered about that orientation:

$$(320^\circ\text{–}330^\circ) \rightarrow \begin{bmatrix} \text{East Ithaca} \\ (006^\circ\text{–}021^\circ) \\ \\ (342^\circ) \\ \text{West Ithaca} \end{bmatrix} \rightarrow (352^\circ) \rightarrow (003^\circ)\,.$$

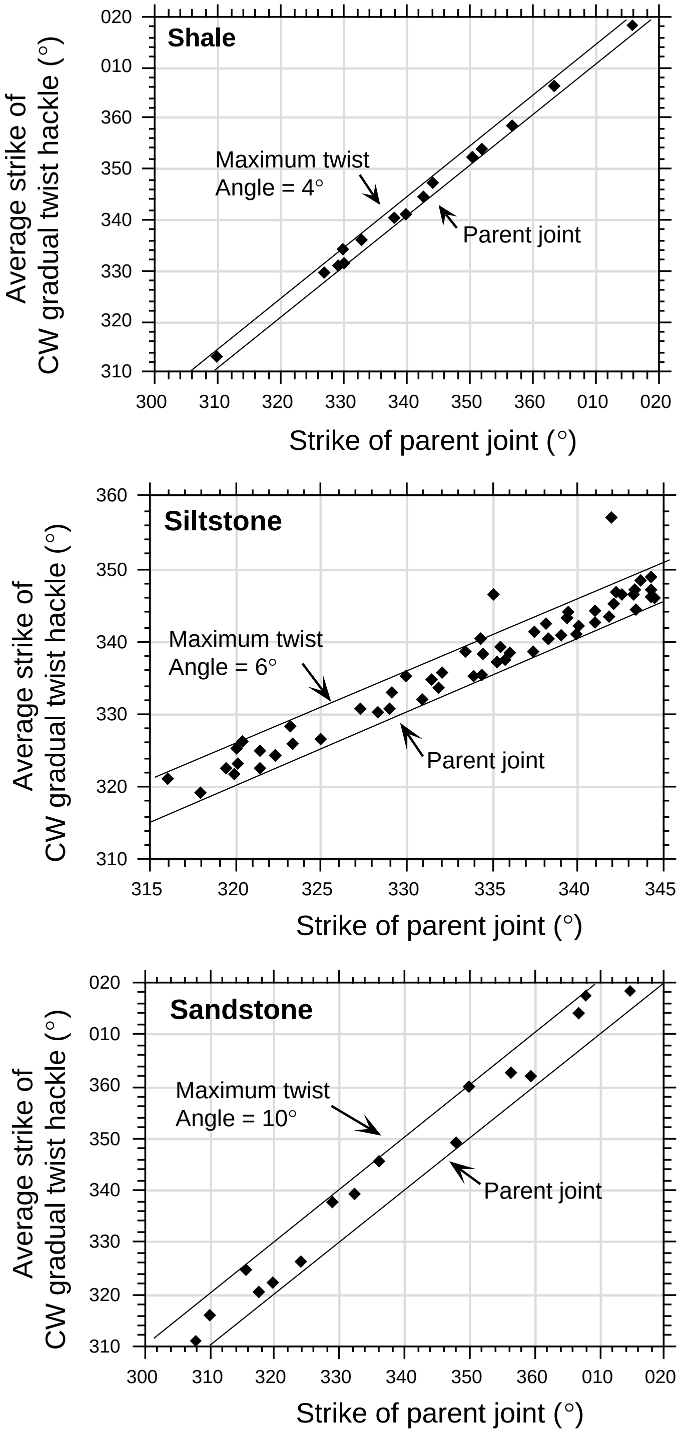


Figure 13. Change in the angle between parent joint and the clockwise (CW) gradual twist hackles according to lithology. The maximum twist angle increases as the clastic grain size becomes larger.

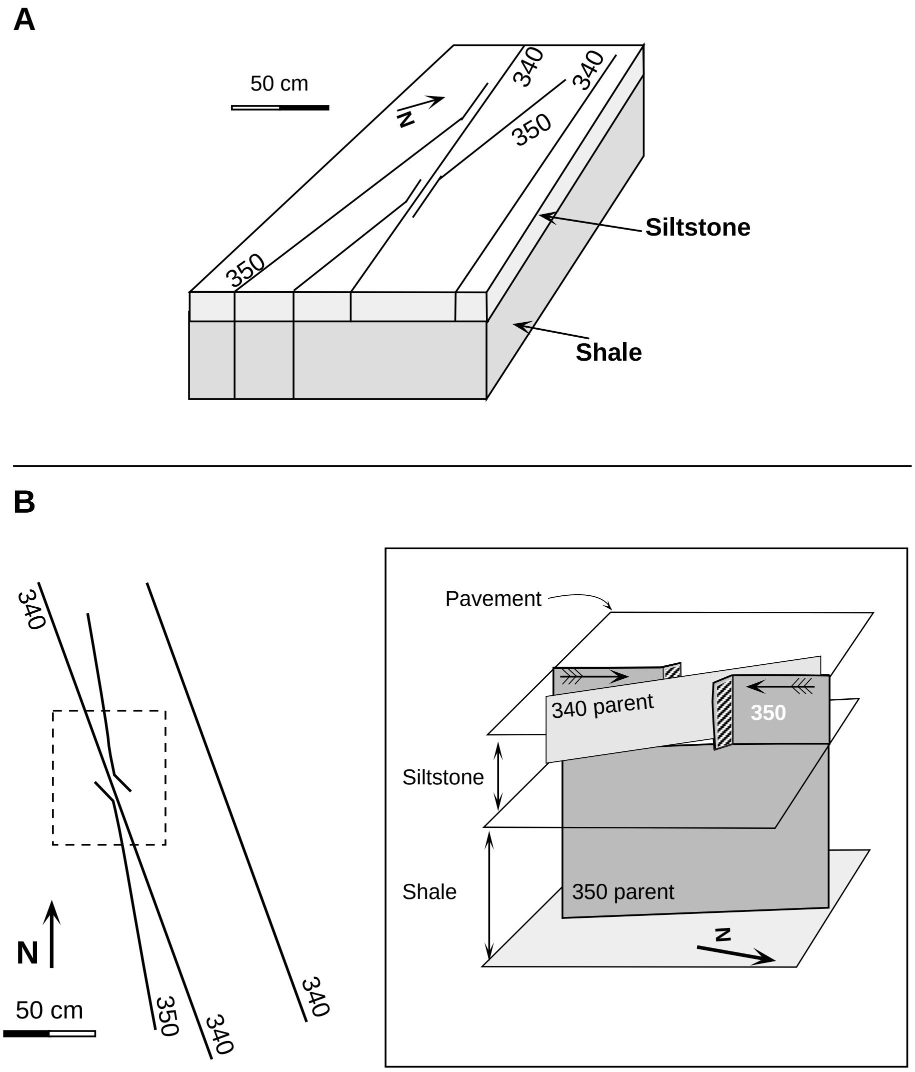


Figure 14. A schematic of parent joint interaction in Taughannock Falls, New York. (A) Joints within the siltstone layers are straight, except those that propagate in the shale curve or kink as they approach the older 340° joints in the siltstone. (B) Tip fringe cracks forming as the tip of the 350° joint in the shale abruptly kinks as it approaches the 340° joint in the siltstone. Arrows in the three-dimensional diagram indicate the propagation direction of the 350° joint.

Other post-Alleghanian joint sets are also found throughout the detachment sheet. One post-Alleghanian 070° set is best developed in black shale below the Rhinestreet Formation (Loewy, 1995). Where present, fringe cracks are always counterclockwise from these parent joints (Fig. 11E). The 070° joints are cut by Middle Jurassic kimberlite dikes (Kay et al., 1983) in the vicinity of Ithaca, and therefore, are older than Middle Jurassic. Another post-Alleghanian 000° set consists of short, curviplanar to planar joints that occasionally abut earlier 070° joints. The 000° set is the youngest joint set documented in this paper. These joints strike parallel to the Mesozoic kimberlite dikes (Martens, 1924; Parker, 1942).

DISCUSSION

Arguments for a Temporal Change in Stress Orientation

Fringe cracks originate when an advancing joint surface encounters a shear couple. If the advancing joint enters a volume of rock subject to a stress field misaligned relative to that guiding the parent joint, transverse adjustments in crack propagation due to mixed-mode loading cause the joint to break down into fringe cracks (Lawn, 1993). If the misaligned stress field was present prior to joint propagation, the misalignment is spatial. If the misalignment took place after propagation and arrest of the parent joint, the misalignment is temporal. Evidence suggests that within the Appalachian plateau detachment sheet, the shear couple was imparted during a temporal misalignment when the regional stress field was rotated about a vertical stress axis, S_v. The strongest evidence for this progressive misalignment of the remote horizontal stresses, S_H and S_h, is the regional distribution of fringe cracks with a uniform sense of twist or tilt.

Our data show regional trends in fringe crack geometries; with clockwise twist and tilt angles found in the west and counterclockwise twist and tilt angles most common in the east (Fig. 11). This regional distribution of fringe cracks is consistent with a temporal change in orientation of the remote stress field. The distribution is also uniform throughout a layered sequence of sandstones, siltstones, and shales. A nonuniform sense of rotation within a layered sequence would have indicated a spatial change in local stress orientation rather than a temporal change in orientation of the remote stress field. In fact, it is difficult to imagine a local mechanism causing such consistently uniform spatial changes in the stress field from one bed to the next and one outcrop to the next. Even in outcrops such as those at Taughannock Falls, where we find both senses of twist angle, abutting within the outcrops suggests a connection to a broader regional remote stress history with clockwise fringe cracks developing prior to counterclockwise fringe cracks (Fig. 14).

The apparent lack of structures at the margin of parent joints and the continuous plumes tracing from the parent joints to the gradual twist hackles are curious. One interpretation is that the fringe cracks propagated as a continuous rupture from their parent joint without arrest. If the rupture propagation from parent to fringe crack was uninterrupted and continuous, and mixed-mode loading was imposed during the joint propagation event, the front end of the parent joint should curve or hook in response to the same mixed-mode loading. Curving and hooking of parent joints were not found in conjunction with gradual twist hackles. The parent joints are planar, indicating that joint propagation ran through the lower portion of the bed without leaving its plane and without breaking up through to the top bed boundary (Figs. 1 and 8). Consequently, our interpretation is that joint propagation along the lower portion of the bed was arrested within the bed before a temporal change in the remote stress field orientation. Only later, as fringe cracks grow in response to mixed-mode loading, does the joint break through to the upper bed boundary. Perhaps the reason that gradual twist hackles are not more common in siltstone beds is that in most cases the initial rupture of the parent joint broke through to the upper contact with shale, leaving no opportunity for later gradual twist hackle development.

Such temporal changes in remote stress orientation have been modeled experimentally (Cooke and Pollard, 1996). During these experiments, propagation of a mode I crack was stopped before mixed-mode loading was imposed. This is our model for gradual twist hackle growth on the Appalachian plateau. However, from the description of the experiments, it is not clear whether reinitiation of crack propagation was continuous or discontinuous. In short, data on twist and tilt angles point to a temporal change in the orientation of remote stress rather than a spatial change in the orientation of the local stress on a bed-by-bed basis.

Twist Angle and the Role of Lithology

Although twist hackles reflect the sense of the remote stress field rotation, fringe cracks propagate normal to the local least compressive stress, which is often not in the same orientation as the remote least compressive stress, σ_1^r (Pollard et al., 1982). The type of breakdown (continuous or discontinuous) at the joint tip depends largely on the magnitude of the remote stress rotation, α, the stress ratio, *R*, and the elastic modulus of the rock. The gradual twist hackles in the Appalachian plateau detachment sheet resemble those described by Pollard et al. (1982) as a continuous or smooth twist zone,

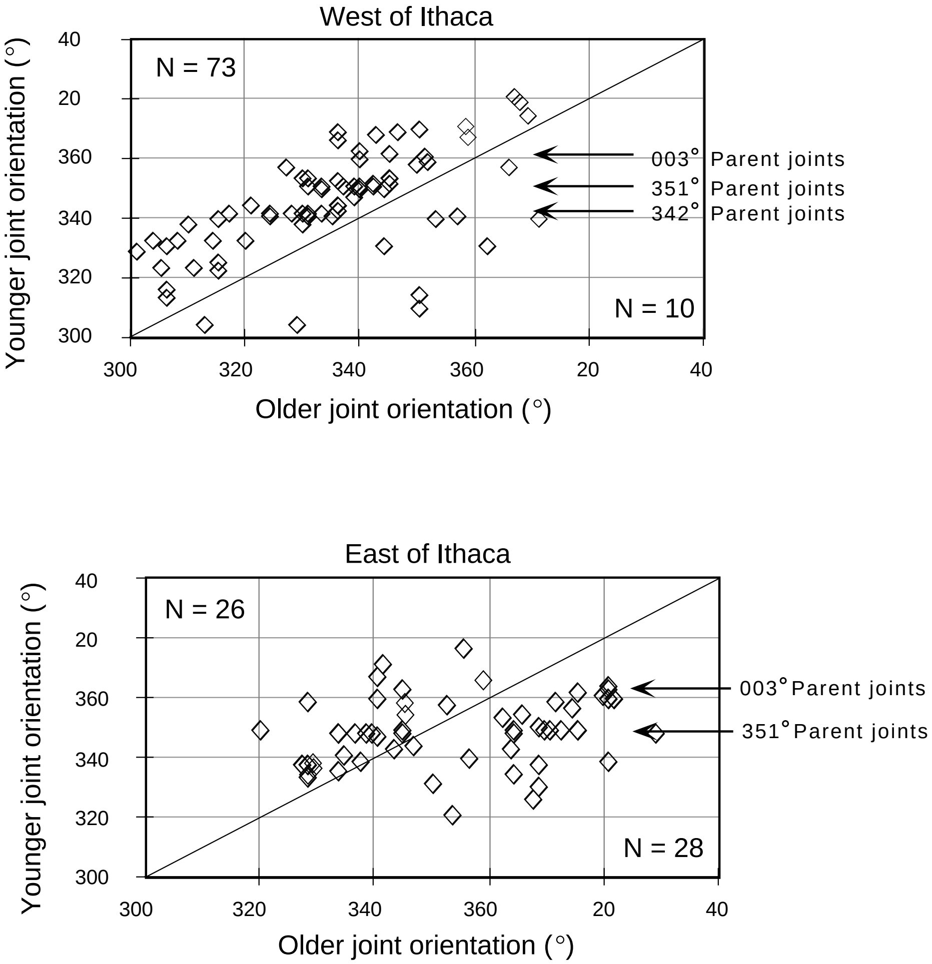


Figure 15. Abutting relationships west and east of Ithaca, New York. The diamond symbols above the straight line indicates clockwise abutting relationship, whereas those under the line are counterclockwise rotations. The abutting of joints west of Ithaca is dominated by clockwise rotations, but mixed rotations are found east of Ithaca.

TABLE 1. MECHANICAL DATA

	Conditions at a depth of 3–4 km					Field data				Conditions at gradual-abrupt boundary				
Lithology	Twist hackle type	S_v (MPa)	S_H (MPa)	S_h (MPa)	P_i (MPa)	R	α (°)	v	β (°)	K_{ic} (MP_a= $m^{1/2}$)	R–boundary	Internal pressure at R-boundary	Driving stress at R-boundary (MPa)	Joint height at R-boundary (m)
Shale	Gradual	–78	–78.8	–77.5	81.5	5.15	10	0.14	4.43					
	Abrupt	–78	–78.8	–77.5	78.8	1.00	10	0.14	13.05	1.5	1.77	79.30	1.80	0.22
Sandstone	Gradual	–78	–80.5	–74.5	81.5	1.33	10	0.06	9.44					
	Abrupt	–78	–80.5	–74.5	78.8	0.43	10	0.06	14.76	2	1.27	81.31	6.81	0.03

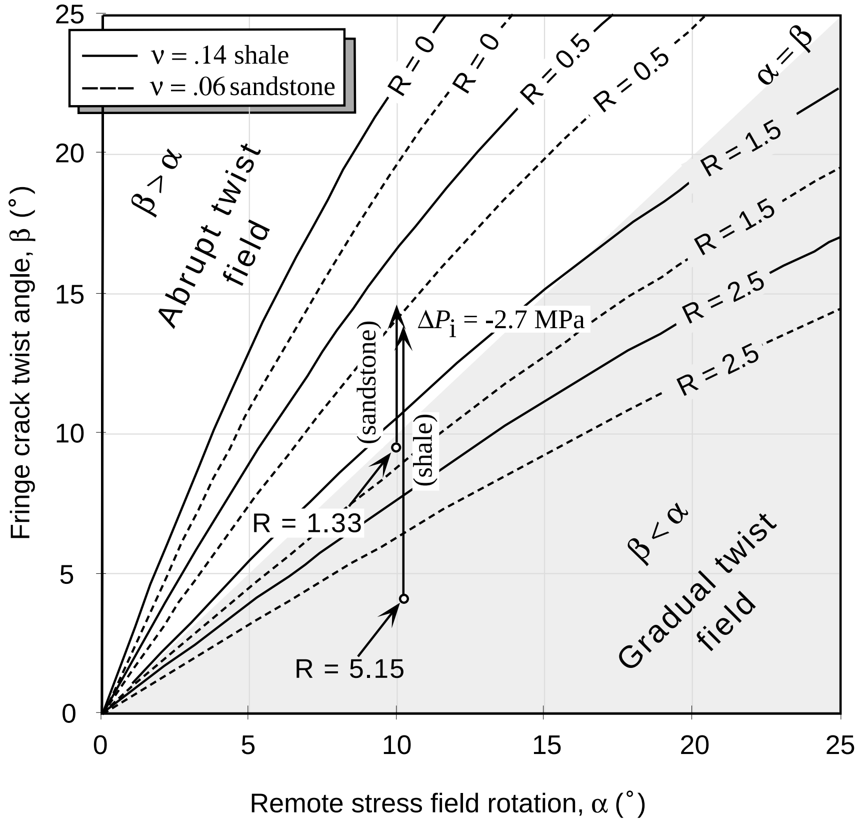


Figure 16. Plot of the twist angle of a fringe crack relative to the corresponding rotation of the remote stress field (adapted from Pollard et al., 1982). The curves are plotted for different stress ratios (R), and for Poisson's ratios of 0.06 (representing sandstone) and 0.14 (representing shale). See text for explanation. Log data from the detachment sheet indicates that ν_{shale} = 0.14 and $\nu_{sandstone}$ = 0.06 (Plumb et al., 1991).

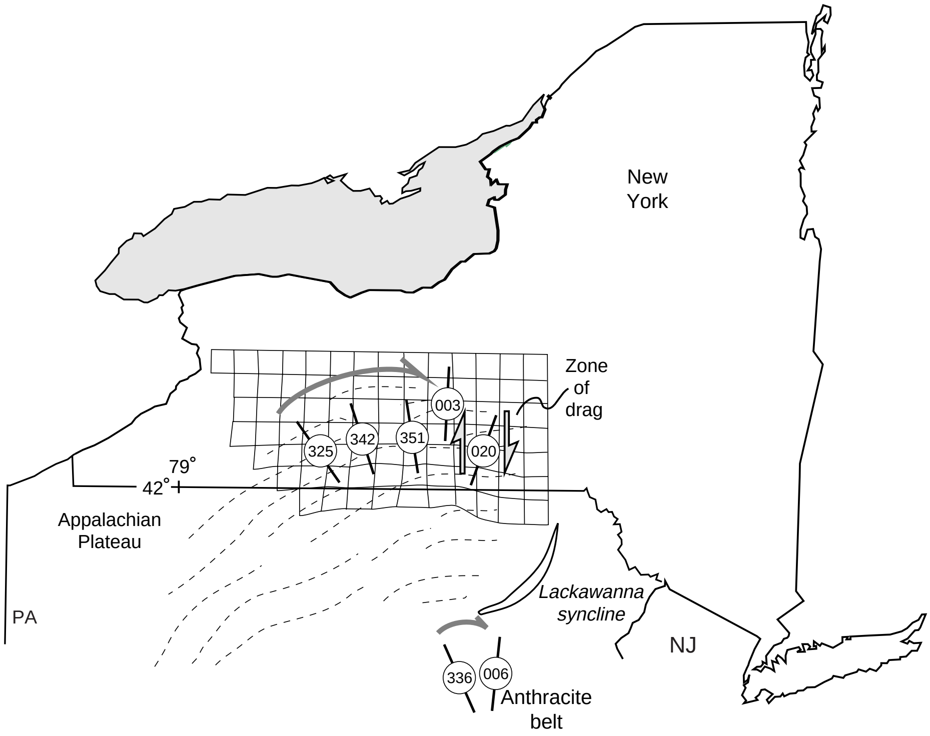


Figure 17. Deformed-state grid given by the displacement field determined from finite strain as indicated by deformed crinoid columnals and cleavage (adapted from Geiser, 1988). Dashed lines are traces of the fold axes. The samples with numbers indicate the trends of joint sets from the Appalachian Plateau (this study) and data on the orientation of the Alleghanian stress field in the anthracite belt of Pennsylvania (Gray and Mitra, 1993).

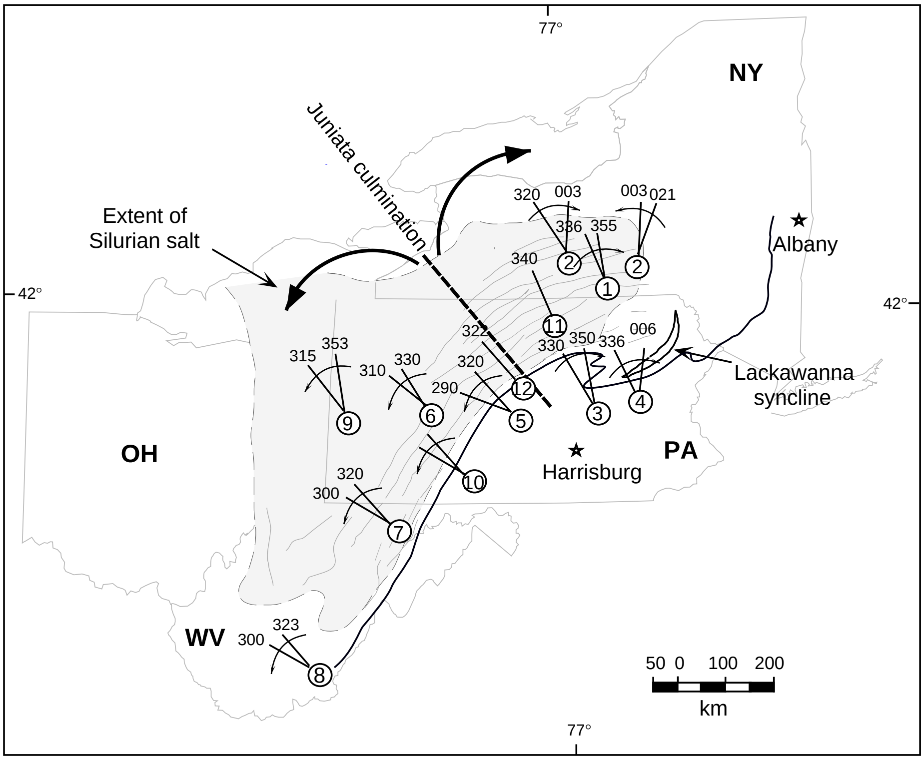


Figure 18. A model for the rotations of the Alleghanian stress field in the Central Appalachian Mountains. The heavy black line is the boundary between the Valley and Ridge and Appalachian Plateau. The short straight segments indicate the first and last stages of deformation determined by the following authors indicated by the corresponding number: 1, Engelder and Geiser (1980); 2, this paper; 3, Nickelsen (1979); 4, Gray and Mitra (1993); 5, Nickelsen (1988); 6, Nickelsen and Hough (1967); 7, Dean et al. (1984); 8, Dean et al. (1988); 9, Evans (1994); 10, Nickelsen (1996); 11, Spiker and Gray (1997); 12, Nickelsen and Engelder (1989). The thin arrows indicate the local sense of rotation, and the thick arrows indicate the regional sense of rotation proposed in this study. The heavy dashed line marks the location of the Juniata culmination.

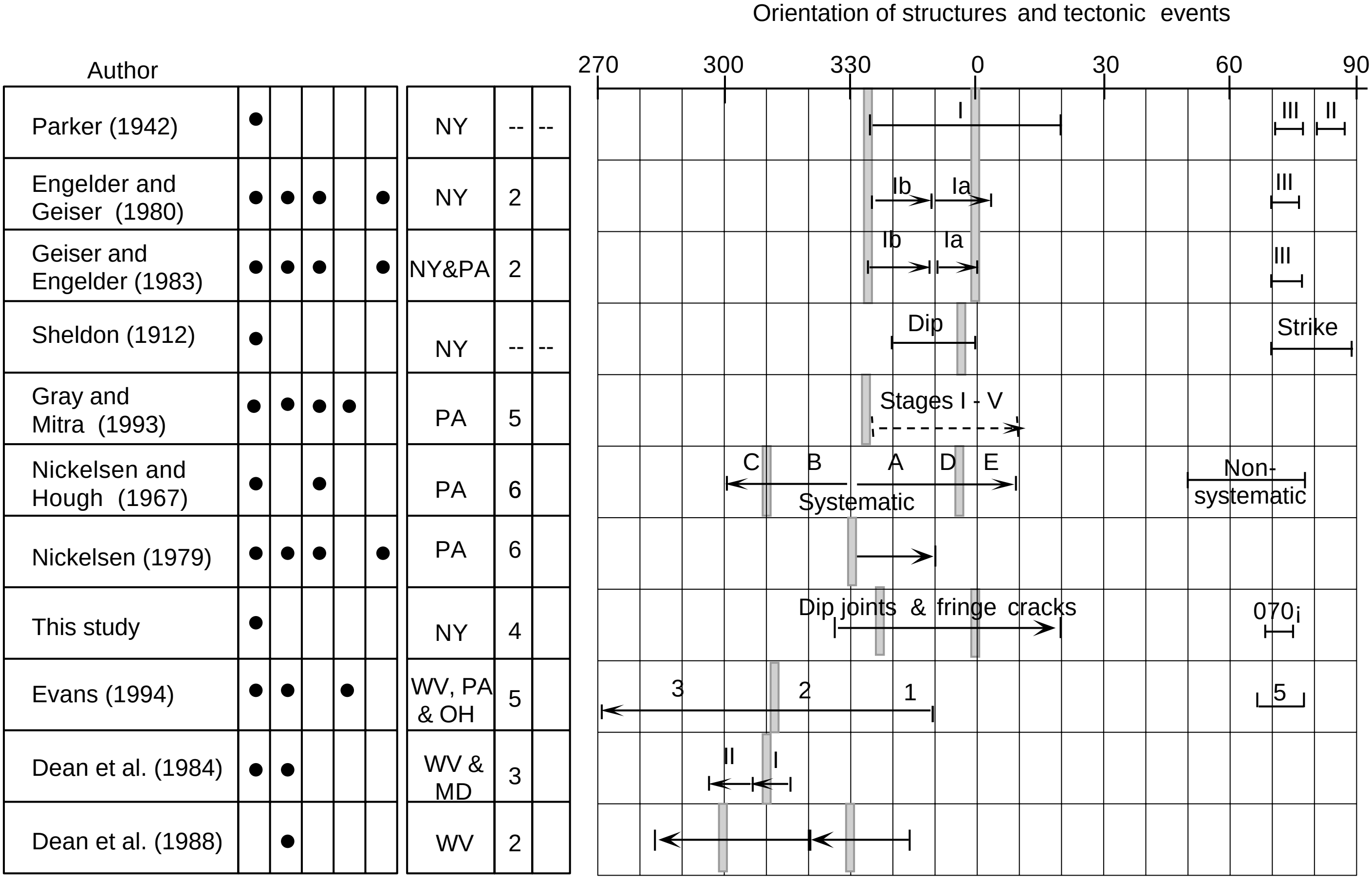
where $\beta < \alpha$ (i.e., the twist angle of the fringe crack is less than the rotation angle of the remote stress). In contrast, abrupt twist hackles in the detachment sheet are the field analogs of the discontinuous or rough zone (Pollard et al., 1982), where b > a. We are encouraged that the theoretical explanation for gradual and abrupt twist hackles offered by Pollard et al. (1982) applies to the detachment sheet because their theory predicts that the twist angle of abrupt twist hackles should be larger, as is found in the Appalachian plateau (Fig. 12). The following discussion gives an interpretation of the parameters that might have controlled the twist angle of twist hackles as a function of lithology within the detachment sheet.

Effect of Elastic Properties. The differences in β as measured on gradual twist hackles within shale, siltstone, and sandstone beds is striking (Fig. 13). According to equation 2, if both sandstone and shale beds are subject to the same *R* and a regional α, the twist angle will depend on the value of ν for each bed. Thus, in the detachment sheet, joints in beds with lower ν should break down with smaller twist angles. Geophysical log data indicate that sandstones and siltstones from the Catskill delta have a lower ν than the shales (Plumb et al., 1991). Consequently, the beds of coarser clastic rocks should contain joints with a smaller twist angle. Based on our observation that joints in sandstone beds have the larger twist angles (Fig. 13), a dependence on ν can be ruled out as the sole explanation for the variation of twist angle with lithology.

Effect of Stress and Pore Pressure. Apparently, elastic properties are subordinate to differential stress and pore pressure within the three lithologies in controlling twist angles. If so, we can estimate the relative magnitude of pore pressure using the rotation angle of gradual twist hackles in different lithologies and some reasonable assumptions about principal stresses. We already know some characteristics about in situ conditions. First, the surface morphology on parent joints is consistent with joints driven by high internal pressure, where $P_i > |S_h|$ (Lacazette and Engelder, 1992). Second, stress measurements within the Appalachian plateau detachment sheet show that sandstones carry a higher differential stress than shale interbeds (Evans et al., 1989). This is common in other sandstone-shale sequences as well (e.g., Warpinski, 1989). Assuming that all beds were affected by the same regional α under these conditions, equation 2 predicts that the twist angle in sandstone layers should be larger than the twist angle for shale. This is consistent with our data showing that $\beta_{shale} \leq 4°$, and $\beta_{sandstone} \leq 10°$ (Fig. 13).

To estimate pore-pressure conditions for twist hackle development we assume that P_i is the same in adjacent beds of sandstone and shale and that $\alpha = 10°$ in all beds. Estimates of burial history suggest that twist hackle propagation took place at a depth of 3–4 km within the detachment sheet (cf. Evans, 1995), so we assume that σ_2^r ($S_v = \rho gz$) ≈ –78 MPa. Based on the analysis of calcite twinning, the differential stress in sandstone was estimated to be 6 MPa during the Alleghanian orogeny (Engelder, 1982). This stress difference is about 50% less than that measured in sandstone beds but close to that measured in shale of the detachment sheet using hydraulic fracture (Evans et al., 1989). Layer-parallel shortening and vertical jointing requires that $S_H < S_v < S_h$ (tensile stress is positive) during development of the gradual twist hackles. Hence, to satisfy this condition we set σ_1^r (S_h) = –74.5 MPa and σ_3^r (S_H) = –80.5 MPa in the sandstone using the more conservative estimate of stress from calcite twinning. We now use equations 1 and 2 to calculate a P_i that will yield $\beta \approx 10°$ (see Table 1). For $\sigma_1^r - \sigma_3^r = 6$ MPa in the sandstone and a crack-driving stress of 7 MPa (i.e., $P_i = 81.5$ MPa) the result is $R = 1.33$ and a twist angle of 9.4° (Figs. 13 and 16).

Having established the local pore pressure (i.e., $P_i = 81.5$ MPa), we can now calculate the stress in the shale interlayers that will lead to gradual twist hackles having $\beta \approx 4°$. A crack-driving stress of 4 MPa (i.e., $P_i = 81.5$ MPa) and $R = 5.15$ gives a twist angle of 4.4° (Figs. 13 and 16). Here we find that σ_1^r (S_h) = –77.5 MPa and σ_3^r (S_H) = –78.8 MPa for a differential stress of



Author								
Parker (1942)	●					NY	--	--
Engelder and Geiser (1980)	●	●	●		●	NY	2	
Geiser and Engelder (1983)	●	●	●		●	NY&PA	2	
Sheldon (1912)	●					NY	--	--
Gray and Mitra (1993)	●	●	●	●		PA	5	
Nickelsen and Hough (1967)	●		●			PA	6	
Nickelsen (1979)	●	●	●		●	PA	6	
This study	●					NY	4	
Evans (1994)	●	●		●		WV, PA & OH	5	
Dean et al. (1984)	●	●				WV & MD	3	
Dean et al. (1988)		●				WV	2	

Figure 19. Selected data on the sense of rotation of the regional stress field in the central Appalachian Mountains during the Alleghanian orogeny.

1.3 MPa in the shale. For both the sandstone and shale layers, the internal pressure, P_i, must exceed the absolute value of both σ_1^r and σ_3^r in order for R to be consistent with the formation of gradual twist hackles. The significance of this result is that stress associated with the relative difference between gradual twist angles in sandstone and shale is consistent with the relative difference between stress in sandstone and shale as measured using other techniques such as hydraulic fracturing. Note also that the higher value of σ_1^r in the sandstone beds leads to early joint development in these beds rather than in the interlayered shales. The earliest jointing is found within the siltstone and sandstone beds of the detachment sheet (Engelder, 1985).

Our view of the development of gradual twist hackles requires that the rate of joint propagation is high relative to the rate of change in orientation of a regional stress field. If so, initial propagation must run along the bottom of some beds and arrest near the central portion of some beds to await a change in stress orientation. Arrest, which must take place before the entire bed is ruptured, occurs upon a decrease in internal pressure (Lacazette and Engelder, 1992). However, cycling of internal pressure to reinitiate propagation of twist hackles favors the development of abrupt twist hackles. Following the arrest of the parent joint it is assumed that $P_i < |\sigma_1^r|$, whereby $R < -1$ (equation 1). As the joint is recharged and internal pressure increases toward the propagation condition, $P_i > |\sigma_1^r|$, the stress ratio traverses through the field of abrupt twist hackles as defined by $-1 < R < \sim 1.5$ depending on the lithology (unshaded area of Fig. 16). According to equation 3, the boundary between abrupt and gradual twist hackles is $R = 1.27$ for a sandstone. For gradual twist hackles to form in sandstone beds, the internal pressure must increase enough to drive R upward above 1.27 and into the shaded area of Figure 16 without reinitiating propagation of the parent joint. When $R = 1.27$, the joint driving stress is 6.8 MPa within the sandstone. In a sandstone bed with a fracture toughness (K_{ic}) of 2 MPa • $m^{1/2}$ (Scott et al., 1992), an elliptical joint with a short axis of ~6 cm is required to hold the internal pressure without propagation to allow the condition $R > 1.27$ and the formation of gradual twist hackles. This approaches the vertical dimension of the parent joints decorated with gradual twist hackles (Fig. 8). For shale with $K_{ic} = 1.5$ Mpa • $m^{1/2}$, the development of gradual twist hackles requires a joint driving stress of 1.8 MPa, which is too large relative to that required by the dimension of parent joints in shale of the Moscow Formation of the Hamilton Group (Fig. 7).

When $\sigma_1^r - \sigma_3^r$ is low, R is very sensitive to small decreases in internal pressure. As joints grow, the joint tip stress intensity increases, thus requiring a smaller crack-driving stress for continued propagation. Hence, the internal pressure required to drive joint propagation would drop as a natural consequence of joint growth (Engelder and Lacazette, 1990). The larger twist angles for abrupt twist hackles (Fig. 9) may arise as a consequence of this sensitivity to a change in P_i. For example, using the same values for stress as given here, a drop in P_i of 2.7 MPa within the shale beds will drop R from 5.15 to 1.00. With $R \approx 1.0$, twist hackles are abrupt and the resultant twist angle is 13° in shale (see Fig. 12) when $\alpha = 10°$ (see arrow in Fig. 16). The same drop in internal pressure within adjacent sandstone beds has less effect on the twist angle but nevertheless leads to abrupt twist hackles in sandstone (Figs. 12 and 16). The formation of both gradual and abrupt twist hackles within the Appalachian plateau detachment sheet is consistent with the long-term decrease in internal pressure as the size of parent joints become larger.

Progressive Development of the Regional Stress Field

Pattern of Parent Joint Sets. Data on abutting of parent joints helps resolve the issue of whether there are more than two joint sets extending several hundred kilometers along strike in a fan-shaped pattern as proposed by Engelder and Geiser (1980). If the early joints in the Tully Limestone at Taughannock Falls correlate with the 320°–330° set found more than 100 km to the west, then the earliest 320°–330° set does not fan, but rather is an indication that the same joint set appears in different lithologies in different locations. If the 342° set in the western portion of the study area is contemporaneous with the 006° to 021° joint set in the east, then we have identified a joint set that is found in a fan-shaped pattern. Superimposed on this fanning pattern are two more joint sets, each differing in strike about 10°. Individual sets are best seen in the data for abutting of parent dip joints (Fig. 15), where later joints cluster at 342°, 351°, and 003°. This interpretation of joint pattern development is consistent with that presented by Nickelsen and Hough (1967), where joints of one set cluster about one orientation rather than fanning. However, we cannot reject the interpretation (Engelder and Geiser, 1980) that a single joint set fans over several hundred kilometers around the Appalachian orocline.

The pattern of dip joints in the Appalachian Plateau detachment sheet developed through four stages, as indicated by both the abutting of parent joints and the rotation angle of fringe cracks. The regional pattern of parent joints is due to the overlapping pattern of joint sets with different strikes. The pattern developed from west to east as progressively younger joint sets propagated within a stress field rotating in a clockwise manner. During this progressive development of structures in the detachment sheet, the Alleghanian stress field sweeps through an angle of roughly 40° from 320° to north-south. To the southeast in the anthracite region of the Valley and Ridge, structures record a clockwise rotation of the Alleghanian stress field through an angle of 30° (336° to 006°) (Gray and Mitra, 1993). Although the magnitude of the stress field differs slightly from the Plateau to the Valley and Ridge, the correlation is close enough to suggest that both areas recorded the same tectonic history, which involved a clockwise rotation of the horizontal stress field.

Counterclockwise Propagation of Fringe Cracks near the Eastern Boundary. Fringe cracks, coupled with the abutting geometries of parent joints, provide a record of the path followed by the Alleghanian stress field during the structural development of the Appalachian Plateau detachment sheet. Not only do these structures indicate the orientation of the stress field when they formed, they also preserve a record of the temporal sense of rotation of the stress field. The fidelity of the record of stress field rotation from the fringe cracks and abutting geometries can be tested by comparing the rotation of the Alleghanian stress field and strain within the detachment sheet. An isostrain map for layer-parallel shortening of the detachment sheet was constructed from data on the orientation of both deformed fossils and cleavage (Geiser, 1988). Layer-parallel shortening fans from west to east in a radial pattern (Fig. 17). The east-west lines display a uniform spacing (i.e., strain gradient) except east of Ithaca in the eastern portion of our study area, where the rectangular grid is distorted and the east-west grid lines are more closely spaced. This region of the most distorted grid coincides with the region containing parent joints decorated with fringe cracks reflecting a counterclockwise rotation on the Alleghanian stress field (Fig. 11, A–D). It is this distribution of fringe cracks relative to strain that provides the basis for inferring a tectonic history of the detachment sheet.

In the eastern portion of our study area evidence is strong for the counterclockwise sense of stress field rotation after the formation of an initial set of dip joints striking between 006° and 021°. Such tectonics are indicated by both fringe cracks and abutting geometries. Relative to its orientation farther west (i.e., 342°), the 20° to 30° misalignment of the early stress field to the east is significant. We note that this misalignment occurs in the area of the pinchout of Silurian salt, which served as a convenient detachment surface. Our interpretation is that the misaligned stress field east of Ithaca is associated with rock drag, produced by the lack of salt detachment at the eastern edge of the area. Drag at the edge of the detachment sheet set up local remote stress field controlling the orientation of early parent joints striking between 006° and 021° (see Geiser, 1988). A later stress field producing both the 352° and 003° sets reversed the sense of shear on the parent joints along the eastern boundary of the detachment sheet such that later fringe cracks are oriented counterclockwise from parent joints.

TECTONIC HISTORY OF THE APPALACHIAN PLATEAU DETACHMENT SHEET

A final reconstruction of the tectonic history of the Appalachian plateau detachment sheet must be consistent with the following observations.

1. Fringe cracks on dip joints reflect a clockwise stress field rotation in the west, a counterclockwise stress field rotation in the east, and in an area near Ithaca showing both senses of rotation (Fig. 11, A–D).
2. The rotation angle for counterclockwise fringe cracks is generally larger than the angle for clockwise fringe cracks.
3. When developed in the same outcrops, the parent joints in the shale are oriented clockwise relative to parent joints in the siltstone layers.
4. The relative ages of parent joints indicated by the abutting relationships show a clockwise rotation of the stress orientation from west to east, except along the eastern portion of the study area.

In the following section, we summarize the tectonic events associated with the propagation of parent joints and, subsequently, fringe cracks within the study area, which is the northeastern portion of the larger Appalachian plateau detachment sheet (Figs. 6 and 18).

Structural Sequence in the Northeastern Portion of the Detachment Sheet

320°–330° Parent Joint Set. The earliest parent joints in our study area are limited to the western region, the area that is closest to the extension of the Juniata culmination into the plateau (Fig. 17). This set includes joints ranging over about 10° of strike (320° to 330°). The reason for this range of strike is not clear in light of the better-aligned later joint sets. This same joint set is found west of the Juniata culmination and in the detachment sheet as far south as West Virginia (Fig. 18). However, areas west and southwest of the Juniata culmination are characterized by a counterclockwise sequence of joint development. Zhao and Jacobi (1997) reported that, west of our study area, joints striking from 322° to 340° predate joints at 312°–320° and a second group of joints at 280°–305°. Evans (1994) reported that, west of the Juniata culmination, the earliest joint set strikes 350° and is followed by the 320° to 330° joints. In central New York, the earliest structures include folding (042° fold axes) of the Tully Limestone (Younes and Engelder, 1995). Because the shortening direction indicated by the deformation of fossils is at a significant clockwise angle with the earliest joints (Engelder and Geiser, 1980), these earliest joints apparently predate significant layer-parallel shortening. The earliest joints in the Valley and Ridge also predate appreciable layer-parallel shortening (Nickelsen, 1979). Early joints occur throughout the stratigraphic section near the Juniata culmination, yet farther east they are found only below the Tully Limestone. The orthogonal relationship between the fold axes of the Tully Limestone and the early joints suggests the synchronous timing of the two structures. At this stage detachment within the salt decollement may have initiated but was not well developed. Farther southeast, early fold axes of the Lackawanna syncline are parallel to those found in the Tully Limestone.

342° Parent Joint Set. The propagation of 342° parent set marks the initiation of significant detachment along the Salina salt, as indicated by deformed fossils. As the stress orientation rotated clockwise, early stages of layer-parallel shortening were recorded as cleavage in the Tully Limestone. As the amount of layer-parallel shortening increased, the eastern edge of the detachment sheet began to drag where the eastern salt pinch-out prevented easy detachment. As a consequence of this drag, a shear couple developed within the eastern region of the detachment sheet so that the local stress field was rotated considerably clockwise relative to that found in the rest of the detachment sheet. Joints in the eastern region propagate in orientations ranging from 006° to 021°. During this tectonic stage, folding continued in the section above the Tully Limestone. A clockwise stress field rotation, east of the Juniata culmination, is reflected in the initial development of clockwise fringe cracks in the western region of the study area.

351° Parent Joint Set. A third stage is marked by the propagation of 351° joints. By this stage, parent joints had propagated throughout most of the northern detachment sheet and drag along the east edge of the detachment sheet was at a maximum. This was the first stage during which counterclockwise fringe cracks formed along the eastern edge of the detachment sheet. Kinks equivalent to the 351° parent joints are also found throughout the western portions of the sheet.

003° Parent Joint Set. The continuing clockwise rotation of the Alleghanian stress field is next indicated by 003° joints. It is possible that the kinks showing a counterclockwise angle had developed during this stage as a result of north-south compression. The general north-south orientation of the kinks (Fig. 11D) and their constant angles to the parent joint for both clockwise and counterclockwise sets (Fig. 12) indicate that they are related to the same event. This interpretation is also supported by the mechanical requirement that kinks will only form after arrest of their parent joint.

070° Parent Joint Set. This stage of jointing, best developed in black shales (Loewy, 1995), is most difficult to date. The 070° joints are a manifestation of tectonic relaxation before abnormal pressure within shales of the Catskill delta could leak off (McConaughy and Engelder, 1999). The 070° set carries twist hackles that are always rotated counterclockwise (Fig. 11E).

000° Parent Joint Set. The propagation of a second north-south joint set is post-Alleghanian. These late joints formed parallel to the orientation of the kimberlite dikes cutting the detachment sheet. The kimberlite dikes were dated as Early Jurassic and consequently, it is possible that this set is also early Mesozoic in age. This later 000° set may be a manifestation of deformation associated with continuing slip on faults of the Clarendon-Linden zone (R. Jacobi, 1998, personal commun.). The 003° and 000° sets are also distinguishable through differences in length and planarity.

Tectonics on Either Side of the Juniata Culmination

The Juniata culmination correlates with a regional lineament known in central Pennsylvania from surface geology and magnetic and gravity anomalies (Gold and Parizek, 1976). The joint propagation sequence around the Juniata culmination indicates that paleostress trajectories rotated away from parallelism with the culmination in opposite directions, leading to a clockwise sequence of structures to the east and north of it, and a counterclockwise sequence of structures to the west and south of it (Figs. 18 and 19) (Younes, 1996). The trend of the Juniata culmination is parallel to the oldest joints in the detachment sheet (320°–330°). Nickelsen and Hough (1967) mapped five sets of dip joints in the Pennsylvania portion of the detachment sheet (sets A–E). Set A, oriented 330°, is parallel to the Juniata culmination and perpendicular to the Lackawanna syncline, and is flanked by joint sets D and E to the northeast, and joint sets B and C to the southwest. Based on the similarities between the joint orientations in central New York (this study) and those in northeastern Pennsylvania, and also on the similarities between those in southeastern Pennsylvania to those in West Virginia (Dean et al., 1984, 1988), we interpret the joint sets of Nickelsen and Hough (1967) as a manifestation of clockwise stress field rotation in the northeast (set D) and counterclockwise rotation in the southwest (sets B and C). This interpretation is consistent with Evans (1994) analysis west of the culmination. Zhao and Jacobi (1997) reported a clockwise superposition of joints to the east of the Juniata culmination and a counterclockwise superposition of joints west of the feature.

Exposures of clockwise and counterclockwise fold rotations in the Antes Shale of the Sinking Valley fault zone, Pennsylvania, show a transport direction that is compatible with transport parallel to the Juniata culmination (Nickelsen and Engelder, 1989). The direction of transport was estimated as 322°, similar to the oldest trends in our study area. Deformation at the Allegheny front near Williamsport, Pennsylvania, shows a single transport direction at 340° (Spiker and Gray, 1997). Nickelsen (1988) noted that the Jacks Mountain fault, farther south, has been intersected by a series of small wrench faults from which he was able to determine the compression direction. These directions fall into orientation about 322°, then 335°, and then 312°, which indicates both senses of stress field rotation that might be expected for locations near the culmination. On a larger scale, the Juniata culmination divides both the Appalachian Plateau and Valley and Ridge into an area of a clockwise paleostress rotation to the east and an area of counterclockwise paleostress rotation to the west (Fig. 18).

CONCLUSIONS

The character of fringe crack development is dependent on lithology. Gradual twist hackles are found in clastic rocks regardless of grain size, whereas abrupt twist hackles are most common in shale with their parent joints found in coarser siltstone and sandstone beds. Gradual twist hackles in sandstone develop with larger twist angles than those found in shale. In contrast, the abrupt twist hackles in shale display the largest twist angles. Theory indicates that this is behavior largely controlled by the difference in stress conditions in the shale and coarser grained clastic rocks rather than by rock properties. The geometry of the gradual twist hackles is consistent with low stress differences (< 6 MPa) in the clastic section where the joints were driven by a relatively high (~81 MPa) internal fluid pressure.

Fringe cracks are, indeed, systematic across a geological province to the extent that they are useful as a tool for unraveling the tectonic history of the region. In the northeastern portion of the Appalachian Plateau detachment sheet, fringe cracks reflect the clockwise sense of Alleghanian stress field rotation seen to the southeast in the anthracite district of the Pennsylvania Valley and Ridge. Both fringe cracks and abutting of parent joints suggest that the clockwise rotation of the Alleghanian stress field is more akin to a continuous series of tectonic events rather than two punctuated phases, as originally proposed by Geiser and Engelder (1983). However, the eastern edge of the detachment sheet was dragged at the salt pinchout to contribute to a locally perturbed remote stress field, as reflected in the counterclockwise sense of fringe cracks in this area.

Joints coaxial with the Juniata culmination are the earliest joint sets in the Appalachian Plateau detachment sheet and in the Valley and Ridge both east and west of the Culmination. With later joint development, the Juniata culmination divides the Alleghanian stress rotation into a clockwise domain to the east and a counterclockwise domain to the west.

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