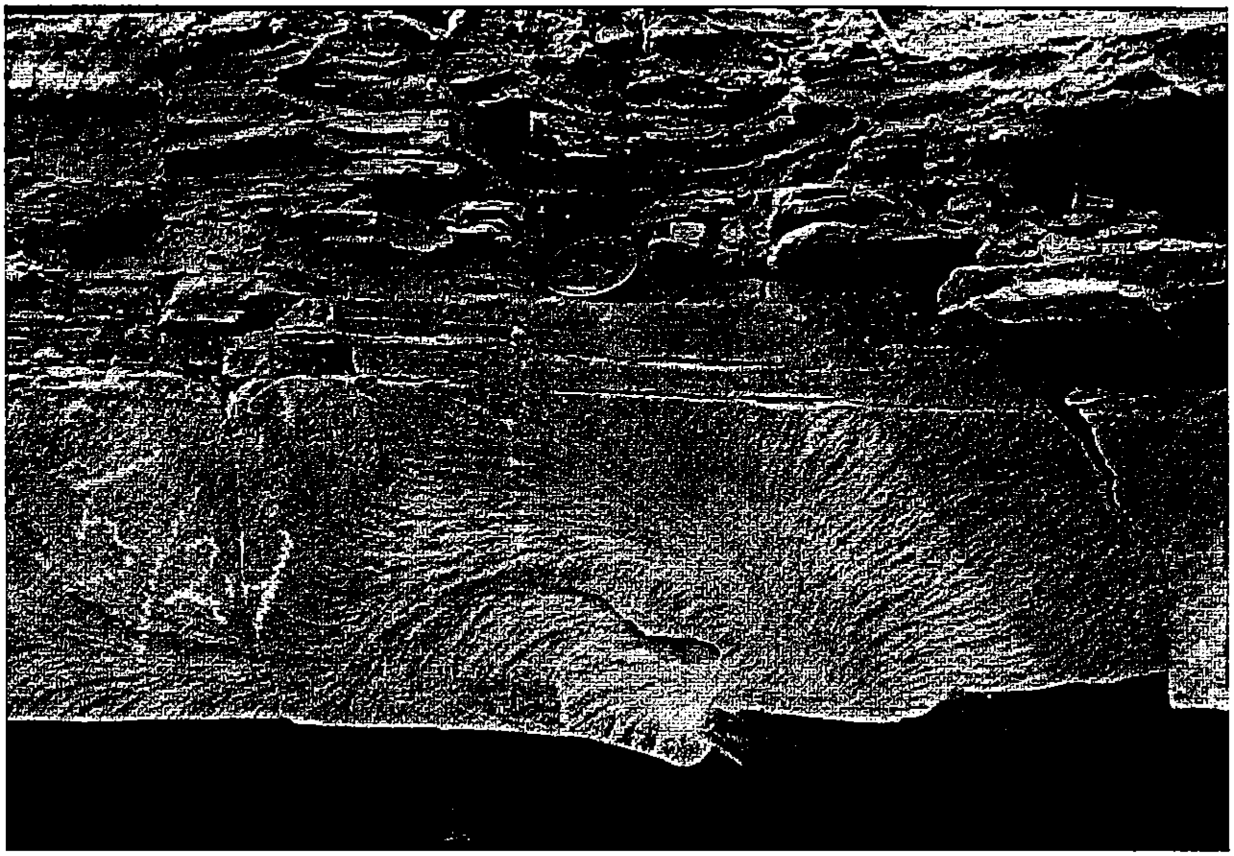
Fractography of Glasses and Ceramics V: Post Conference Field Trip

sponsored by

New York State College of Ceramics at Alfred University
Penn State's Seal Evaluation Consortium (SEC)

# *The Fractography of Joints: Natural analogs for failure in glasses and ceramics*

Terry Engelder
Department of Geosciences
The Pennsylvania State University
University Park, PA 16802
jte2@psu.edu



The Finger Lakes District, New York
July 2006

## *FRACTOGRAPHY OF GLASSES AND CERAMICS V*

# *Finger Lakes District Field Trip: The Fractography of Joints*

### Introduction

Stops during the one-day trip following the Rochester meeting on Fractography of Glass and Ceramics (V) are located in the vicinity of Watkins Glen and Ithaca, New York (Fig. 1). These five outcrops contain 'world-class' examples of natural cracks with surface morphologies that are the subject of study and debate dating back almost a century (e.g., Sheldon, 1912) and continuing to this day (see references). These natural cracks, called joints by geologists, propagated in the marine portion of a river delta (the Catskill Delta) that is a close analog to the Mississippi Delta, offshore Louisiana. The sandstones and shales of the Catskill Delta are approximately 360 Ma (million years) old with two phases of joint propagation at approximately 305-295 Ma and 275-265 Ma.

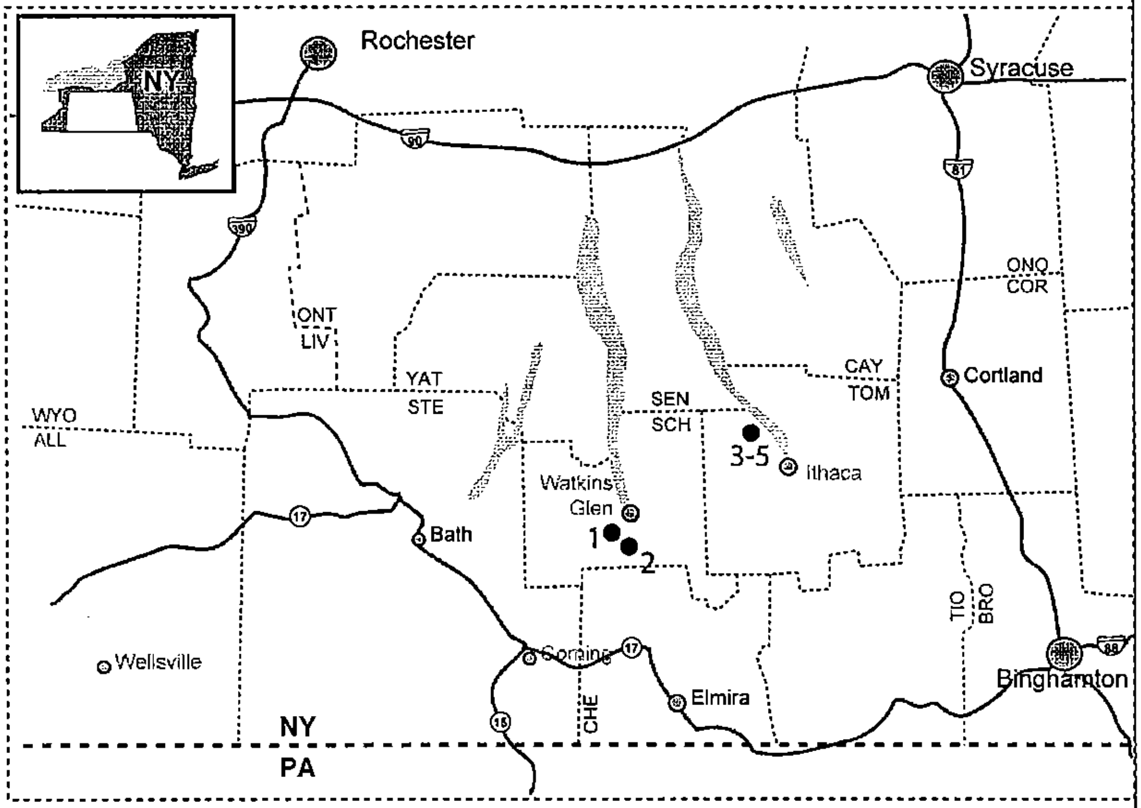


Fig. 1: Stops for the Fractography Field Trip. Stops 1 & 2 are near Watkins Glen , New York, whereas Stops 3 to 5 are located in Taughannock Falls State Park north of Ithaca, New York.

## Stop 1: Joint initiation and the structures or flaws responsible for that initiation - (*Route 14 at Chef's Cafe between Montour Falls and Watkins Glen*):

*Key References*: McConaughy (1997); McConaughy and Engelder (2001)

*Lithology*: Ithaca Formation of the Genesee Group.

*Purpose*: To examine joint initiation points on cross-fold (i.e., cross-fold) joints; To examine the development of composite cross-fold joints.

*Background*: Early theories on crack propagation were based on the premise that most brittle materials contain microscopic holes that later became known as "Griffith flaws". These "Griffith flaws" serve to concentrate tensile stresses so that crack growth is favored in the vicinity of the stress concentration. Flaw-like holes are found in clastic rocks in the form of pore space.

If all pore space favored joint propagation, clastic rocks would be so closely jointed that the rock might resemble a deck of playing cards. However, early theories on crack propagation pointed out the larger flaws favored crack propagation at lower tensile stresses. The reason was that larger flaws concentrated stress more than smaller flaws. Joint initiation will take place at low tensile stresses where only the largest of flaws favors jointing.

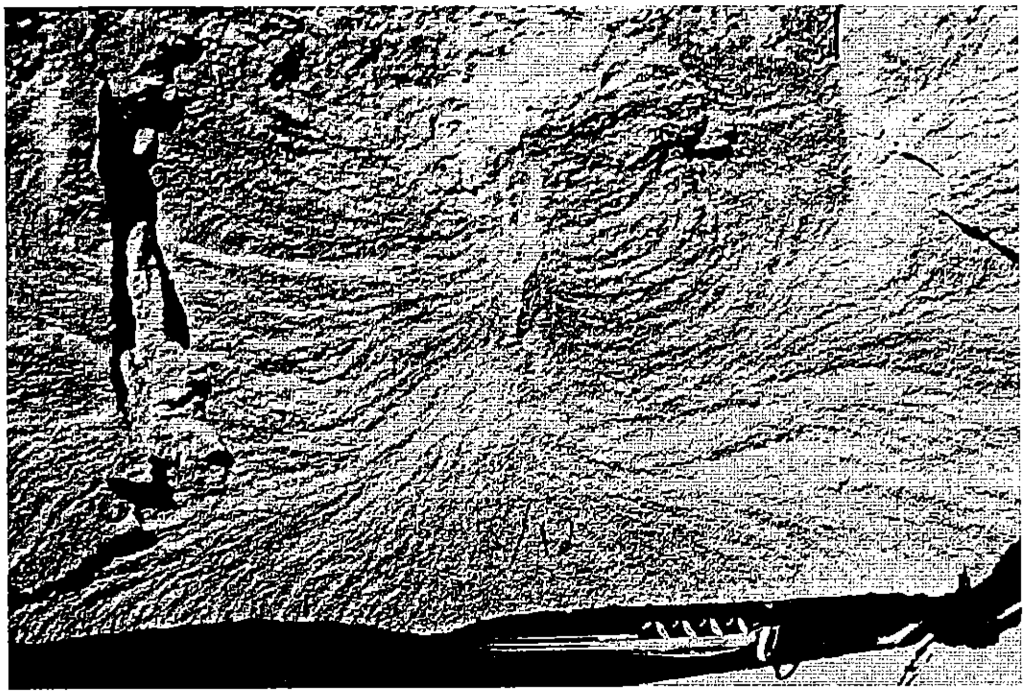


Fig. 2. Joint initiation joint at a worm borrow (after McConaughy & Engelder, 2001. Swiss knife for scale.

**Inclusions** within the Ithaca Member siltstones are of two basic varieties; fossils and concretions. The fossils are typical near-shore fauna, primarily brachiopods and crinoids. The fossils commonly occur as death assemblages of brachiopod shells (shell hash), interpreted as storm deposits. These may occur as irregular layers associated with hummocky bedding, or as discrete lens, generally less than a meter in lateral extent. Plumes associated with these storm deposits commonly initiate all along the contact between the deposit and the surrounding siltstone, rather than at any single, identifiable point. Propagating plumes that come in contact with a lens of shell hash tend to curve along the contact rather than continuing through the lens. In some cases the extreme inhomogeneity of such zones makes it difficult to ascertain the nature of the plume. I found instances of plumes initiating from individual fossils to be rare in the Watkins Glen outcrops. In fact, we do not find a single clearly documented case.

The second type of inclusions are concretions (Fig. 3). These are often the most difficult to identify. The concretions in the Ithaca siltstones frequently occur as nodules of pyrite, but subsequent alteration changes many of them to iron oxides that continue to weather in the moist climate. When viewed in outcrop, all that may remain of the concretion is some relict iron staining. Vertical burrows containing organic matter may develop into concretions, thus blurring the distinction. I reserved the burrow classification for those features with a typical burrow-like geometry, and applied the term inclusion to those features of less certain origin. Inclusions, as applied here, were exclusively found in mid-bed. Initiation points originating at centrally located inclusions tended to radiate in all

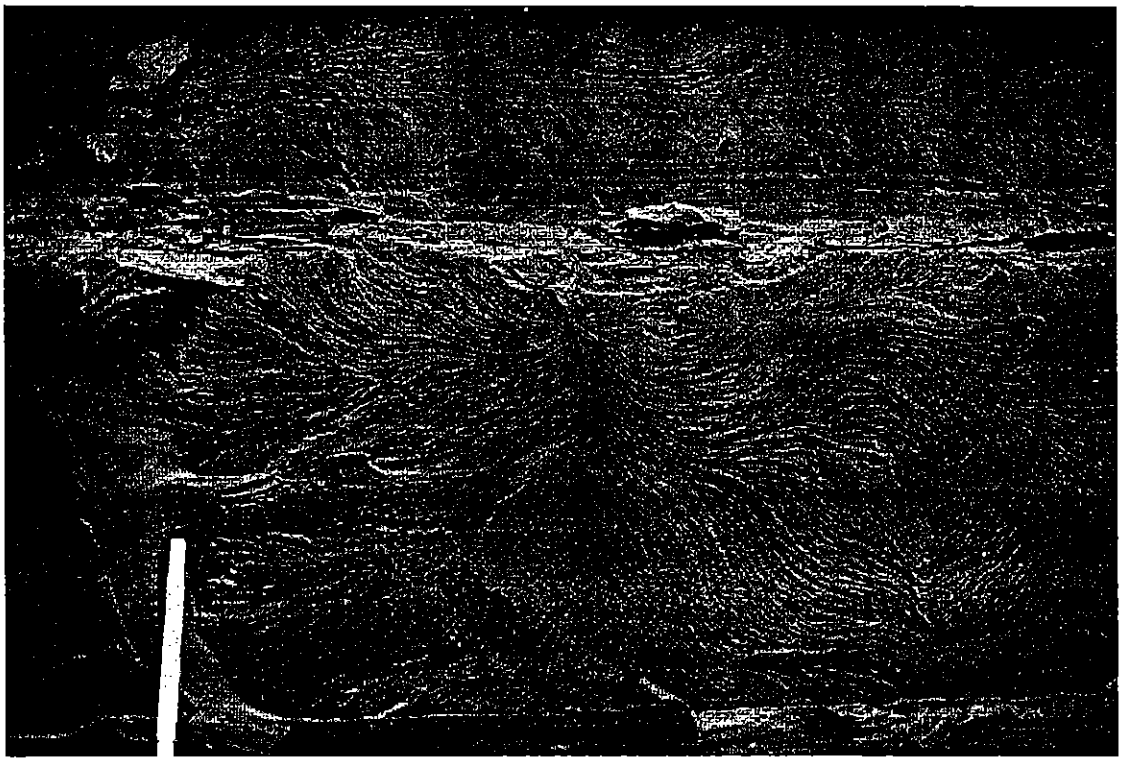


Fig. 3. Initiation point off of small pyrite concretion seen at Stop 2 (after Bahat and Engelder, 1984).

directions. As was the case with vertical burrows, plumes tended to initiate all along the perimeter of the inclusion rather than at some specific point.

*Observations*: At the Chef's Cafe outcrop, joints in five siltstone beds of the Ithaca Formation contain flaws in the form of flute casts. Joint surface morphology serves as a witness indicating the joint propagation initiates at the corners of these flute casts which are found at the bottom of siltstone beds. In four of the beds joint initiation is found at the bottom of the bed boundary where a siltstone flute cast projects down into the underlying shale. The plumose surface morphology shows that joint propagation continued upward from the flute casts and then outward along the joint until another joint was encountered.

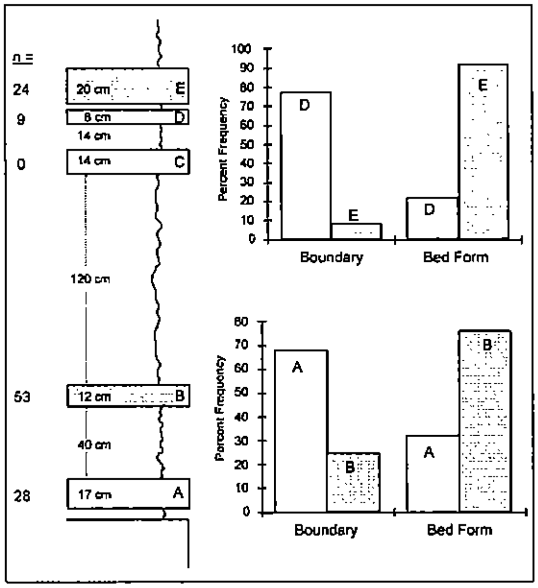


Fig. 4. Initiation points at Stop 1

The type of initiation point varies from bed to bed. Beds B and E have initiation points at bed forms, mainly flute cases. Beds A and D have initiation points at bed boundaries. Figure 4 shows the distribution of joint initiation points within four beds. The reason that there is a difference in type of initiation point is illustrated by the pair of siltstone beds (Beds D and E) which comprise a composite joint that consists of two joints nearly co-planar with each other. Plumose morphology shows that the upper bed (Bed E) contains the common joint initiation joints on the bottom bed boundary where flute casts are located. The upper joint of the composite joint shows a characteristic propagation and arrest as described above. However, the underlying bed (Bed D) joints contains initiation points on the top of the bed. Here is an example where the overlying bed cracks and then transmits a stress concentration across the thin shaly interface between the two beds. The stress concentration is enough to cause the lower bed to joint by initiation at the top of the bed where no flute casts are found. The lower joint runs for larger distances in a single rupture than the upper bed. When the joint rupture jumps to the lower bed, propagation continues for some distance suggesting a larger or more energetic driving stress. The lower joint outruns the upper joint as is indicated by small circular ruptures off of upper bed flute casts that touch the lower joint. These joints are bypassed by another longer rupture starting at another initiation point.

Portions of some joints in the siltstone beds show uniformly spaced arrest lines indicating that joint propagation was not one continuous event. In general, the average horizontal distance between arrest lines is slightly larger than the thickness of the beds:

| thickness (cm) | average spacing (cm) |
|---|---|
| 17 | 21 |
| 20 | 36 |
| 18 | 23 |
| 10 | 10.5 |

The significance of repeated arrest line will be discussed at the next stop.

## Stop 2: Joint growth in siltstone and shale - "The Lacazette Joint" - (*Route 414 at the intersection of Route 14 in Watkins Glen*):

*Key References*: Bahat and Engelder (1984); Engelder (1985); Brown and Scholz (1985); Lacazette and Engelder (1992); Scott et al. (1992); Younes and Engelder (1999).

*Lithology*: Ithaca Formation of the Genesee Group.

*Purpose*: To examine the effect of lithology (siltstones vs. shales) on cross-fold (i.e., cross fold) joint development in thick-bedded clastic rocks. To examine the process of fluid-driven joint propagation and growth. To examine the relationship between joint development and the Alleghanian (late Carboniferous) Orogeny.

*Background*: Another unusual aspect of outcrops on the Appalachian Plateau is the variety of well-developed markings on the surfaces of joints in both the siltstones and shales. A composite of barbs and arrest lines leaves a delicate plumose structure on the surface of joints in siltstone (Bahat and Engelder, 1984). The barbs consist of a fine roughness (low relief elements) on the joint surface which were caused by local out-of-plane crack propagation. This roughness forms ridges parallel to the direction of rupture propagation. Out-of-plane propagation is believed to be caused by microscopic inhomogeneities, such as grain boundaries in the siltstone. Because the shale is more homogeneous on a microscopic scale there is less tendency for out-of-plane crack propagation. Hence, the shales show no surface morphology equivalent to plumose structures on the siltstones.

Three types of plumes observed in siltstones of the Appalachian Plateau include: straight plumes; curving plumes; and rhythmic plumes (Figure 4). For the rhythmic plumes the fan perimeter designate loci of arrest lines. The arrest lines are convex toward the direction of fracture propagation.

This outcrop also contains clues about the tectonic history of the Alleghanian Orogeny in the Central Appalachians. A stress field rotation may be inferred from the jointing sequence. In situ stress measurements by the hydraulic fracture technique, demonstrate that least horizontal stress ($S_h$) is not the same in interlayered siltstones and shales (Evans et al., 1989). In basins where the $S_h$ is less than the vertical stress ($S_v$), the shale layers have a higher $S_h$ (Warpinski, 1989). Mechanisms leading to this difference include compactional diagenesis;

failure by frictional slip; and elastic deformation during overburden loading or unloading.

If high pore pressure develops before driving joints, all evidence points toward equal magnitude of $P_p$ from one interlayered bed to the next. In this case the first bed to develop fluid driven joints will be the bed with the lowest $S_h$, the siltstone beds in a passive continental margin setting. Unlike commercial hydraulic fractures driven by high-volume pumps fluid driven joints draw upon a limited reservoir. Propagation of natural joints would rapidly exhaust pore fluid in the vicinity of the joint. This would lead to arrest until the joint could recharge for another propagation increment.

During a tectonic event the orientation of earth stress is known to change. If there were significant time between propagation of joints in siltstones and joints in shale, joints in these lithologies may not be aligned. In this case the direction of rotation of the stress field is known if the sequence of jointing can be discovered. Based on the preceding argument for stress in siltstones and shales, the orientation of joints in the siltstone layers would point to the earlier stress field orientation.

*Observations*: As this roadcut along Route 414 was excavated, benches were carved out by taking advantage of the jointed rock. The base of the roadcut is dominated by Upper Genesee Group shales. About mid level in the exposed section thicker siltstone stringers are intercalated with the shale. At the top of the roadcut siltstones dominate. This roadcut is best viewed in the late morning when the sun strikes the joint surfaces at a high angle. After about 11:30 AM when the joint surfaces no longer receive direct sunlight, the surface morphology is far more difficult to see.

Lithological control is fundamental to the development of joints within the Appalachian Basin as is nicely illustrated by this outcrop. Vertical joints within the shales strike at 341°-343°, whereas vertical joints within the siltstone beds strike at 331°-334°. Although important in controlling joint development, the differences between siltstone and shale within the Ithaca Formation of the Genesee Group are subtle. The outcrop criterion for distinguishing a siltstone from a shale is based purely on the orientation of the joint set that a particular bed is carrying. Beds that carry "siltstone" joints have a clay/quartz ratio between 0.71 and 1.06 with more than 25% of the grains greater than 30 microns. Beds that carry "shale" joints have a clay/quartz ratio between 1.21 and 2.80 and less than 20% of its grains greater than 30 microns.

Joint faces within siltstones contain three varieties of plumose patterns: the straight or s-type plumose marking (Fig. 5A); the curving or c-type plumose marking (Fig. 5B); and the rhythmic c-type plumose marking (Fig. 5C). The straight plume has a linear axis parallel to bedding whereas the curving plume commonly has an axis which divides into several branches which in turn may themselves divide. Barbs radiate from the plume axes of both the s-type and c-type plume patterns. The barbs form a fine surface morphology which indicates the direction of rupture propagation with the rupture moving from the plume axis outward toward the edge of the joint.

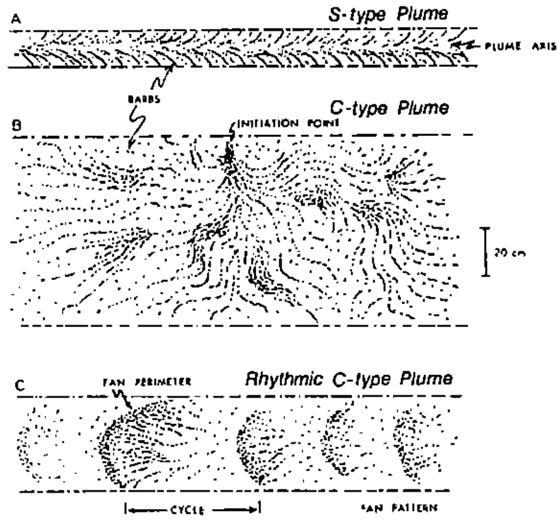


Fig. 5. Various plume patterns observed on siltstone joints (after Bahat & Engelder, 1984).

A feature found on both shale and siltstone joints are arrest lines. These features mark the termination of propagation of individual cracks. A 4 m thick shale bed shows a large arrest line curving on the joint face with the convex side of the line facing in the direction of joint propagation (NNW). This same shale bed contains the 19 cm thick siltstone stringer displaying an s-type plume pattern. Barbs of the s-type plume on the siltstone stringer diverge in the direction of propagation which is toward the NNW and compatible with the large arrest line within the shale. Arrest lines can be observed on the 44 cm thick siltstone bed below the 4m thick shale. These arrest lines are part of the rhythmic c-type plume pattern found on joint faces cutting siltstone beds. Here the arrest lines are spaced less than 1 m apart in contrast to those on the thick shales which are separated by more than 50 m.

The closely spaced arrest lines in siltstone beds may be interpreted in terms of a jointing mechanism. Two phases of the cycle are a slow build-up of pore pressure followed by a fast decrease accompanying the incremental propagation of a joint. This process repeats many times to leave a set of closely-spaced arrest lines. The c-type plumes are found on joints striking at 331°-333°, whereas small siltstone stringers in thick shales show the s-type plumes with joints striking at 341°. The s-type plume is believed to indicate a rapid rupture that extended more then 50 m in a horizontal direction. The length of the rupture is indicated by the distance between the initiation point 50 m to the SSE and the large arrest lines within the 4 m thick shale layers. In contrast, the c-type plumes give the impression of a slower less decisive rupture. Arrest lines spaced at less than a meter on the 332° joints confirm this notion.

A 40 m long cross-fold joint that propagated within a single 44 cm thick bed of siltstone has a plumose surface morphology with multiple arrest lines indicating that cracking occurred in increments rather than in one smooth rupture. the crack increments increase in overall length in the propagation direction over the final 28-m portion of the exposed end of the study joint with the largest increments increasing in length form 0.6 m to 1.0 m. At least three conceptual models based on linear elastic fracture mechanics and fluid flow along joints can be imagined to explain incremental crack growth under conditions of constant stress and pore

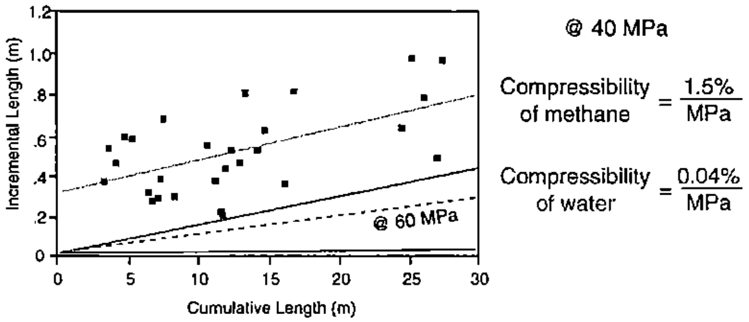


Fig. 6. Incremental growth of joint at Stop 2.

pressure (see Lacazette and Engelder, 1992). Based on quantitative evaluation of the cracking process, compressibility-limited propagation is favored and the driving fluid is identifies as a gas rather than a brine. The gas is identified as a natural gas on the basis of geological constraints (Fig. 6).

## Stop 3: Joint sequence based on edge fringe cracks (*Upper Creek of Taughannock Falls State Park along Falls Road south of Trumansburg*):

*Key References*: Engelder (1985); Pollard and Aydin (1988); Helgeson and Aydin (1991); Engelder (1993).

*Lithology*: Ithaca Formation of the Genesee Group.

*Purpose*: To examine evidence for the sequence of joint development (siltstones before shales) in thin-bedded clastic rocks based on edge fringe cracks.

*Background*: The difference in $S_h$ between siltstones and shales leads to a serial sequence of joint propagation, with initial jointing in the beds of lower $S_h$. Factors such as increased fluid pressure eventually lead to the jointing of adjacent beds of higher $S_h$. Jointing in adjacent beds usually starts at the edges of existing cracks. If there is no rotation of the horizontal stress adjacent joints will parallel initial joints. If there was a stress rotation between jointing events, fringe cracks will develop.

Fringe cracks are a series of small, en echelon fractures , or cracks, emanating from the plane or the edge of a joint. They occur in a variety of geologic settings, and in different rocks types; e.g., sandstone, siltstone, shale, limestone, and granite. Attempts to classify ENE echelon fringe cracks began with Woodworth (1896) who divided a joint into three parts: A joint plane, a fringe, and a rim of conchoidal fractures. Each was subdivided into smaller, clockwise or counterclockwise segments based on the geometry and orientation of the fringe relative to the joint plane. Hodgson (1961) introduced the terms systematic and non-systematic joints, and consequently, revised Woodworth's classification by defining a joint as systematic or non-systematic first; then dividing it into a main joint face, a fringe, and a conchoidal ridge. Kulander and Dean (1985) divided a joint surface's features into three principal parts: a joint face which contains the plume; a continuous twist hackle, a hackle that is still attached to the main joint face; and an abrupt twist hackle, a twist hackle which is separated from the joint face.

Our classification of fringe cracks involves the following scheme. A **parent joint** is one that is planar, persistent, long, and belongs to a regional joint set. A **fringe crack** is a mode I fracture that emerges from the edge or plane of a parent (systematic) joint and rotates out of the plane of the parent joint. **en echelon fringe cracks** (EATH) consist of a series of narrowly spaced fringe cracks. In this paper, we distinguish between different classes of fringe cracks according to their surface geometry, and propagation direction. In this classification, three surface shapes are considered for a propagating fracture: planar (P), if the fringe crack remains in its plane during propagation; curviplanar (CP), if the fringe increasingly twist out of the plane of the previous segment; and curving(C), if the fringe starts as a plane then kinks or curves. The propagation direction is vertical (V) if propagation is normal to bedding, and lateral (L) if propagation is parallel to bedding. Using surface shape and propagation direction leads to five classes of fringe cracks: Lateral Planar (LP), Lateral Curving (LC), Vertical Planar (VP), and, Vertical Curviplanar (V-CP), and vertical-lateral curving (V-LC) where the first word (or letter) denotes the propagation direction from the parent, and the second denotes the surface shape. One class of fringe cracks may contain more than one type; however, a parent joint rarely carry more than one set or type of fringe cracks. In the Appalachian Plateau, NY, we identify four types of EATH, each reflects a specific set of stress conditions and timing. These types are: Lateral fringe cracks (LFC), and tip fringe cracks (TFC) both of which starts as Lateral Planar cracks; Curved Fringe Cracks (CATH) which are Lateral Curved; Twist Hackles (TH) which are Vertical Curviplanr; and Edge Fringe Cracks (EATH) which are Vertical Planar. The LFC and ATH have subsets that have curved tips. Our classification also depends on whether the fringe crack forms in the same bed that hosts the parent joint. Three types of EATH propagate in the same bed: LFC, TH, and TFC, whereas the ATH propagate in beds adjacent to the bed hosting the parent joint.

*Observations*: This outcrop in the Ithaca Shale Member of the Genesee Group at Taughannock State Park contains four of the cross-fold joint sets which may be observed in the Finger Lakes district. Despite the complicated pattern of jointing the rule for the silt-shale jointing holds up with joints in the siltstone striking counterclockwise from joints within the shales. Step down into the stream bed just north of the bridge across Taughannock Creek. At this point several benches have been cut into the northeast bank of the creek. Joints on those benches fall in three sets: 339°, 345°, and 352°. A fine example of a siltstone joint (340°) over a set of shale joints (352°) is seen just north of this point. Further upstream a joint strikes at 301°.

There is strong evidence supporting the argument that the propagation of siltstone joints occurs prior to propagation of the shale joints (Engelder, 1985). This gives a clockwise sense to compressional events of the Alleghanian Orogeny, a relationship found throughout the Central Appalachians. The joint sequence is based on a very fine example of the propagation of cracks downward into an elastic medium (a shale bed) with the driving mechanism being abnormally high fluid pressures in an overlying siltstone bed (this outcrop appeared as the photo on the book jacket of Engelder, 1993). The theory of elasticity predicts that the spacing between cracks is proportional to the length of the cracks. As the cracks are initiated at the top of the shale bed many short cracks form. Upon propagation downward only part of the cracks grow in length, thus the spacing between the longer cracks increases. With further propagation fewer of the cracks continue to grow and, hence, the relationship between crack length and crack spacing is preserved. The spatial association between these cracks in the shale and the overlying joint in the siltstone leaves little doubt that the siltstone joint was present first and acted as the "reservoir" for high pressure fluid responsible for cracking the shale bed. The en echelon cracks in the shale bed at the book cover outcrop called edge fringe cracks. They are one of four types of en echelon fringe cracks that will be observed on this trip. The inventory of fringe cracks also includes twist hackles, tip fringe cracks, and lateral fringe cracks. This sense of rotation of these fringe cracks gives a very strong evidence for the sense of rotation of both the Alleghanian and post-Alleghanian stress fields.

### *Abrupt Twist Hackles (ATH):*

Abrupt twist hackles are vertical planar fringe cracks that emanate abruptly from the edge of a parent joint and are also characterized by alternating long and short cracks in the same pattern of a suppressed growth found in twist hackles.(Fig. 7). This is the only fringe crack that does not propagate in the same bed as the host joint. Because these cracks do not abut at or join the parent joint, they appear to grow across the edge of the parent joint. They are most common in shale layers adjacent to siltstone where individual fringe cracks tend to "arrest" at thin layer boundaries. In the Appalachian Plateau, NY, ATH usually initiate from cross-fold joints in siltstone layers typically less than 30 cm thick and can propagate either upward or downward, or both (cf. Helgeson and Aydin, 1990). Downward propagation is more common than upward propagation. Individual cracks rarely exceed one meter in length or height, and have a spacing that correlates well with the crack length. Because smaller cracks cease propagation at lithologic contacts, it appears that the length of an ATH is governed by the bed thickness. The spacing of ATH, on the other hand is governed by the stress shadow that gives the familiar pattern of suppressed growth. Length-spacing relationships show that, as a rule of thumb, the length of an ATH crack is about twice its spacing. The average amount of rotation of ATH is 28°. Within an ATH set, the individual cracks usually have the same orientation, however, in few examples, smaller cracks tend to rotate away from the parent more than the larger cracks, a behavior similar to that of LFC. ATH differ from LFC in the initiation point: the former initiate from the edge of the parent in a bed adjacent to that hosting the parent joint and propagate vertically, while the latter initiate from the plane of the parent and propagate laterally. Rarely, twist hackles were observed on individual ATH showing the same sense of rotation as their "parents".

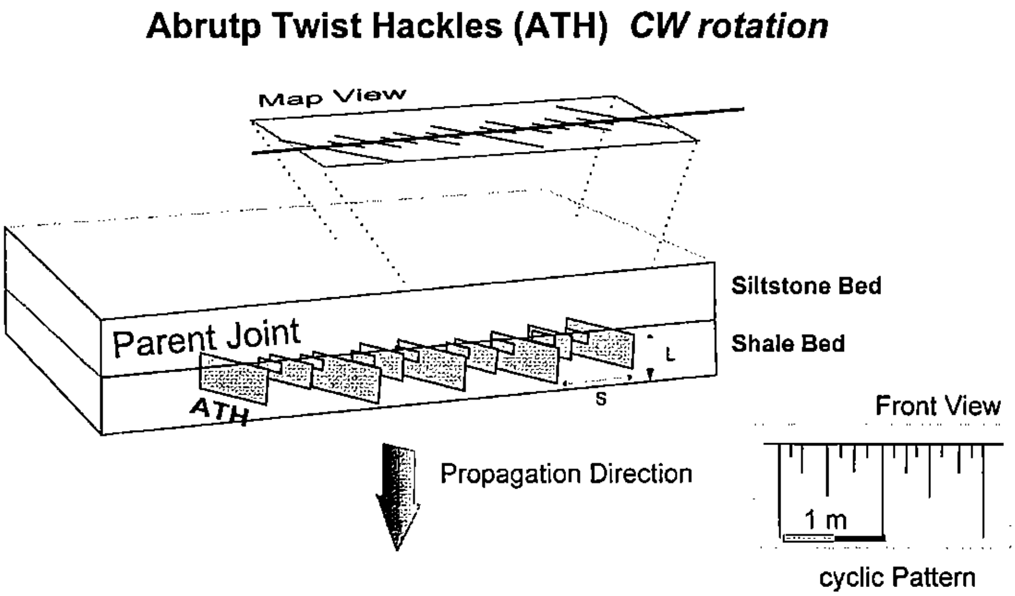


Fig. 7. Schematic picture of abrupt twist hackles such as those seen at Stop 3 (after Younes and Engelder, 1999)

## Stop 4: Joint sequence based on tip fringe cracks - (*Upper Creek of Taughannock Falls State Park along Taughannock Park Road west of intersection with Falls Road south of Trumansburg*):

*Key References*: Kay et al. (1983); Younes and Engelder (1996).

*Lithology*: Ithaca Formation of the Genesee Group.

*Purpose*: To examine evidence for the sequence of joint development (siltstones before shales) in thin-bedded clastic rocks based on the refracturing of siltstone beds. To examine several types of en echelon fringe cracks.

*Background*: Joints tips are the locus of a large stress concentration which can affect adjacent beds. For example, composite joints are a reflection of this concentration reaching through thin shale interfaces to trigger joint propagation in adjacent beds. When the edge of a joint in siltstone reaches a thicker shale the stress concentration at the edge of the crack is not large enough to reach the next siltstone bed but the concentration is confined within the thicker shale bed. Still the stress concentration can cause a shale to rupture even if the stress field has rotated as is the case for edge fringe cracks as was seen at Stop 3.

When a joint in shale abuts a siltstone bed the same principal applies which is that the stress concentration from the shale joint is projected into the siltstone bed. In this case, propagation upward into the siltstone is eased because $S_h$ in the siltstone is generally lower than in the shale. Fracturing back up into the siltstone layers leads to the development of curving abrupt twist hackles (CATH) (Fig. 8).

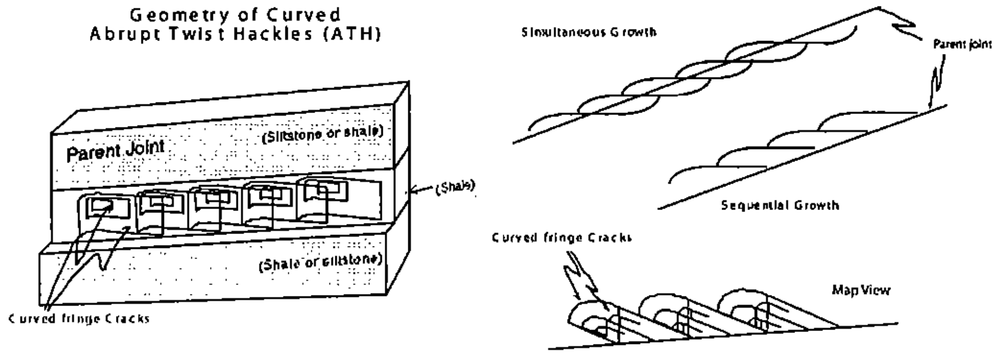


Fig. 8. A schematic picture of curved abrupt twist hackles seen at Stop 4 (after Younes and Engelder, 1999).

One class of ATH is characterized by a surface that propagates as a planar segment which curves before it terminates on the neighboring crack. We call these curved edge fringe cracks (CATH). All CATH propagate laterally (Fig. 8). This feature is characteristic for every crack in the en echelon set regardless of the crack's size such that larger CATH "enfold" smaller ones. In a single set of CATH, individual cracks were observed to curve from one or both ends of the crack suggesting that they initiate either sequentially, or simultaneously respectively. In the former case, it is possible for cracks to initiate sequentially and then curve towards the neighboring crack after a specific overlap distance, while in the latter, all cracks initiate simultaneously along a line parallel to the parent then curve and terminate at the neighboring cracks.

Like ATH, CATH have a lithologic affinity towards shales and rarely towards siltstones. The height of a crack is often restricted to the bed thickness and is well correlated to the crack spacing. The only morphology that was observed associated with CATH is a "rib-like" roughening that form at the point of maximum curvature as the crack starts to deviate from its straight path. Like ATH, CATH are restricted to the Genesee Group where the alternating siltstone and shale layers favor their propagation.

*Observations*: This outcrop shows early-formed siltstone joints (340°) contained within the siltstone layers without jumping into adjacent shale beds. Later, after a stress field rotation, joint propagation into the shale layers (350°) is triggered by a higher driving stress. Here the second joint set in the shale layers is more closely spaced and thus, better developed. 350° joints within shale beds propagate back against the siltstone layers and trigger jointing of the siltstone beds in the 350° orientation (Fig. 9).

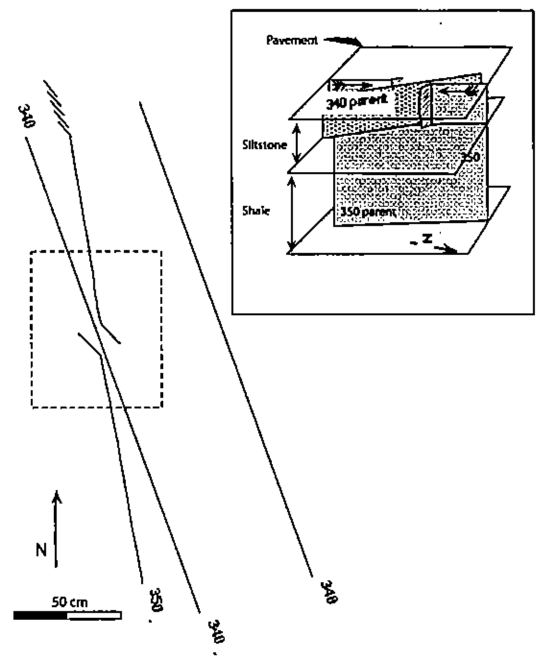


Fig. 9. An example of refracturing in siltstone layers from joints in adjacent beds of shale (after Younes and Engelder, 1999).

The sequence of joint formation is clearly seen by examining the joints within the siltstone layers. The 340° joints are planar and propagate cleanly through the entire lateral extent of the outcrop. Although the 350° joints are planar they do not cut through the 340° joints. When the 350° joints approach the 340° joints, the former joints rotate to propagate parallel to the 340° direction and in most cases they curve even further to propagate away from the 340° joints with a bearing of roughly 330°. This interaction is interesting because deep-formed joints generally crosscut. This is seen in outcrops of the Geneseo black shale that contain ENE joints cutting cleaning through cross-fold joints.

Evidently the fluid pressure necessary to cause the propagation of the 350° joints in shale and then the siltstone layers was high enough to open earlier 340° joints. The net result is that the 340° joint acted like a free surface across which the stress concentration of the 350° joint tip could not project. According to theory, high compressive stresses parallel to the 340° joints could cause the 350° joints to curve away from the earlier joints.

The sense of rotation of fringe cracks associated with most of the parent joints within shale (350° joints) is counter-clockwise (CCW). This gives a sense that the Alleghanian stress field has rotated in two directions. However, evidence from this outcrop suggests that the CCW fringe cracks are associated with refracturing adjacent siltstone beds from parent joints in shale. The refracting is the manifestation of a local stress field associated with the presence of an existing joint set in the siltstone layers rather than some more regional tectonic feature.

Having stated that the CCW behavior at Ithaca is local, a plot of the distribution of edge fringe cracks with a CCW sense of rotation shows their presence in several outcrops east of the longitude of Ithaca (Figure 8a). Although this observation is surprising in light of all the work testifying to a CW rotation of the Alleghanian stress field, there may be an explanation for a smaller region of fringe cracks showing a CCW sense of rotation. These ideas will be discussed at Stop 4 on Day 3.

## Stop 5: The Hanging Valley Stop: (*Route 89 at Taughannock Falls State Park north of Ithaca*):

*Key References*: Sheldon (1912); Engelder and Geiser (1979); Engelder, et al. (1987).

*Lithology*: Tully Limestone and Geneseo (black shale) Formation of the Genesee Group.

*Purpose*: To examine the development of joints within black shales of the Geneseo Group; To examine structures that develop in the Tully Limestone; To examine the inside of a pressure compartment where gas may have been the dominant pore and joint fluid.

*Background*: The mechanism favored for the generation of overpressures within the Catskill Delta Complex is the volume increase reaction associated with the maturation of hydrocarbons within organic rich shales. Within the Appalachian Basin the higher joint density of black shales supports the argument that maturation of hydrocarbons was, indeed, responsible for the abnormal fluid pressures.

Devonian black shales in the Appalachian Basin have higher joint densities than adjacent gray shales (Kubik, 1993). Joint density compilations from Eastern Gas Shales Project (EGSP) core data (Cliffs Minerals, 1982) show that Devonian black shales of the Appalachian Basin contain more joints than adjacent gray formations. During this field trip we shall see that joint distribution in outcrop is consistent with these observations. This joint density is essential to the exploitation of black shales as unconventional (as opposed to common porous reservoirs, i.e. sandstone) natural gas reservoirs. Matrix permeability of these shales is very low, on the order of $10^{-8}$ md, yet they are rich reservoir rocks (Jochen and Hopkins, 1993). The abundant resources may be accessed through secondary permeability, joints. Because higher productivity is found in shales with higher natural fracture densities, production from the shales is dependent upon natural fractures (Kubik, 1993).

Organic content of outcrop samples was measured using a UIC Coulometrics carbon coulometer. Total organic carbon (TOC) of several core samples from the Catskill Delta Complex in New York State was also measured. Additional core TOC data were found in USGS Open File Report 80-810.

Organic carbon content is higher in the core data than in the outcrop data, suggesting that weathering has an effect on organic content. Regardless of the effects of weathering, black shales contain more organic carbon than the adjacent gray shales. The Rhinestreet Formation has the largest disparity between black and gray shales, with the highest TOC found in the black shales and the lowest TOC found in the gray shales.

The outcrops of the hanging valley stop are consistent with a heavily fractured pressure compartment. Water has a density to give a gradient of about 0.45 psi/ft. Freely circulating water will achieve this gradient even when overpressured.

Pressure compartments are surrounded by seals but inside fluid circulation is free to establish a hydrostatic gradient (0.45 psi/ft). By the same rule, gas has a density to give a gradient as low as 0.03 psi/ft whereas rock density results in a steeper stress gradient ( ≈ 1.0 psi/ft). When either a gas or a liquid (i.e., oil or water) is overpressured in the presence of a tall hydrocarbon column, the pressure of the gas or water might come close to that of the least stress (i.e., $S_h$). If gas or liquid drives joints, the location of these joints will be at the top of the compartment.

*Observations*: Taughannock State Park features a U-shaped hanging valley and 70 m waterfall at the head of a 1.5 km-long gorge cut to the level of Cayuga Lake. Outcrops within the park consist of the Tully Limestone and Geneseo shales in the stream bed of Taughannock Creek and the lower portion of the Genesee Group (the Geneseo shales) exposed on the walls of the gorge. 200 m upstream from the park entrance bedding surfaces of the Tully Limestone may be examined in the stream bed. In another 800 m upstream the stream bed becomes the black shale of the Geneseo Formation.

On beds of the Tully Limestone, a disjunctive cleavage is well developed. The cleavage gives a faint herringbone pattern on the gray pavement of the Tully Limestone. Cleavage domains appear as a wavy trace of a dark selvage against the light gray background of Tully Limestone. Individual selvages extend for tens of cm before ending in many fine branches. The microlithons of Tully Limestone are 5 to 15 cm thick. The spacing of cleavage domains constitutes a weak cleavage according to the classification of Alvarez and others (1978). A general trend for the cleavage of 077° is normal to the compression direction of the Main Phase of the Alleghanian Orogeny in the vicinity of Ithaca, New York. Because the cleavage is wavy any one cm length of selvage might be misoriented from the 077° trend by as much as 15°. Close examination of the selvages will reveal short stylolites pointing in the direction of the Main Phase compression at about 347° ( Stops 3 & 4).

The contact between the Tully Limestone and the Geneseo shales gives a fine example of the relationship between disjunctive cleavage in the limestone and the development of pencil cleavage in the shales. Best examples are found on the north side of the creek (opposite from the trail) about 400 m from the park entrance. The long axes of the pencils within the Geneseo Formation trend at 077° which parallels the strike of disjunctive cleavage within the Tully Limestone. Here the pencils are blocky rectangular solids rather than the long and skinny shape as found in other outcrops of the Appalachian Plateau. The two short dimensions of a pencil cleavage consist of bedding and a disjunctive cleavage normal to bedding.

The Tully Limestone contains none of the cross-fold joints found within the Genesee Group at stops 2, and 3. Limestone effects joint development in a different manner than siltstone and shale. The best developed joints in the Tully Limestone are several sets of en echelon cracks found on the second bench of Tully Limestone about 300 m from the park entrance. Individual cracks within

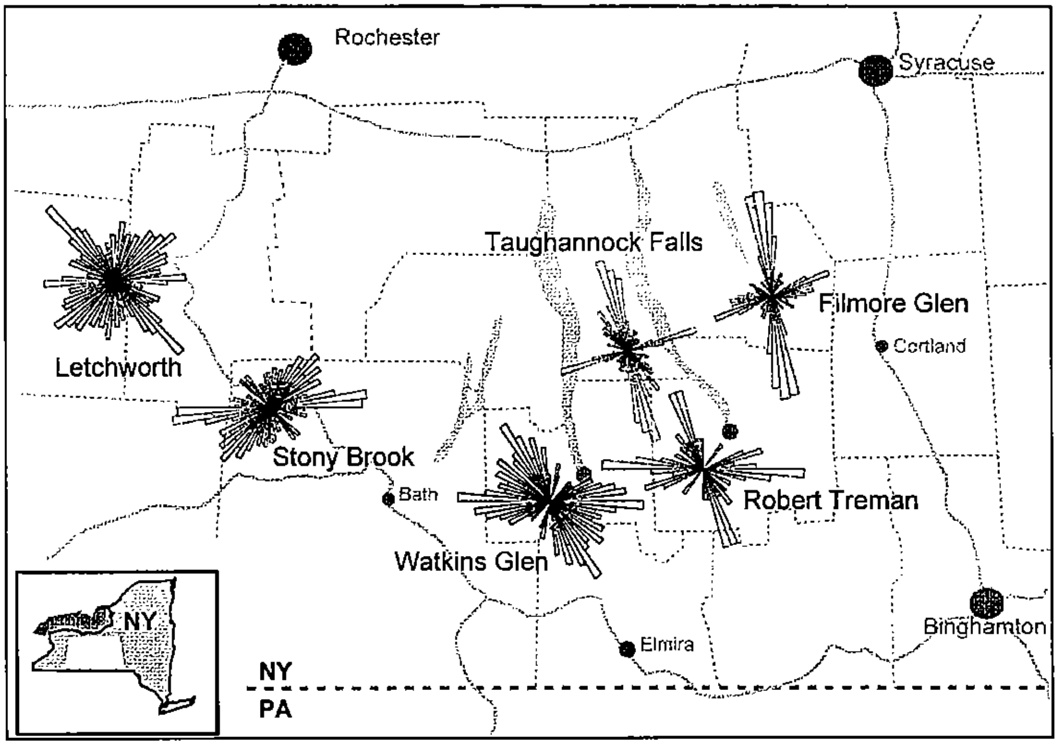


Fig. 10. The orientation of joint sets of the Finger Lakes District, Appalachian Plateau (after Lash et al., 2004).

the en echelon set strike at 316° whereas the shear couple indicated by the en echelon zone strikes at 324°. There seems to be no clear relationship between these en echelon cracks and the Alleghanian Orogeny.

On walking upstream Taughannock Creek makes a right-hand turn at the point where cross-fold joints appear within the Genesee shales. Here it is common to see later subparallel cross-fold joints (330°) curving into and abutting earlier cross-fold joints (340°). This abutting of cross-fold sets is not found at other stops and is difficult to explain in the context of a two phase Alleghanian Orogeny. Note that good examples of ENE joints are common in the creek bed upstream from this point. This joint set will be dominate outcrops in several stops (Fig. 10). The rocks in the walls of Taughannock Creek gorge present an example of the contrast in behavior of cross-fold joints within thick (> 50 m) sequences of homogeneous black shale versus gray shale.

From the Taughannock Creek cross-fold joints can be traced continuously up the valley wall for a large fraction of the exposure of the Geneseo shales. The joints propagate so that their vertical dimension is as large or larger than their horizontal (parallel to strike) dimension. Vertical joint growth was not impeded in the Geneseo Shale in contrast with previous stops where vertical joint growth was arrested by bedding interfaces. Another interesting observation is that the cross-fold joints are much better developed (i.e., more closely spaced) in the gray shales of the overlying Ithaca Formation. The increase in joint density in a vertical direction in these gorge outcrops is largely a function of the pore pressure gradient in an overpressured rock. If rocks of this gorge can be viewed as a pressure compartment, then the top of the compartment is the location where absolute pore pressure is closest to rock stress. Fluid-driven joints would then be more common or better developed in the upper portion of a pressure compartment. Based on evidence seen at the route 414 outcrop in Watkins Glen (Stop 2), the fluid for driving these joints in the gray shales was a natural gas.

## Selected References:

References with Engelder as a coauthor are available as pdf files on T. Engelder's web site (Google: "Engelder Homepage")

Alvarez, W., Engelder, T. and Geiser, P., 1978, Classification of solution cleavage in pelagic limestones, Geology, v. 6, p. 263-266.

Bahat, D. and T. Engelder, 1984, Surface Morphology of Joints of the Appalachian Plateau, New York and Pennsylvania, Tectonophysics, 104, 299-313.

Brown, S.R., and Scholz, C.H., 1985, Broad bandwidth study of the topography of natural rock surfaces: *Journal of Geophysical Research,* v. 90., p. 12,575-12,582.

Davis, D. M. and T. Engelder, 1985, The role of salt in fold-and-thrust belts, Tectonophysics, 119, 67-88.

Engelder, T., 1979a, The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York State, Tectonophysics, 55, 289-310.

Engelder, T., 1979b, Mechanisms for strain within the Upper Devonian clastic sequence of the Appalachian plateau, western New York, Amer. J. Sci., 279, 527-542.

Engelder, T., 1982a, A natural example of the simultaneous operation of free-face dissolution and pressure solution, Geochimica et Cosmochimica Acta, 46, 69-74.

Engelder, T., 1982b, Is there a relationship between regional joints and contemporary stress within the lithosphere of North America?, Tectonics, 1, 161-177.

Engelder, T., 1984, The Apparent Role of Pore-Water Migration During the Deformation of Foreland Fold and Thrust Belts, J. Geophys. Res., 89, 4319-4325.

Engelder, T., 1985, Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, J. of Structural Geology, 7, 459-476.

Engelder, T., 1993, Stress Regimes in the Lithosphere: Princeton Press, Princeton, New Jersey, 451 p.

Engelder, T., 2004, Tectonic implications drawn from differences in the surface morphology on two joint sets in the Appalachian Valley and Ridge, Virginia: Geology, v. 32, p. 413-416.

Engelder, T. and R. Engelder, 1977, Fossil distortion and decollement tectonics of the Appalachian Plateau, Geology, 5, 457-460.

Engelder, T. and P. Geiser, 1979, The relationship between pencil cleavage and lateral shortening within the Devonian section of the Appalachian Plateau, New York, Geology, 7, 460-464.

Engelder, T. and P. Geiser, 1980, On the use of regional joint sets as trajectories of paleostress fields during the development of the appalachian plateau, New York, J. Geophys. Res., 85, 6319-6341.

Engelder, T. and P. Geiser, 1984, Near Surface In Situ Stress Part IV: Residual Stress on the Tully Limestone, Appalachian Plateau, New York, J. Geophys. Res., 89, 9365-9370.

Engelder, T., and Gross, M., 1993, Curving cross joints and the neotectonic stress field in eastern North America, Geology, v. 21, p. 817-820.

Engelder, T., Haith, B.F., and Younes, A., 2001, Horizontal slip along Alleghanian joints of the Appalachian plateau: evidence showing that mild penetrative strain does little to change the pristine appearance of early joints: Tectonophysics, v. 336, p. 31-41.

Engelder, T. and G. Oertel, 1985, The correlation between under-compaction and tectonic jointing within the Devonian Catskill Delta, Geology, 13, 863-866.

Evans, K., and Engelder, T., 1989, Some problems in estimating horizontal stress magnitudes in "thrust" regimes, International Journal of Rock Mechanics and Mining Sciences v. 26, p. 647-660.

Evans, K., Engelder, T. and Plumb, R. A., 1989, A detailed description of in situ stress variations in Devonian Shales of the Appalachian Plateau: Journal of Geophysical Research, v. 94, p. 7125-7154.

Evans, K., Oertel, G. and Engelder, T., 1989, Correlated anomalies of in situ stress and nature compaction in Devonian shales of the Appalachian Plateau: An insight into the of Alleghanian deformation, Journal of Geophysical Research, v. 94, p. 7155-7170.

Gross, M., and Engelder, T., 1991, A case for neotectonic joints along the Niagara Escarpment: Tectonics v. 10,. p. 631-641.

Gross, M., Engelder, T., and Poulson, S., 1992, Veins in the Lockport Dolomite: Evidence for an Acadian fluid circulation system: Geology, v. 20, p. 971-974.

Hancock, P. L. and Engelder, T., 1989, Neotectonic Joints: Geological Society of America Bulletin, v. 101, p. 1197-1208.

Helgeson, D.E., and Aydin, A., 1991, Characteristics of joint propagation across layer interfaces in sedimentary rocks: Journal of Structural Geology, v. 13, p. 897-911.

Hirt, A.M., Evans, K.F., and Engelder, T., 1995, Correlation between magnetic anisotropy and fabric for Devonian shales on the Appalachian Plateau: Tectonophysics, v. 247, p. 121-132.

Hodgson, R.A., 1961a, Classification of structures on joint surfaces: American Journal of Science, v. 259, p. 493-502.

Kay, S. M., Snedden, W. T., Foster, B. P. and Kay, R. W. 1983. Upper Mantle and Crustal Fragments in the Ithaca Kimberlites. Journal of Geology, v. 91, p. 277-290.

Kulander, B.R., and Dean, S.L., 1985, Hackle plume and joint propagation dynamics. *in* Stephannson, O. (Ed.), Fundamentals of rock joints: International Symposium on Fundamentals of Rock Joints, Bjorkliden, Sweden, Proceedings, p. 85-94.

Lash, G.G., and Engelder, T., 2005, An analysis of horizontal microcracking during catagenesis: Example from the Catskill Delta Complex: American Association of Petroleum Geologists Bulletin, v. 89, p. 1433-1449.

Lash, G.G., Loewy, S., and Engelder, T., 2004, Preferential jointing of Upper Devonian black shale, Appalachian Plateau, USA: Evidence supporting hydrocarbon generation as a joint-driving mechanism: in Cosgrove, J. W., and Engelder, T., eds., The initiation, propagation, and arrest of joints and other fractures: Geological Society of London Special Publications, v. 231, p. 129-151.

Marshak, S. and T. Engelder, 1985, Development and distribution of tectonic cleavage and stylolites in limestones of a fold-thrust belt in eastern New York State, J. of Structural Geology, 7, 345-359.

McConaughy, D.T., and Engelder, T., 1999, Joint interaction with embedded concretions: Joint loading configurations inferred from propagation paths: Journal of Structural Geology, v. 21, p. 1637-1652.

McConaughy, D.T., and Engelder, T., 2001, Joint initiation in bedded clastic rocks: Journal of Structural Geology, v. 23, p. 203-221.

Oertel, G., Engelder, T. and Evans, K., 1989, A comparison of the strain of crinoid columnals with that of their enclosing silty and shaly matrix on the Appalachian Plateau, New York, Journal of Structural Geology, v. 11, p. 975-993.

Plumb, R.A., Evans, K. F., and Engelder, T., 1991, Geophysical log responses and their correlation with the bed-to bed stress contrasts in Paleozoic rocks of the Appalachian Plateau, New York: Journal of Geophysical Research, v. 96, p. 14,509-14,528.

Ruf, J.C., Rust, K.A., and Engelder, T., 1998, Investigating the effect of mechanical discontinuities on joint spacing: Tectonophysics, v. 295, p. 245-257.

Savalli, L., and Engelder, T., 2005, Mechanisms controlling rupture shape during subcritical growth of joints in layered rock: Geological Society of America Bulletin, v. 117, p. 436-449.

Scanlin, M.A., and Engelder, T., 2003, The basement versus the no-basement hypothesis for folding within the Appalachian Plateau Detachment Sheet: American Journal of Science, v. 303, p. 519-563.

Scott, P.A., Engelder, T., and Mecholsky, J.J., 1992, The correlation between fracture toughness anisotropy and surface morphology of the siltstones in the Ithaca Formation, Appalachian Basin: in Evans, B. and Wong, T-F., eds., Fault mechanics and transport properties of rocks, Academic Press Ltd., London, p. 341-370.

Sheldon, P., 1912, Some observations and experiments on joint planes, I: Journal of Geology, v. 20, p. 53-70.

Srivastava, D., and Engelder, T., 1990, Crack-propagation sequence and pore-fluid conditions during fault-bend folding in the Appalachian Valley and Ridge, Central Pennsylvania: Geological Society of America v. 102, p. 116-128.

Srivastava, D., and Engelder, T., 1991, Fluid evolution history of brittle-ductile shear zones on the hanging wall of the Yellow Springs thrust, Valley and Ridge Province, Pennsylvania, U.S.A.: Tectonophysics, v. 198, p. 23-34.

Woodworth, J.B., 1896, On the fracture system of joints with remarks on certain great fractures: Boston Society of Natural Historical Proceedings 27, p. 163-183.

Younes, A., and Engelder, T., 1999, Fringe cracks: Key structures for the interpretation of progressive Alleghanian deformation of the Appalachian Plateau: Geological Society of America Bulletin, v. 111, p. 219-239.