THE USE OF JOINT PATTERNS FOR UNDERSTANDING THE ALLEGHANIAN OROGENY IN THE UPPER DEVONIAN APPALACHIAN BASIN, FINGER LAKES DISTRICT, NEW YORK

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REGIONAL SIGNIFICANCE

Abundant evidence (deformed fossils) for layer parallel shortening in western New York indicates the extent to which the Alleghanian Orogeny affected the Appalachian Plateau (Engelder and Engelder, 1977). In addition to low amplitude (< 100 m) long wave length (< 15 km) folds the Upper Devonian sediments of western New York contain many mesoscopic-scale structures including joints that can be systematically related to the Alleghanian Orogeny.

Based on the nonorthogonality of cleavage and joints, the Alleghanian Orogeny in the Finger Lakes District of New York consists of at least two phases which Geiser and Engelder (1983) correlate with folding and cross-cutting cleavages in the Appalachian Valley and Ridge. To the southeast of the Finger Lakes District the earlier **Lackawanna Phase** is manifested by formation of the Lackawanna syncline and Green Pond outlier and the development of a northeast-striking disjunctive cleavage within the Appalachian Valley and Ridge mainly from the Kingston Arch of the Hudson Valley southwestward beyond Port Jervis, Pennsylvania (Fig. 1). Within the Finger Lakes District, New York, a Lackawanna Phase cleavage is absent; and one finds instead a cross-fold joint set which is consistent in orientation with a Lackawanna Phase compression. In bedded siltstone-shale sequences (i.e. the Genesee Group) this cross-fold joint set favors development in the siltstones (stops 1# and 2#). The **Main Phase** is seen as the refolding of the Lackawanna syncline and Green Pond outlier, as well as the development of the major folds in central Pennsylvania. Main Phase structures within the Finger Lakes District include an east-west striking disjunctive cleavage in the Tully Limestone (stops 4# and 5#), a pencil cleavage in the Geneseo shales (stop 4#), deformed fossils in the Genesee Group (stop 1#), and cross-fold joints which are orthogonal with the cleavage and deformed fossils in shales (stop 1#) (Engelder and Engelder, 1977; Engelder and Geiser, 1979, 1980, 1984). Outcrops of Tully Limestone at Ludlowville (stop 5#) contain a Main Phase disjunctive cleavage which truncates nonorthogonal Lackawanna Phase cross-fold joints, showing that the Lackawanna Phase predates the Main Phase (Engelder, 1985).

Many outcrops of the Appalachian Plateau contain more than one cross-fold joint set (Fig. 2). Those cross-fold joints attributed to the Lackawanna Phase strike counterclockwise from those attributed to the Main Phase. Cross-cutting cleavages in northeastern Pennsylvania have the same relationship with the later shortening event clockwise from the earlier event (Fig. 1). One exception to this rule was discovered recently by Scott (1986) who has documented two shortening directions in the Tully Limestone at Portland Point which is 3 km SSE of Ludlowville. At Portland Point the later shortening direction appears to be counterclockwise from the direction of the earlier shortening event.

LITHOLOGICAL CONTROL OF JOINTING

This field trip will examine the relationship between lithology and jointing. During a study of regional joints in the vicinity of Ithaca, New York, Sheldon (1912) recognized that certain joint sets favored certain lithologies. Strike joints were common in shales but less well-developed in interfingered siltstone beds. In the same region of the Appalachian Plateau, Parker (1942) noted that plumose markings were rare on strike joints but commonly occurred on cross-fold joints. These studies and those elsewhere (e.g. Stearns, 1968; Nelson and Stearns, 1977) make it clear that the host lithology is an important parameter in influencing the development of regional joint sets as well as their surface morphology.

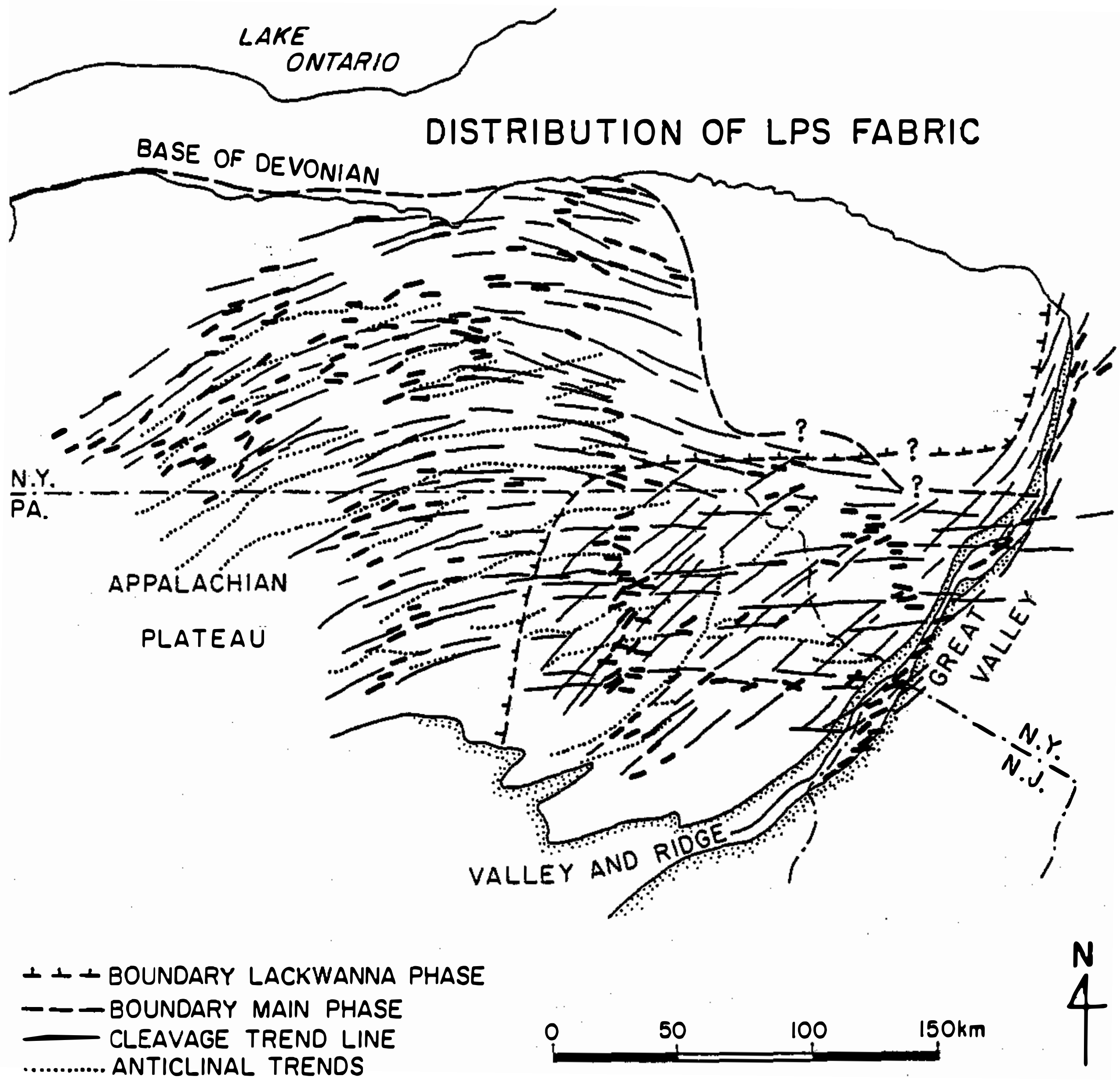

Figure 1. The distribution of layer-parallel shortening (LPS) fabrics across the Appalachian Plateau of New York. The trend-line map was prepared by connecting data points (thick lines) with nearly parallel cleavage planes. The orientation of the cleavage planes is shown by a plot of the strike of cleavage planes (after Geiser and Engelder, 1983).

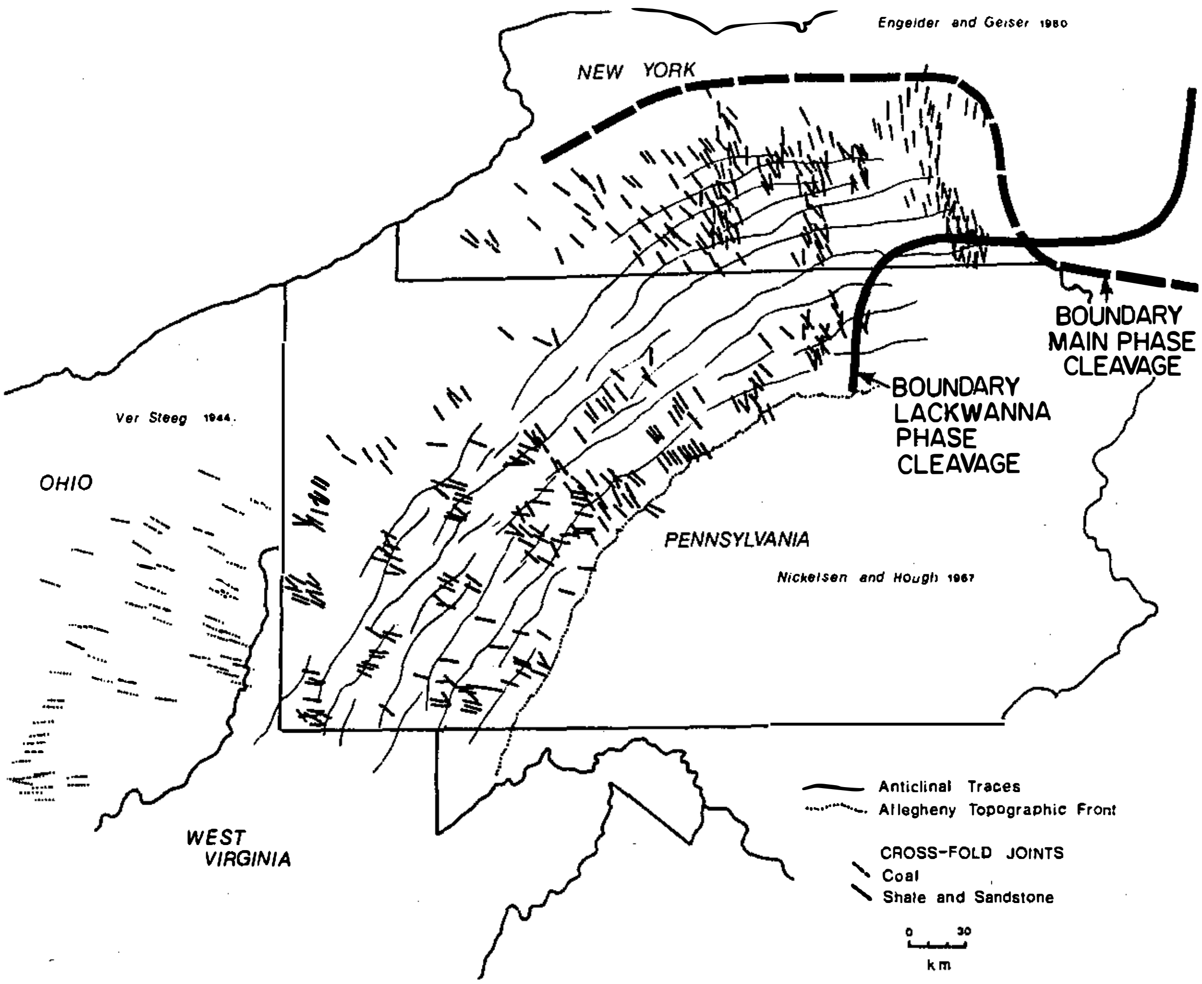

Figure 2. The distribution of cross-fold joints and cleavage within the Central Appalachians (after Engelder, 1985). Cleavage, imprinted during the Lackawanna Phase of the Alleghanian Orogeny, affected the area south of the solid line whereas cleavage imprinted during the Main Phase of the Alleghanian Orogeny affected the area south of the dashed line.

The five stops of this trip will view the same stratigraphic section that Sheldon (1912) examined. The major units include the Genesee Formation (deWitt and Colton, 1978) or Genesee Group (Van Tyne, 1983), the Tully Limestone, and the Hamilton Group (Van Tyne, 1983). Figure 3 shows deWitt and Colton's (1978)stratigraphic column for the Genesee Formation. The first three stops will examine the Ithaca Member of the Genesee Formation. Stop 4# will examine the Tully Limestone, Geneseo Shale Member, and the Penn Yan Shale Member. Stop 5# will examine the Moscow Shale of the Hamilton Group and the Tully Limestone.

Three general lithologies will be examined: a bedded siltstone-shale sequence (the Ithaca Member), a homogeneous shale (the Geneseo Shale Member and Moscow Shale) and a limestone (the Tully Limestone). Each of these three lithologies has a characteristic joint-orientation pattern and characteristic surface morphology. In addition, surface morphology varies among the various cross-fold joint sets discussed in Sheldon (1912), Parker (1942), and Engelder and Geiser (1980). Surface morphologies have been used to make the case that the cross-fold joint sets mapped by Engelder and Geiser (1980) are fundamentally different from each other.

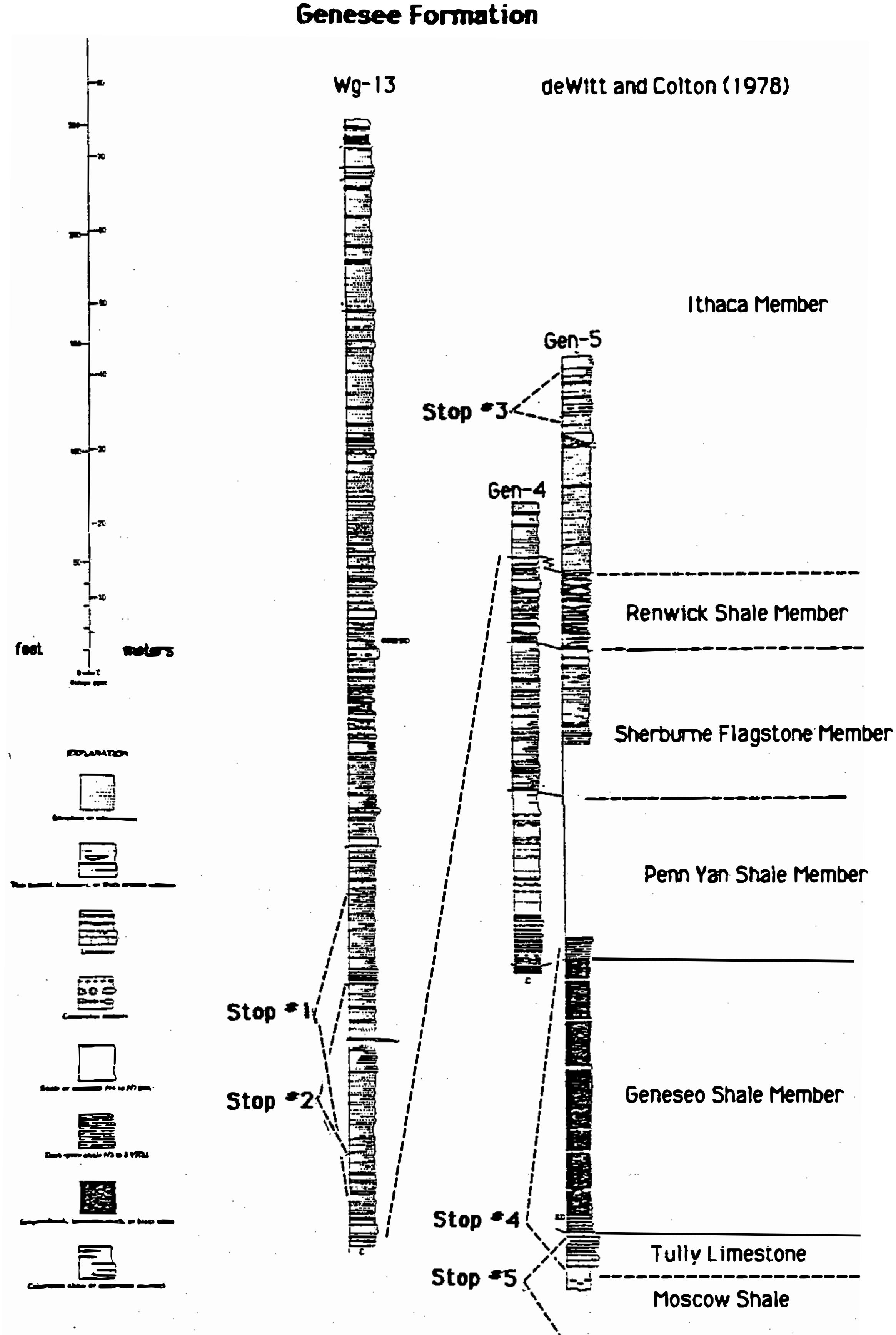

Figure 3. Genesee Formation sections Wg-13, Gen-4 and Gen-5 (after deWitt and Colton, 1978). Stops #1, #2, #3, #4, and #5 are shown in the Ithaca Member, Geneseo Shale Member, Tully Limestone, and Moscow Shale respectively.

Within the Appalachian Plateau evidence is overwhelming that the joints formed in extension rather than shear (Engelder, 1982). Surface morphology on joints is distinct from slickensided surfaces on shear fractures. The pattern on joints is called a plumose structure; it constitutes all "delicate tracery of feathery lines" (Woodworth, 1896) diverging from either a straight or sinuous axis. Plumose patterns form during the propagation of a crack (joint) with motion on the crack face normal to the plane of the crack. By the late 19th century geologists recognized that the feather (plume) patterns on joints contained information about the process of joint propagation (Woodworth, 1896). Plumose patterns form on the surface of extension fractures (joints) where the plume records the development of the joint whose rupture front is perpendicular to the barbs of the plume (Fig. 4). Despite the large number of descriptions of the markings on joint faces (Hodgson, 1961; Roberts, 1961; Syme-Gash, 1971; Kulander et al., 1979) none adequately distinguishes the end members of the family of plumose markings observed on the Appalachian Plateau.

STOP 1: LITHOLOGICAL CONTROL OF CROSS-FOLD JOINTS IN THE UPPER GENESEE GROUP, WATKINS GLEN, NEW YORK

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.

As this roadcut at Watkins Glen 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. In walking uphill along Route 414 from the town of Watkins Glen, find at the base of the roadcut a 15 cm thick siltstone with plume structures nicely developed on a joint face. Stratigraphic levels within the Genesee Group of this roadcut are referenced from the bottom of this 15 cm thick bed. 10 siltstone beds or groups of beds may be used as markers in describing the 34 m thick roadcut. Key beds are located according to Table I.

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 Member of the Genesee Formation are subtle. Figure 5 shows histograms for the grain size distribution and composition of siltstones and shales from stop #1. At stop #1 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 and1.06 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.

Table I

Bed Number	Stratigraphic Level (m from base)	Landmark or Road Sign
1	0 m	"Slow traffic keep right" sign
2	4 m	Natural Gas Pipe Line
3	12 m	"JCT 14" sign
4	16 m	"Village Speed Limit 30 MPH"
6	22 m	"55 MPH" sign
7	25 m	top portion of thick shale
8	27 m	caution sign for deer

Another unusual aspect 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 roughnesses (low relief elements) on the joint surface which were caused by local out-of-plane crack propagation. This roughness forms ridges

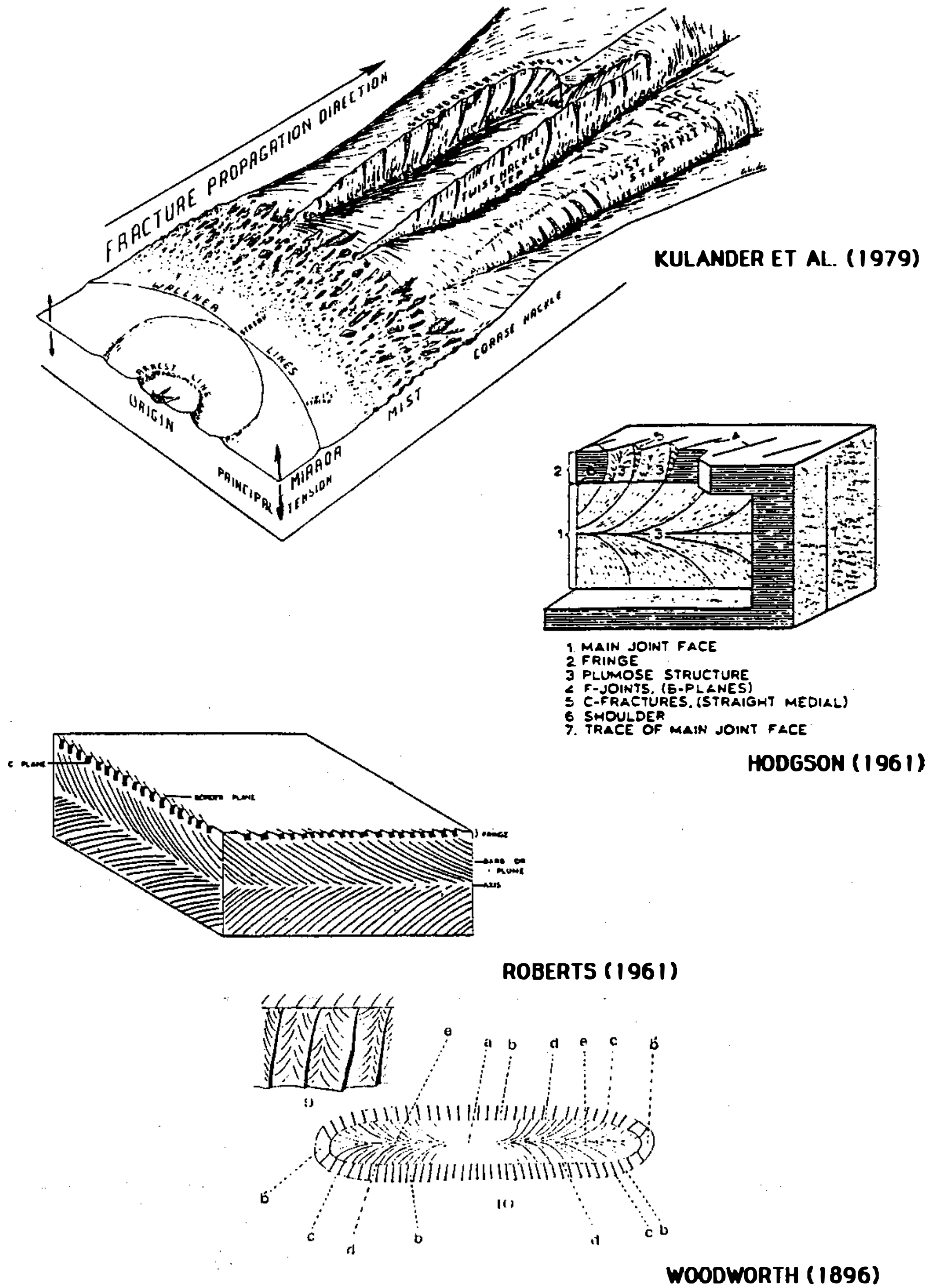

Figure 4. Plumose patterns from Woodworth (1896), Hodgson (1961), Roberts (1961), and Kulander et al. (1979). Woodworth (1896) distinguishes a fringe (b) and a plume axis (e). The fringe of Woodworth (1896), Roberts (1961), and Hodgson (1961) is the area of twist hackle steps of Kulander et al. (1979).

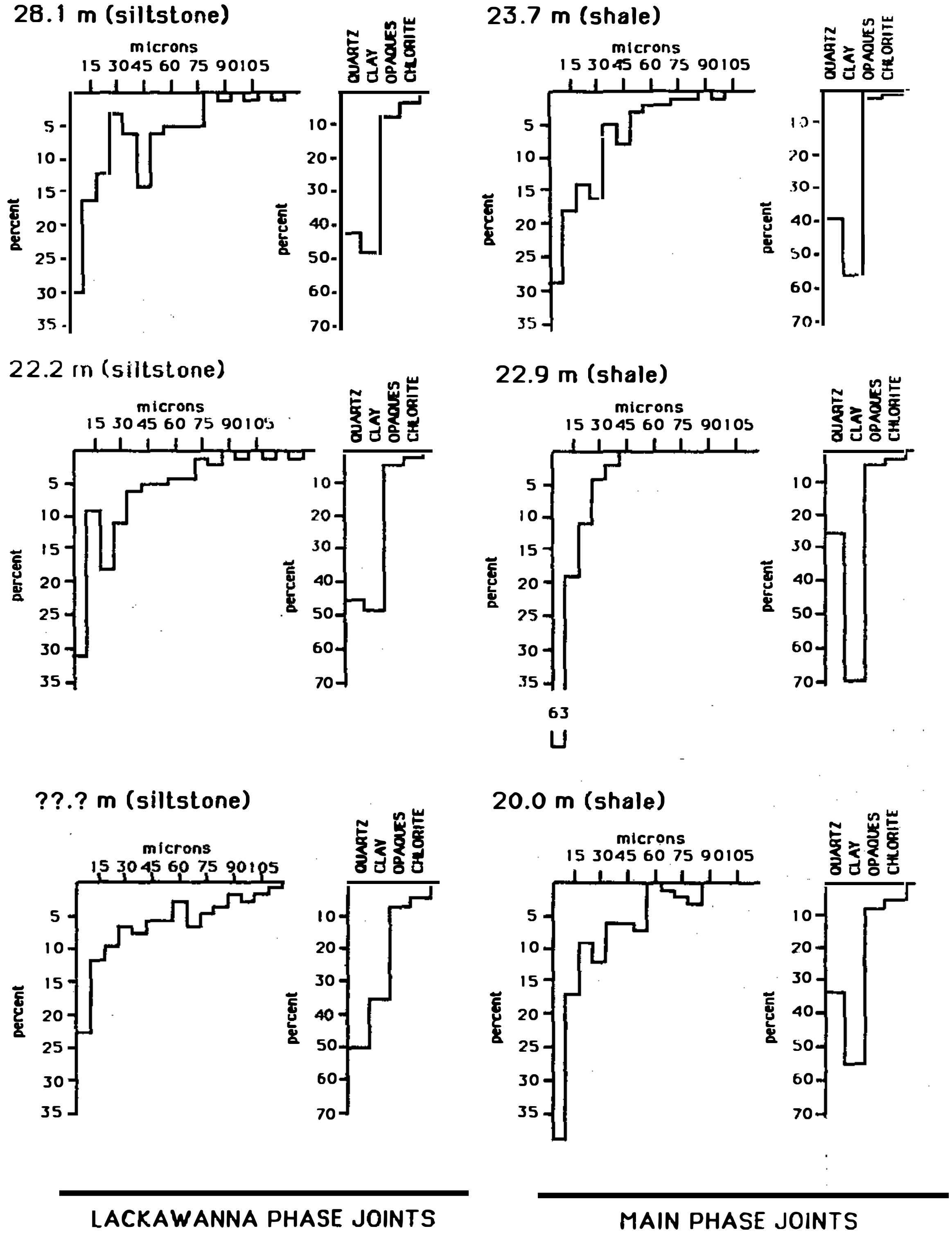

Figure 5. Histograms showning the grain-size distribution and composition of "shales" and "siltstones" from Stop #1. Location of each sample designated in terms of vertical distance within the outcrop. The exact loca - tion of one "siltstone" sample unknown.

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 micro-scopic 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.

Joint faces within siltstones contain three varieties of plumose patterns: the straight or s-type plumose marking which is displayed in the 19 cm thick siltstone bed (#7) at the 25.7 m level (Fig. 6A); the curving or c-type plumose marking which is best displayed in siltstone (bed #8) at the 29 m level (Fig. 6B); and the rhythmic c-type plumose marking which is displayed on the 44 cm thick siltstone bed (#6) at the 22.4 m level (Fig. 6C). 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.

The plumose structures may be traced backward to their initiation point. Cracks initiate at inclusions within the rock such as fossils, concretions, ripple marks, or microcracks. These inclusions are stress risers that permit the magnification of a far field stress to overcome the local tensile strength of the rock. At stop 1# most initiation points are bedding plane boundaries. The 19 cm thick siltstone stringer (#7) at the 25.7 m level contains four or more initiation points at the top of the bed. In contrast, the 44 cm thick stringer (bed # 6)shows initiation points on the bottom of the bed. Higher in the section (≈ 29 m level) siltstone beds are cut with initiation points within the bed.

A feature found on both shale and siltstone joints are arrest lines. These features mark the termination of propagation of individual cracks. The 4 m thick shale bed, at the 24 m level, 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 (bed #7) 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. Within the same shale bed another joint terminates against the arrest line after propagating in the SSE direction as is again indicated by the barbs on the s-type plume within the siltstone stringer (bed #7). Arrest lines can be observed on the 44 cm thick siltstone bed (#6) at the 22.4 m level. 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 bed #6 may be interpreted in terms of a jointing mechanism. The deeper portion of the Appalachian Basin is undercompacted (Engelder and Oertel, 1985). Such undercompaction indicates that abnormal pore pressures once prevented normal pore collapse. Pore pressures approaching the weight of the overburden are capable of initiating and driving natural hydraulic fractures. The closely-spaced arrest lines within the siltstone beds suggests a cyclic rupture. 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°, (this is considered the normal orientation for joints in siltstone layers at stop 1#) whereas small siltstone stringers (i.e. bed #7) in thick shales show the s-type plumes with joints striking at 341°. The s-type plume in bed #7 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.

The difference between joint propagation in the shales and joint propagation within the siltstones is further understood by placing the timing of their propagation within a regional context. On upper benches of the outcrop (at the 34 m level) deformed crinoid columnals show that the layer parallel shortening (LPS) during the

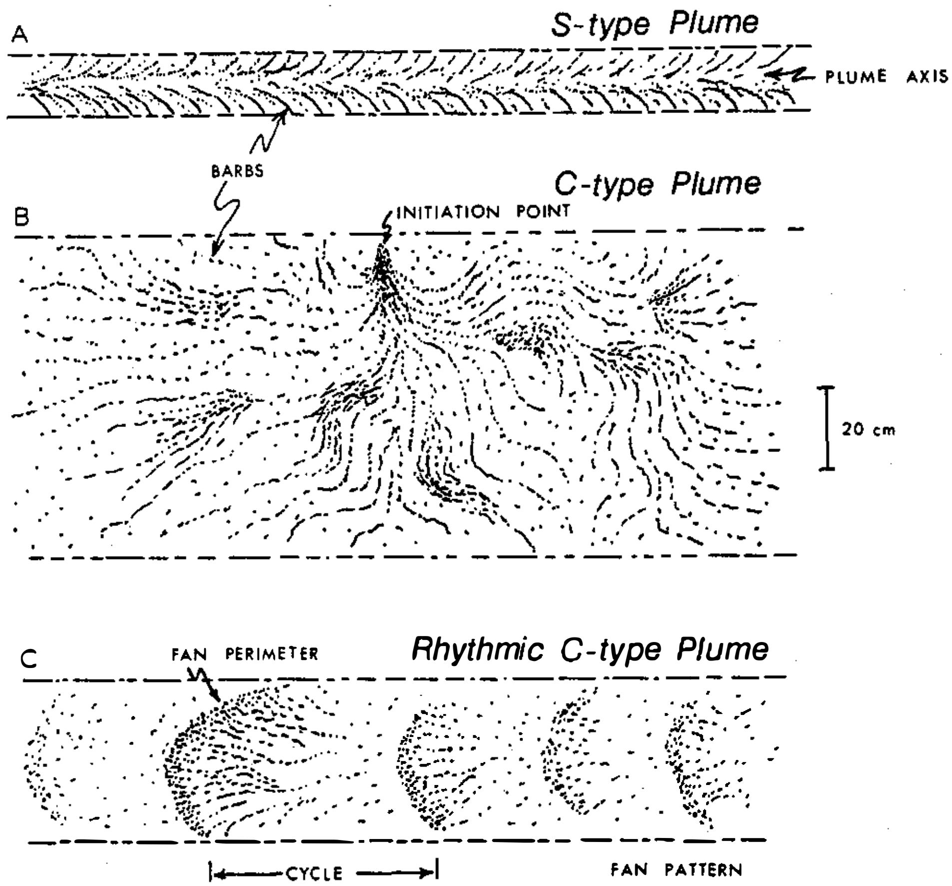

Figure 6. Various plume patterns observed on the surfaces of vertical joints in siltstones of the Finger Lakes District. A. Straight plume (bed #7). B. Curving Plume (bed #8). C. Rhythmic plume (bed #6). (after Bahat and Engelder, 1984).

Alleghanian orogeny was oriented at 341°. Geiser and Engelder (1983) interpret this LPS direction as a principal compression direction during the Main phase of the Alleghanian Orogeny. At Watkins Glen the othogonality of shale joints and LPS indicated by deformed fossils suggests that the shale joints propagated during the Main Phase. If this is so them when did the joints within the siltstone beds propagate?

The joints within the siltstone are believed to precede those within shales. First, early joints at Ludlow - ville, New York (stop 5#) appear to be cut by Main Phase cleavage. These joints strike a few degrees counter - clockwise from the Main Phase LPS. Secondly, in a deeply buried siltstone-shale sequence the siltstones are known to show a lower least principal stress compared to shales. If joints are hydraulic fractures propagating under high fluid pressures, the joints in beds with the lower least principal stress will propagate first. Third, the preferred orientation of chlorite within the siltstone beds is compatible with a LPS counterclockwise from the LPS affecting the shales (Oertel and Engelder, 1986). Elsewhere in the central Appalachians, the Lackawanna Phase LPS precedes the Main Phase LPS with a counterclockwise compression (Fig. 2).

STOP 2: MULTIPLE JOINTING IN THE UPPER GENESEE GROUP AT WATKINS GLEN

This location just west of Watkins Glen also consists of benches in a roadcut. A 4-5 m thick siltstone unit is the major component of each bench. Here the relationship between lithology and jointing is less straight forward than was found at stop 1#.

A 3-m thick siltstone within the upper bench contains cross-fold joints (334°-336°) which propagate to but not across the contact between the siltstone and the adjacent shales. This again demonstrates how lithological changes act to stop the vertical propagation of joints. However, joints originating within the underlying shale cross into the overlying interface to propagte upward into the siltstone. This latter behavior breaks the rule that lithological changes stop vertical joint propagation. Note that joints within the siltstone are planar whereas the joints in the adjacent shale are less planar.

Both the siltstones and shales of the upper bench carry joints of more than one orientation. At the very south end of the upper bench the siltstone contains joints of two orientations. A joint striking 336° is on top of a joint striking at 343°. Close examination suggests that the joint striking at 343° propagates in a layer that looks more like a shale than the adjacent layer. There are subtle changes in lithology within units that at a distance apprear homogeneous to jointing. The shale package below the 3-m thick siltstone has siltier units with joints striking at 336° versus shalier units with joints at 348°

The lower bench of this roadcut contains three cross-fold joint sets with strikes of 334°, 341°, and 004°, respectively. The three joint sets are best viewed just downhill from the north 414-east 79 sign within a face of the lower bench. All three joints have propagated in the same 4 m thick unit of siltstone beds. Again the rule of lithological selectivity of jointing is not obeyed. If it is accepted that the sets at 334° and 341° correlate with those at the previous stop, then the set at 004° requires explanation. We must also wonder if it is possible to fit three cross-fold joint sets into a regional context.

Geologists are in general agreement that tectonic joints are found as othogonal partners to fold axes within fold thrust belts. The exact details concerning the mechanism for maintaining orthogonality are subject to debate. Engelder and Geiser (1980) took the position that, as fold axes curved around the Central Appalachian trend, members of a single joint set on the Appalachain Plateau changes orientation to maintain a position subnormal to local fold axes. A single joint set may then be traced along strike of the Plateau fold belt for more than 100 km. Nickelsen and Hough (1967) took the opposite view which was that one joint set did not change orientation along strike. Rather individual joint sets maintained a constant orientation within a smaller region and a local joint set of another orientation propagated to maintain "orthogonality" to the local folds of a different orientation.

100 km east of the Watkins Glen area the 004° orientation is far more common than at Watkins Glen. By Engelder and Geiser's (1980) interpretation the 004° joints in this outcrop are stray cross-fold joints with no tectonic significance. By Nickelsen and Hough's (1967) interpretation the 004° joints are the western most manifestation of the common cross-fold joint set found in the vicinity of Binghamton, New York. The distance between outcrops is too large to resolve this issue.

STOP 3: LITHOLOGICAL CONTROL OF MULTIPLE JOINT SETS IN ITHACA SHALE OF THE GENESEE GROUP AT TAUGHANNOCK STATE PARK

This outcrop 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 back 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°.

Here the question is which joint sets correlate with those seen at stops 1# and 2#? Does a 333° joint in siltstone at stop 1# correlate with a 340° joint in siltstone at stop 3#? Likewise, does a 342° joint in shale at stop 1# correlate with, say, a 352° joint in shale at stop 3#? Or should a correlation be made strictly on common orientation such as the 342° at stop 1# with the 340° at stop 3#? These are questions that will probably never be answered to everyone's satisfaction.

Strike joints (080°-090°) are irregular in plan view and widely-spaced in this outcrop. This irregular form is common for strike joints throughout the Appalachian Plateau. Strike joints are believed to propagate upon uplift and, hence, be very late in origin.

STOP 4: DISJUNCTIVE CLEAVAGE AND JOINTING IN THE TULLY LIMESTONE AND GENESEO SHALE AT TAUGHANNOCK FALLS STATE PARK

Taughannock State Park features a U-shaped hanging valley and 50 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 Geneseo shale.

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 10s 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°. At stop 1# the compression direction was 341°.

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 about 400 m from the park entrance. The long axes of the pencils within the Genesee Shales 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.

At stop 4# the Tully Limestone contains none of the cross-fold joints found within the Genesee Group at stops 1#, 2#, and 3#. Limestone affects 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 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 righthand 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.

The rocks in the walls of Taughannock Creek gorge present an example of the behavior of cross-fold joints within thick (> 50 m) sequences of homogeneous shale. From the Taughannock Creek the tectonic 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. In contrast with stops 1#,2#, and 3# where vertical joint growth was arrested by bedding interfaces, vertical joint growth was not impeded in the Geneseo Shale. This is best seen at the point where the gorge makes a right turn 1000 m from the park entrance. After rounding the right turn in the creek bed, look up on the southeast side of the gorge. Here cross-fold joints are displayed on the southern wall whereas strike joints are displayed on the eastern wall. Across the creek from this point cross-fold joints can be seen on the northern wall. The cross-fold joints are better developed and more closely spaced. This same effect can be seen at the falls where (facing the falls) rocks to the left of the falls show cross-fold joints whereas those to the right of the falls show widely spaced strike joints. Note that cross fold joints become irregular within 50 m above the top of the Tully Limestone.

Engelder (1985) distinguishes tectonic joints (those caused by abnormal pore pressures during tectonic compression) from release joints (those caused by erosion and controlled in orientation by an pervasive fabric such as disjunctive cleavage). At the right turn in Taughannock Creek the cross-fold joints are tectonic joints and the strike joints are release joints. Evidence for the development of abnormal pressures during tectonic (cross-fold) joint propagation include the undercompaction of the Geneseo shales (Engelder and Oertel, 1985). Note that good examples of release joints are common in the creek bed upstream from this point. In general the release (strike) joints tend to be less regular in profile than tectonic (cross-fold) joints.

STOP 5: THE RELATIONSHIP BETWEEN DISJUNCTIVE CLEAVAGE AND JOINTING IN TULLY LIMESTONE AND THE UPPER HAMILTON GROUP IN SALMON CREEK AT LUDLOWVILLE, NEW YORK

Rocks within this outcrop include the Tully Limestone (in the bed of Salmon Creek) above the Upper Member of the Hamilton group (seen below the falls). The major mesoscopic structure within the Tully Limestone is a spaced solution cleavage indicating a compression direction of about 005°. Within just about 4 km between stop 4# and stop 5# the compression direction as indicated by cleavage has changed by more then 20°. This is one of the most abrupt changes in LPS within the entire New York Plateau. Less than 2 km south of this outcrop the Tully Limestone is cut by several faults as seen in the Portland Point Quarry. Here local stuctures overprint a relatively homogeneous strain pattern.

Calcite filled veins striking between 340° and 345° dominate within the Tully Limestone of this outcrop. These veins seem to be cut by the spaced cleavage indicating that the veins propagated first. This cross-cutting relationship is taken as evidence that 345° joints are Lackawanna in age whereas the cleavage correlates with the Main Phase deformation.

Overcoring tests at this outcrop show a residual maximum compressive stress normal to the trend of the cleavage (i.e. 005°) (Engelder and Geiser, 1984) (Fig. 7). This residual stress is believed to have been locked into the Tully Limestone during the Main Phase of the Alleghanian Orogeny.

In the pavement of the stream below the falls the Hamilton Group carries joints striking between 70° and 75°. On the eastern wall of the falls just under the Tully Limestone 340°-345° joints are well developed in the Hamilton Group.

On the far side of the stream a few trilobites may be seen weathering out of the polished surface of the stream bed.

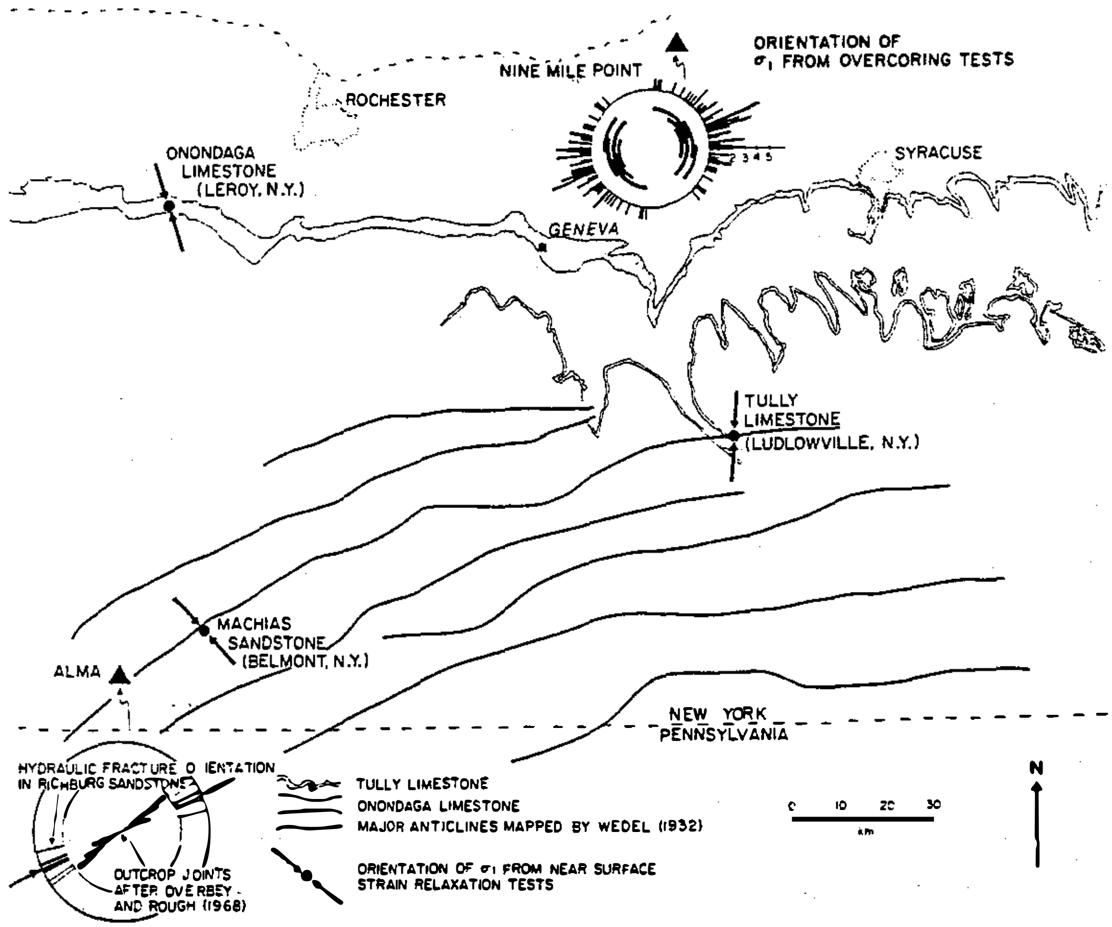

Figure 7. The location of strain relaxation experiments in the Tully Limestone, Machias Sandstone, and Onondaga Limestone. Overcoring data from Nine Mile Point represent the orientation of maximum horizontal compressive stress for 74 measurements (Dames and Moore, 1978). The variation in azimuth from each of six test holes shown inside the rose diagram. The orientations of nine hydraulic fractures from Alma are shown, with the average azimuth located by the inward pointing arrows (Overby and Rough, 1968)

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ROAD LOG FOR THE USE OF JOINT PATTERNS IN UNDERSTANDING THE ALLEGHANIAN OROGENY

CUMULATIVE MILAGE	MILES FROM LAST POINT	ROUTE DESCRIPTION
0.0	0.0	STOP 1# ---- Travel south on Franklin Street in the town of Watkins Glen, New York and find the intersection of New York State routes 14 and 414 on the south side of town. At that intersection park in the parking lot of the Yankee Pedlar. From the parking lot the outcrop is viewed by walking uphill along route 414.

Leave stop 1# by driving north along Franklin Street which is both routes 14 and 414. (Montour Falls Quadrangle)

0.7	0.7	Turn right to follow route 414 at 4th Street.
2.3	1.6	STOP 2# ---- Intersection of New York State routes 79 and 414. Park downhill from the North 414-East 79 sign. From this intersection stop 2# is viewed by walking downhill and south along route 414. Leave stop 2# by driving east along route 79.
3.7	1.4	Burdett
8.8	5.1	At intersection of New York State routes 79 and 227 bear left along 227 towards Reynoldsville and Perry City.
14.8	6.0	Perry City. Bear left on route 227 to Trumansburg.
18.9	4.1	Trumansburg at the intersection of routes 227 and 96 turn right or south along route 96.
20.0	1.1	At Cemetery Road across from the Trumansburg High School turn left and then take an immediate right to follow Falls Road south.
22.0	2.0	Left on Taughannock Road
22.1	0.1	STOP 3# ---- Park at the Falls Road Bridge which crosses Taughannock Creek. The outcrop is just upstream from the bridge. Leave the outcrop by driving south.
22.4	0.3	Intersection of Jacksonville Road and Gorge Road. Turn left and drive east or downhill on Gorge Road.
24.1	1.7	STOP 4# ---- At the interestion of Gorge Road and Route 89 turn left on 89 and proceed north about 200 m to the parking lot of Taughannock Falls State Park. The outcrop can be viewed by walking east or upstream along Taughannock Creek. Leave stop 4# by driving south along route 89. (Ludlowville Quadrangle).
33.5	9.4	Ithaca at the intersection of New York State routes 89, 96, and 79. Turn left and follow routes 96 and 79 into town.
34.0	0.5	Ithaca at the intersection of New York State routes 13, 34, 79, and 96. Turn left and follow route 13 and 34 north.
35.8	1.8	Exit four-lane highway to following route 34 north towards Auburn.
41.7	5.9	South Lansing at the intersection of New York State routes 34 and 34B. Turn left and follow 34 B to the north.
42.7	1.0	Turn right and follow Brickyard Road to the north.
43.5	0.8	Turn right and follow Main Street into Ludlowville.
43.9	0.4	STOP 5# ---- Enter park at the north end of Main street in Ludlowville. Walk northeast 50 m to the outcrops in the bed of Salmon Creek.