Alleghanian deformation within shales and siltstones of the Upper Devonian Appalachian Basin, Finger Lakes District, New York

Terry Engelder, Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802
Peter Geiser, Geology Department, University of Connecticut, Storrs, Connecticut 06268
Dov Bahat, Department of Geology and Mineralogy, Ben-Gurion University of the Negev, Beer Sheva, Israel

LOCATION

The effects of the Alleghanian Orogeny on marine sediments of the Catskill Delta may be examined at two locations in the Finger Lakes District of New York State (Fig. 1). The first location lies at the junction of New York 14 and 414 south of Watkins Glen, New York. Here, a 100-ft (30-m)-thick section of the upper Genesee Group may be followed for 1,300 ft (400 m) along the New York 414 roadcut southwest of the intersection. Park in town near the intersection and walk uphill from the intersection. Many benches may be reached by climbing over the guard rail of New York 414.

The second location is at Taughannock Falls State Park on New York 89 6.6 mi (11 km) north of Ithaca, New York, where a 200-ft (60-m)-deep gorge contains a continuous outcrop of the Tully Limestone and the overlying Genesee Group. Park at the entrance along New York 89. Outcrops may be viewed by walking westward from the entrance along the trail on the south side of Taughannock Creek. The pavement of the creek bed may be examined by climbing down into the creek bed at many points along the trail. The trail also permits excellent views of the rock walls of the gorge.

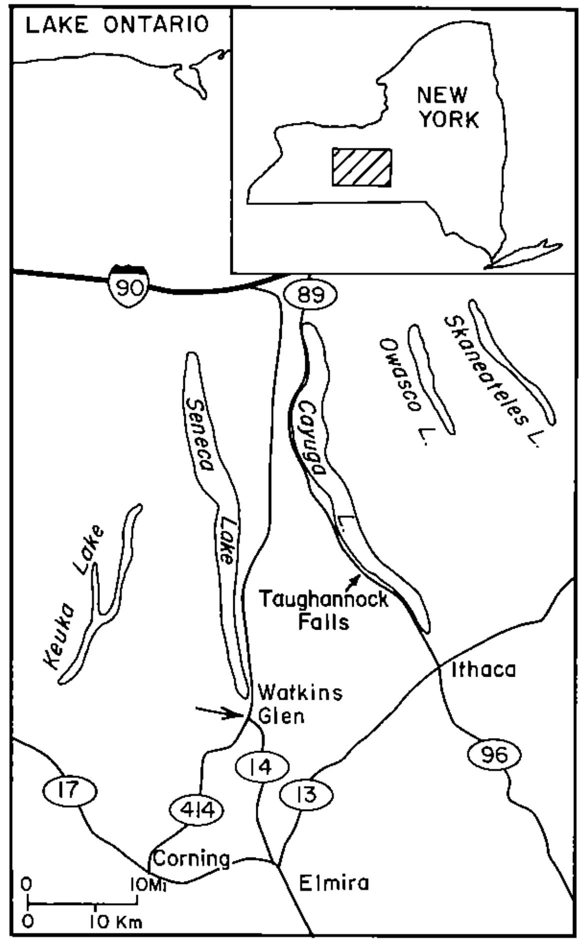

Figure 1. Geographic location of Taughannock Falls and Watkins Glen.

SIGNIFICANCE

The discovery of abundant evidence (deformed fossils) for layer parallel shortening in western New York (Engelder and Engelder, 1977) led us to recognize the extent to which the Alleghanian Orogeny affected the Appalachian Plateau. 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 that can be systematically related to the Alleghanian Orogeny. The Watkins Glen and Taughannock Falls locations are two of the best for introducing these structures.

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 that Geiser and Engelder (1984) 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. 2). Within the Finger Lakes District, New York, a Lackawanna Phase cleavage is absent; one finds instead a cross-fold joint set that is consistent in orientation with a Lackawanna Phase compression. In the Genesee Group this cross-fold joint set favors siltstones. In the valley and ridge, 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, a pencil cleavage in the Geneseo shales (Engelder and Geiser, 1979), deformed fossils in the Genesee Group (Engelder and Engelder, 1977), and cross-fold joints that are orthogonal with the cleavage and deformed fossils in shales (Engelder and Geiser, 1980). Outcrops of Tully Limestone at Ludlowville (2.4 mi; 4 km east of Taughannock Falls) contain a

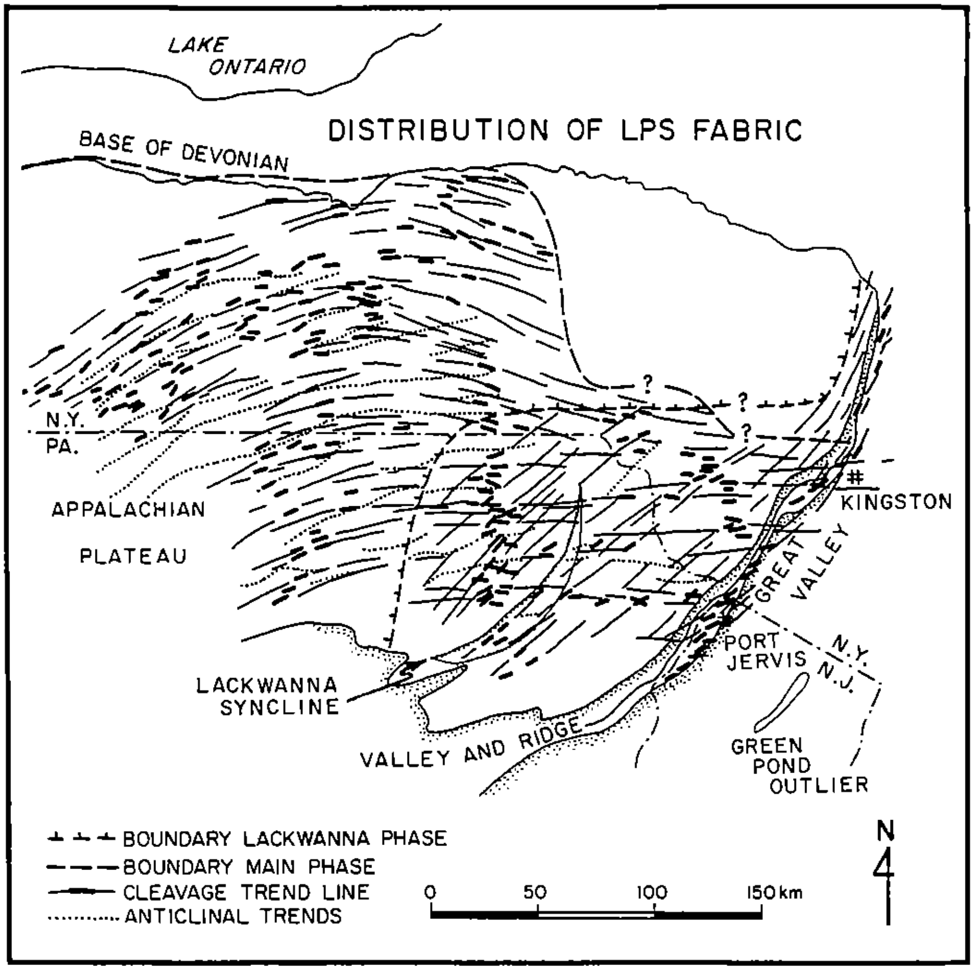

Figure 2. The distribution of layer-parallel-shortening (LPS) fabrics across the Appalachian Plateau of New York. The trend-line map was prepared by connecting data points (thick lines) with nearly parallel cleavage planes. The orientation of the cleavage planes is shown by a plot of the strike of cleavage planes (after Geiser and Engelder, 1983).

Main Phase disjunctive cleavage which truncates nonorthogonal Lackawanna Phase cross-fold joints, showing the age relationship between the Lackawanna and Main Phases (Engelder, 1985).

Many outcrops of the Appalachian Plateau contain more than one cross-fold joint set (Fig. 3). 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 (Fig. 2).

SITE INFORMATION

Stop 1: Watkins Glen. This roadcut is best viewed in the late morning when the sun strikes the joint surfaces at a high angle. After about 11:30 A.M. 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, siltstone stringers are intercalated with the shale. At the top of the roadcut, siltstones dominate. In walking uphill along New York 414 from the town of Watkins Glen, find at the base of the roadcut a 6-in-thick (15-cm) 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 6-in-thick (15-cm) bed. Ten siltstone beds or groups of beds may be used as markers in describing the 112-ft-thick (34-m) roadcut. Major siltstone beds appear above bed #1 as follows: bed #2 ~13 ft (4 m); #3 ~40 ft (12 m); #4 ~53 ft (16 m); #5 ~69 ft (21 m); #6 ~73 ft (22 m); #7 ~83 ft (25 m); #8 and #9 between 89 and 99 ft (27 and 30 m); and #10 ~109 ft (33 m). Beds #7 through #10 are multiple beds. Key siltstone beds are a 7.6-in-thick (19 cm) siltstone stringer (#7) within a shale at the 84.8-ft (25.7-m) level and a 17.6-in-thick (44 cm) siltstone bed (#6) at the 73.9-ft level (22.4 m). Bed #6 stands out as an isolated bench just over half

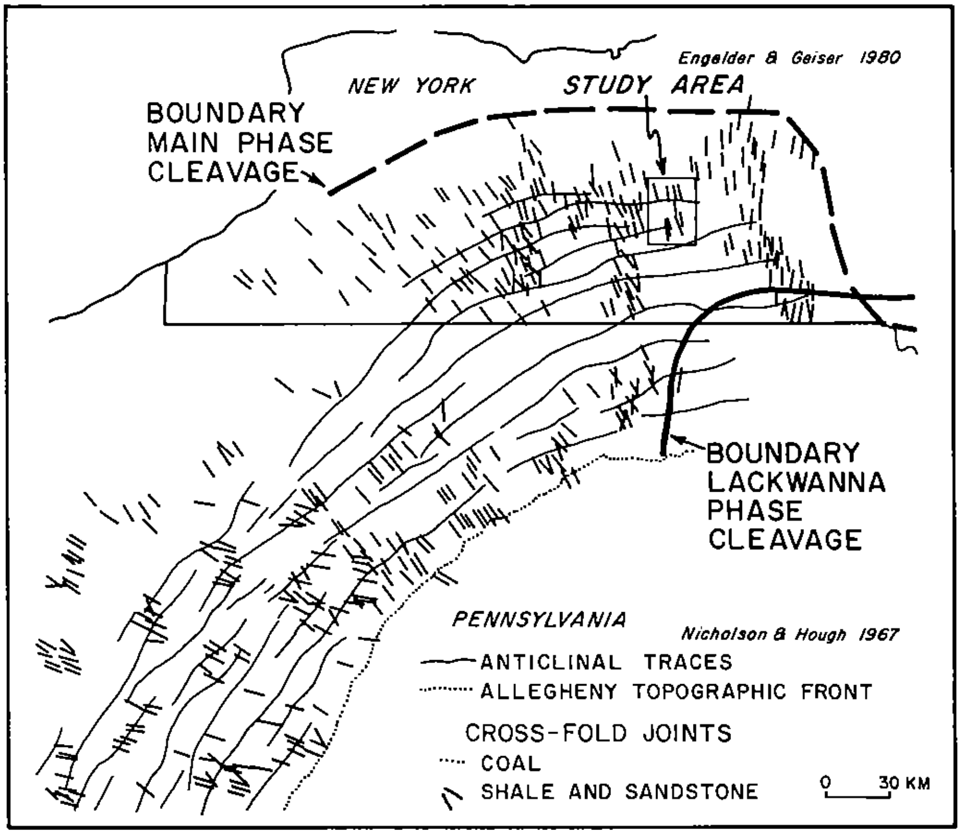

Figure 3. The distribution of cross-fold joints and cleavage within the Central Appalachians (after Engelder, 1985). Cleavage imprinted during the Lackawanna Phase of the Alleghanian orogeny affected the area south of the solid line whereas cleavage imprinted during the Main Phase of the Alleghanian orogeny affected the area south of the dashed line.

way up the roadcut. The key shale bed is the 13-ft-thick (4 m) bed found just above siltstone bed #6 and located between the 7.39-ft and 86.5-ft (22.4-m and 26.2-m) level.

One unusual aspect of this roadcut is the lithological control of the jointing. Vertical joints within the shales strike at 341°–343°, whereas vertical joints within the siltstone beds strike at 331°–334°. Another unusual aspect is the variety of well-developed markings on the surfaces of joints in both the siltstones and shales. Joint surface markings of particular interest include barbs (very fine hackles) and arrest lines. A composite of these barbs and arrest lines gives a delicate plumose marking 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 and 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 the barb and ancillary 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 8-in-thick (19 cm) siltstone bed (#7) at the 84.8-ft (25.7-m) level (Fig. 4A); the curving or c-type plumose marking, which is best displayed in siltstone (bed #8) at the 95.7-ft (29-m) level (Fig. 4B); and the rhythmic c-type plumose marking, which is displayed on the 18-in-thick (44 cm) siltstone bed (#6) at the 73.9-ft (22.4-m) level (Fig. 4C). The straight plume has a linear axis parallel to bedding, whereas the curving plume commonly has an axis that divides into several branches that 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, that indicates the direction of rupture propagation, with the rupture moving from the plume axis outward toward the edge of the joint.

The plume 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 the New York 414 roadcut, most initiation points are bedding plane boundaries. A good example of this effect is found on the joint

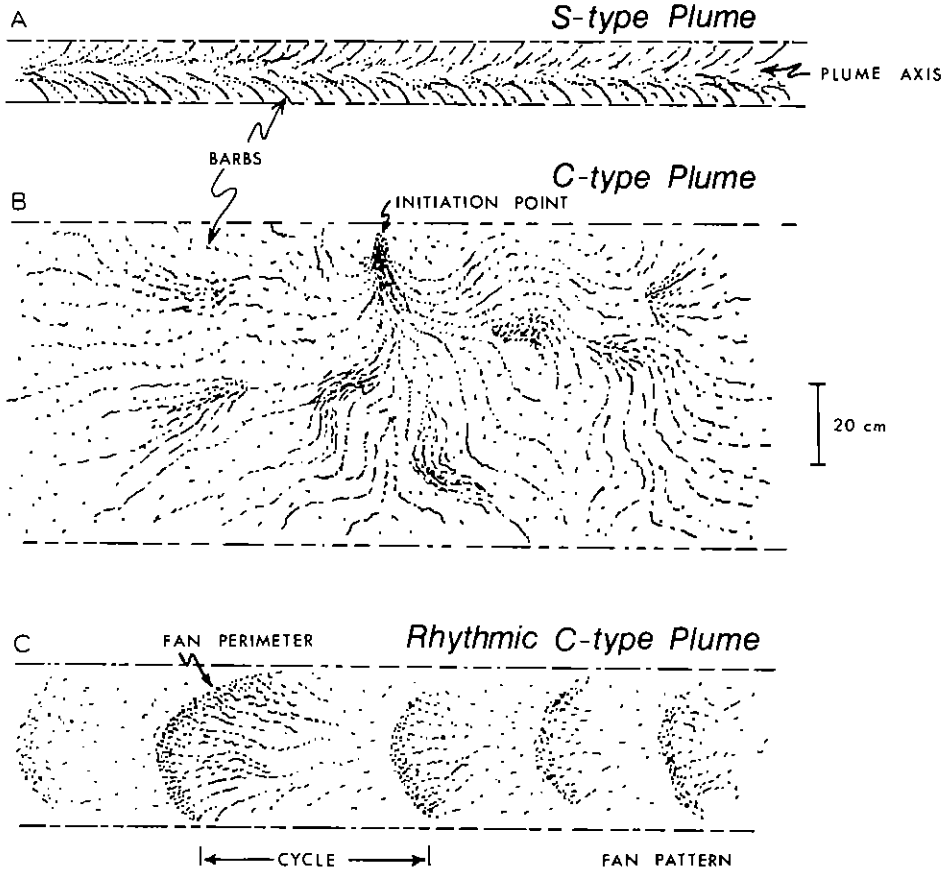

Figure 4. Various plume patterns observed on the surfaces of vertical joints in siltstones of the Finger Lakes District are shown: straight plume (bed #7), curving plume (bed #8), and rhythmic plume (bed #6) (after Bahat and Engelder, 1984).

surface of the 8-in-thick (19 cm) siltstone stringer (#7) at the 84.8-ft (25.7-m) level. The joint within this layer was forced by jointing in the adjacent shales to propagate in the direction of jointing in shale (i.e., 341°, which is highly unusual for jointing within siltstone beds of this roadcut). Four or more initiation points can be found along the 330 ft (100 m) of exposure of this bed. All initiation points are at the top of the bed. In contrast, the 18-in-thick (44 cm) stringer (bed #6) below the 13-ft-thick (4 m) shale bed is cut by a joint striking at 332° and showing initiation points on the bottom of the bed. Higher in the section (approximately 96-ft; 29-m level) siltstone beds are cut by 332° joints with initiation points within the bed.

A feature found on both shale and siltstone joints is arrest lines. These features mark the termination of propagation of individual cracks. The 13-ft-thick (4-m) shale bed, at the 79.2-ft (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 scale shale bed contains the 8-in-thick (19 cm) siltstone stringer (bed #7) displaying an s-type plume pattern. Barbs of this s-type plume 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 indicated by the barbs on the s-type plume within the siltstone stringer (bed #7). Arrest lines can be observed on the 18-in-thick (44 cm) siltstone bed (#6) at the 74-ft (22.4-m) level. These arrest lines are part of the rhythmic c-type plume pattern found on joint faces cutting siltstone beds. There the arrest lines are spaced less than 3 ft (1 m) apart, in contrast to those on the thick shales which are separated by more than 165 ft (50 m).

The closely spaced arrest lines in bed #6 may be interpreted in terms of jointing mechanism. The deeper portion of the Appalachian Basin is undercompacted (Engelder and Oertel, 1985), which is taken to indicate that abnormal pore pressures once prevented normal pore collapse. Pore pressures approaching the weight of the overburden may have caused natural hydraulic fracturing. The closely spaced arrest lines within the siltstone beds suggest the type of cyclic rupture expected of a slow build-up of pore pressure followed by a fast decrease accompanying the incremental propagation of a joint. This process can repeat many times to leave a set of closely spaced arrest lines. Engelder (1985) distinguishes tectonic joints as those caused by abnormal pore pressures during tectonic compression. At Watkins Glen both cross-fold joints are tectonic joints.

The c-type plumes are found on joints striking at 331°–333° (this is considered the normal orientation for joints in siltstone layers in this roadcut), 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 than 165 ft (50 m) in a horizontal direction. The length of the rupture is indicated by the distance between the initiation point 165 ft (50 m) to the SSE and the large arrest lines within the 13-ft-thick (4 m) 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 in the siltstones is further understood by placing the timing of their propagation in a regional context. On upper benches of the outcrop (at the 112-ft; 34-m level), deformed crinoid columnals show that the layer-parallel shortening (LPS) during the 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, then when did the joints within the siltstone beds propagate?

The joints in the siltstone are believed to precede those in shales. First, early joints at Ludlowville, New York are cut by Main Phase cleavage. These joints strike a few degrees counterclockwise from the Main Phase LPS. Second, 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 (Oetel 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: Taughannock Falls State Park. Taughannock State Park features a U-shaped hanging valley and 165 ft (50 m) waterfall at the head of a 0.9-mi-long (1.5 km) gorge cut to the level of Cayuga Lake. Outcrops in the park consist of the Tully Limestone and Genesee shales within the stream bed of Taughannock Creek and the lower portion of the Genesee Group (the Geneseo shales) exposed on the walls of the gorge. About 660 ft (200 m) upstream from the park entrance, bedding surfaces of the Tully Limestone may be examined within the stream bed, whereas 3,300 ft (1,000 m) upstream from the park entrance the stream bed consists of the Geneseo shales.

On beds of the Tully Limestone 660 ft (200 m) from the park entrance, 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 2 to 6 in (5 to 15 cm) thick. This spacing of cleavage domains constitutes a weak cleavage according to the classification of Alvarez and others (1978). The general trend of the cleavage is 077°, which 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°. Further west at the Watkins Glen outcrop this compression direction is 341°.

The contact between the Tully Limestone and the Geneseo shales is 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 1,320 ft (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 take the shape of blocky rectangular solids rather than being long and skinny. In other outcrops of the Appalachian Plateau the pencils are well developed enough to be like a pencil in shape. The two short dimensions of a pencil cleavage consist of bedding and a disjunctive cleavage normal to bedding.

At Taughannock Falls, the Tully Limestone contains neither of the cross-fold joints described at Watkins Glen. The best developed joints in the Tully Limestone are several sets of en echelon cracks found on the second bench of Tully Limestone about 1,000 ft (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.

Cross-fold joints start to appear within the Genesee shales about 3,300 ft (1,000 m) from the park entrance. On walking upstream, Taughannock Creek makes a righthand turn at this point. Here it is common to see later subparallel cross-fold joints (~330°) curving into and abutting earlier cross-fold joints (~340°). These latter joints are the same orientation as the cross-fold joints in shale at Watkins Glen and indicate a compression direction 7° counterclockwise from that indicated by the LPS in the Tully Limestone. However, the abutting of cross-fold sets was not found at Watkins Glen.

The rocks in the walls of Taughannock Creek gorge provide an example of the behavior of cross-fold joints within thick (>165 ft; 50 m) sequences of homogeneous shale. This is best seen at the point where the gorge makes a right turn 3,300 ft (1,000 m) from the park entrance. Looking up on the southeast side of the gorge, cross-fold joints are displayed on the southern wall; strike joints are displayed on the eastern wall. The cross-fold joints are better developed and more closely spaced. 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 a 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 not common in the creek bed. In general the release (strike) joints tend to be less regular in profile than tectonic (cross-fold) joints.

Within the gorge of 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. This is an example of vertical joint growth that is not impeded by bedding interfaces (Engelder, 1985). The Watkins Glen outcrop presents an example where vertical joint growth is impeded by bedding interfaces. At Watkins Glen the growth in the horizontal direction is extreme (>165 ft; 50 m), and vertical growth is limited (<13 ft; 4 m). This latter phenomenon can also be observed at the Falls Road Bridge, which crosses Taughannock Creek at the upper entrance to the park. Take Gorge Road which turns west off of New York 89 just south of the park. Proceed 1.2 mi (2 km) and then make a right turn at the T-intersection with Falls Road.

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