STOP 1: SCHUYLKILL GAP
Ordovician/Silurian contact - unconformity, fault, or both? A little structure; Some retrodeforming (not much); Graywackes/schmaywackies; Turbidites; A very little geomorphology; *This Quadrangle Needs To Be Mapped!*
Leaders: Jack Epstein and Chris Oest

Note: The rail-line is now owned by the Reading and Northern Railroad Company—see http://www.readingnorthern.com/history.html for the line's history and many interesting photos. The company strictly controls access to the grounds. Please stay to the right of the tracks on our way to the steps up to the rail-trail/Appalachian Trail.

Schuylkill Gap is the westernmost of three water gaps in Pennsylvania that we will visit today. The contact between Ordovician and Silurian rocks are or were exposed at three localities in the gap; erosion has had its effect. Lehigh Gap (Stop 3) is the only other place in northeastern Pennsylvania where the contact is exposed. It was temporarily exposed during construction of the Northeast Extension of the Pennsylvania Turnpike. At Schuykill Gap the rocks lie at right angles on either side of the contact. In contrast, beginning several miles (kilometers) to the east and continuing all the way to southeastern New York, a distance of more than 120 mi (193 km), the angular difference does not exceed about fifteen degrees. Our story begins here, first looking at the three Silurian formations above the contact (Bloomsburg, Clinton, and Tuscarora), and the Windsor Township Formation of Ordovician age below the contact. There are several puzzlements here:

1) Is the Ordovician/Silurian contact an angular unconformity or fault, or both?
2) Strangely, the Silurian rocks here appear to be more intensely deformed than the underlying Ordovician rocks.
3) What is the age of the cleavage in the Ordovician rocks? Taconic or Alleghanian?
4) Is it reasonable to retro-deform the Ordovician rocks by rotating the near-vertical Silurian rocks back to horizontal?
5) Why does the Schuylkill River flow in a large meander on the Tuscarora Sandstone which is generally the ridge former in Pennsylvania.
6) There a bunch of distinct structural incongruities in this part of Pennsylvania, enough so as to suggest the name *The Hamburg Triangle* (see that section under "Structural geology").

The stop is divided into five locations, noted on the geologic map, Figure 1. The group will convene at locality *A* where we will note the bedding-cleavage relations and sedimentary structures in the Bloomsburg Red Beds. We will also discuss signals for group movement and deportment between field-trip stops. Then we follow the railroad tracks while staying to the right, crossing the Schuylkill River (the Little Schuylkill River is 100 ft [31 m] to the east), and hiking up the rock steps to the rail-trail. *Arthrophycus* will offer a respite half way up the steps. Then we turn to the right (north) for 200 ft (61 m) to location *B,* which will be self-guiding, as we make friends with the Clinton formation and see just a little bit of cleavage. A

Epstein, Jack and Oest, Christopher., 2012, Stop 1: Schuylkill Gap, *in* Harper, J. A., ed., Journey along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and southeastern New York: Guidebook, 77th Annual Field Conference of Pennsylvania Geologists, Shawnee on Delaware, PA, p. 217-236.

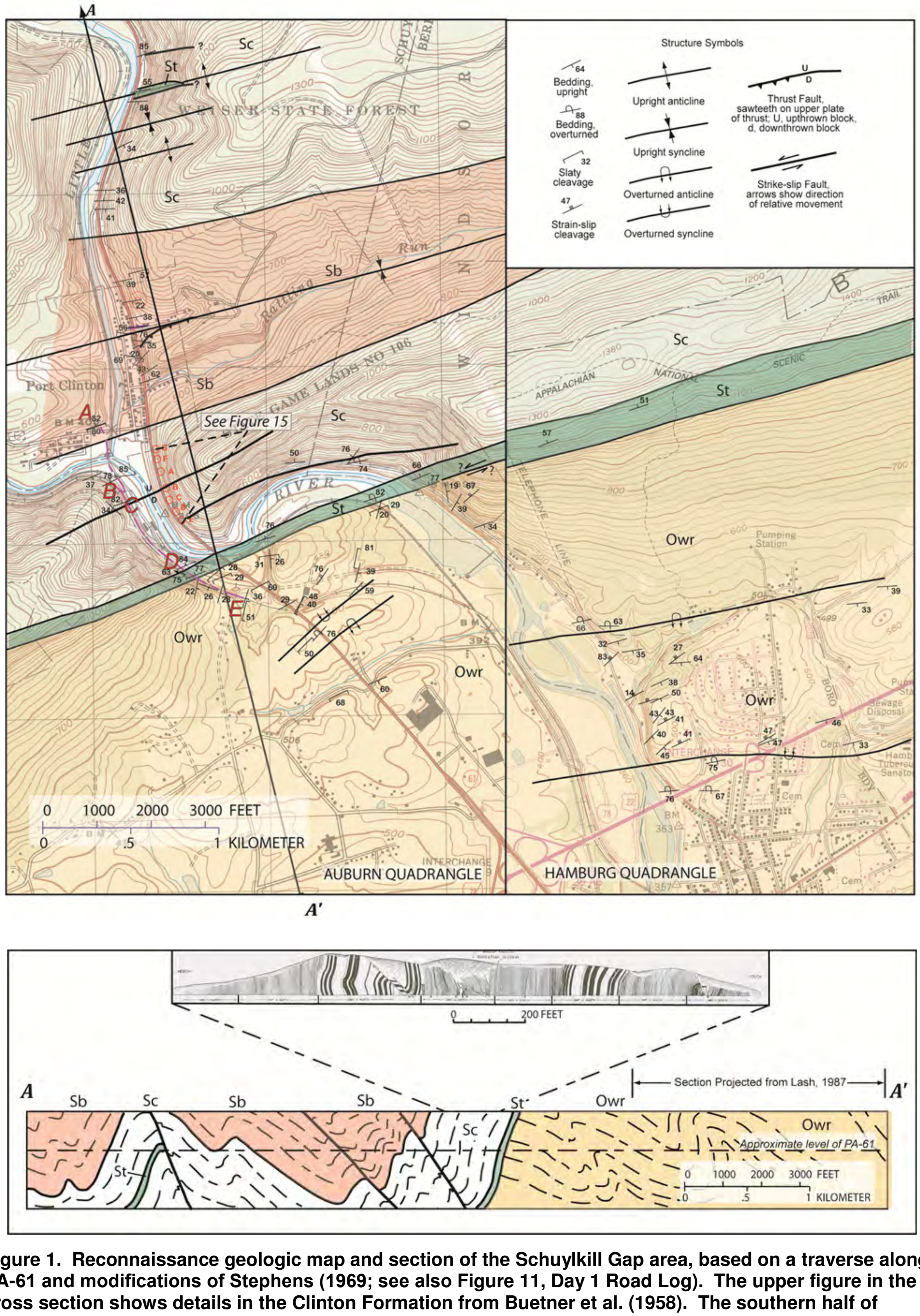

Figure 1. Reconnaissance geologic map and section of the Schuylkill Gap area, based on a traverse along PA-61 and modifications of Stephens (1969; see also Figure 11, Day 1 Road Log). The upper figure in the cross section shows details in the Clinton Formation from Buetner et al. (1958). The southern half of structures in the Windsor Township Formation were projected from the Hamburg Quadrangle (Lash, 1987). Sb, Bloomsburg Formation; Sc, Clinton Formation; St, Tuscarora Sandstone; Owr, Windsor Township Formation. Auburn and Hamburg 7.5-minute quadrangles.

pleasant little fold in the Clinton at *C* will inform us of the abundant structural complexities in the not-that-well exposed Silurian sequence. The Ordovician-Silurian contact will be examined at *D*, where we will perplex ourselves over several of the puzzlements—fault or Taconic unconformity? Why is the river located where it is? Then the group will visit Windsor Township graywackes at *E*, where Chris Oest will discuss their sedimentalogical characteristics. Three blasts from a whistle will inform the group immediately to return to the assembly area for donuts and coffee.

The Rocks at Schuylkill Gap

(Modified from Epstein and Lyttle, 1993, and Stephens, 1969)

Sb, Bloomsburg Red Beds. Red and minor gray to green, shale, siltstone, very fine to coarse-grained sandstone, and minor conglomeratic sandstone with red mudstone intraclasts as much as 3 in. (8 cm) long. About 1,500 ft (457 m) thick.

Sc, Clinton Formation. Gray very fine to coarse-grained, proto quartzite containing flattened argillite cobbles as much as 4 in. in diameter; with red fine-grained hematitic sandstone and siltstone, interbedded with greenish-gray siltstone and shale (Figure 2). Locally contains red shale similar to those in the Bloomsburg Red Beds. About 1,400 ft (427 m) thick. Folded and faulted along PA-61 and Locality *C*.

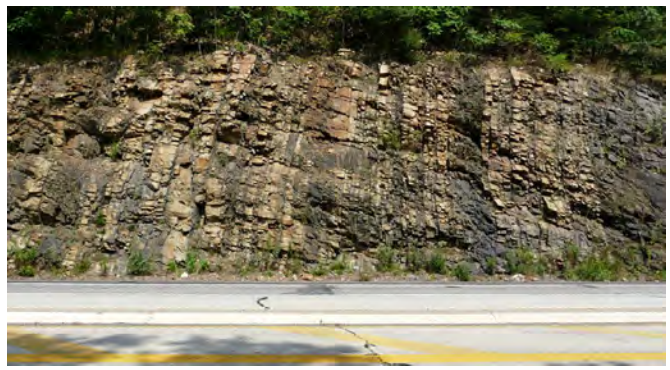

Figure 2. Sandstone and shale in the middle part of the Clinton Formation along PA-61 (mileage 74.7 of the Day 1 Road Log).

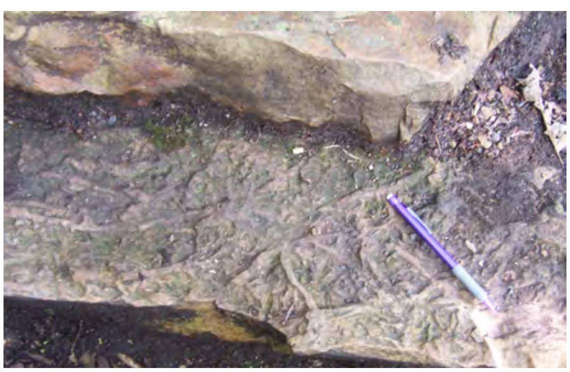

Figure 3. Horizontal burrow, *Arthrophycus* in rock step half-way to the rail trail.

St, Tuscarora Sandstone. Gray, fine- to coarse-grained, partly conglomeratic quartz-sandstone (orthoquartzite) containing pebbles of quartz and minor chert as much as 2 in. long and cobbles of shale as much as 7 in. long; minor gray siltstone and shale. Reported to be no more than 250 ft (76 m) thick by Stephens (1969), but only150 ft (46 m) are well exposed at locality *D*. Stose (1930) reported a thickness of 102 ft (31 m) in the gap. *Arthrophycus* may be found in several places, especially half-way up the rock steps to the rail-trail (Figure 3).

Owtw, Weisenberg Member of the Windsor Township Formation. Gray to olive shale and mudstone to micaceous siltstone . Also minor amounts of gray silicified shale, mudstone, and argillite. In some places, thin-bedded siltstone and limonitic and feldspathic fine- to coarse -grained graywacke sandstone and debris flows of dark-gray chert and silicified mudstone are interbedded with the shale and mudstone. Local channels contain a very distinctive conglomerate with chalky-white-weathering feldspar grains and rare dark volcanic rock fragments. Minimum thickness about 4,600 ft (1,400 m). Formerly called the Martinsburg Formation or Shale or Hudson River Shales.

No Bald Eagle or Juniata rocks are exposed at the gap, whereas they are reportedly to be present at Spitzenburg Hill and Sharps Mountain 1.7 mi (2.7 km) to the east (Stephens, 1969, p. 21).

Ordovician-Silurian Contact; Some Historical Notes

In 1874, Chance (Plate 5, *in,* Leslie, 1883), drew a 2-mi (3-km) long cross section through Schuylkill Gap depicting a large upright syncline with a near-vertical south limb and moderately steep northwest limb, with just a small wiggle in the center of the large fold. He noted the nearly horizontal "Hudson River" in contact with the steeply dipping Oneida white conglomerate" (Tuscarora). He thought they were in fault contact with a throw of more than 3,000 ft (914 m).

Grabau (1921, p. 293) pictured the "unconformity between Hudson River sandstones (nearly horizontal) and Shawangunk conglomerate, steeply inclined and slightly overturned to west. Near Port Clinton, Pennsylvania" (Figure 4) . That exposure is presently overgrown; it is on the other side of the tracks (south) from the outcrop shown in Figure 9.

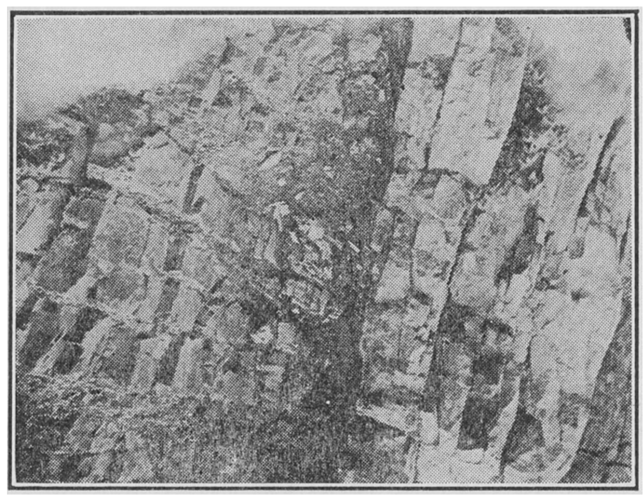

Figure 4. Grabau (1921, p. 293) described this exposure as "Unconformity between Hudson River sandstone (nearly horizontal) and Shawangunk conglomerate, steeply inclined and overturned to the west. Near Port Clinton, Pennsylvania". There appears to be a zone of possible shearing near the contact.

J.W. Miller (1922, fig. 108; see Figure 16*A*) pictured the freshly exposed angular unconformity along the rail-trail.

B.L. Miller (1926) argued for the contact being an unconformity, although minor movement between the two formations and a possible fault gouge was found at the easternmost of the three contact exposures in the gap area. If the 90 degree dip difference at the contact were due entirely to faulting, Miller argued, there should be considerable drag of the shales, but there is none.

Stose (1930) visited three exposures of the contact along the then Reading Railroad and presented a cross section from Hamburg, PA, through Blue Mountain (Figure 5). He

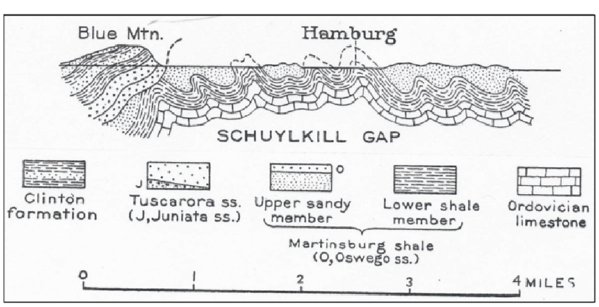

Figure 5. Stose's (1930, p. 636) cross section through Schuylkill Gap showing the contact between the "upper sandy member" of the "Martinsburg shale" (Windsor Township Formaytipon of this report) at the outcrop level.

Figure 6. The unconformable contact west of the Schuylkill River (Stose, 1930, Pl. 9, fig. 1). Locality *D* is on the higher railroad grade. The entire thickness of the Tuscarora is exposed, 105 feet by Stose's statement; about 150 ft 46 m) thick by our calculations). Compare with Figure 16*B*.

commented that there was no evidence for faulting at the westernmost exposure (Figure 6; see Figure 16B). He did note minor crumpling in the "Martinsburg" at the outcrop to the east (Figure 7) which he attributed to "a very minor drag of the shale due to slight differential movement between it and the hard quartzite".

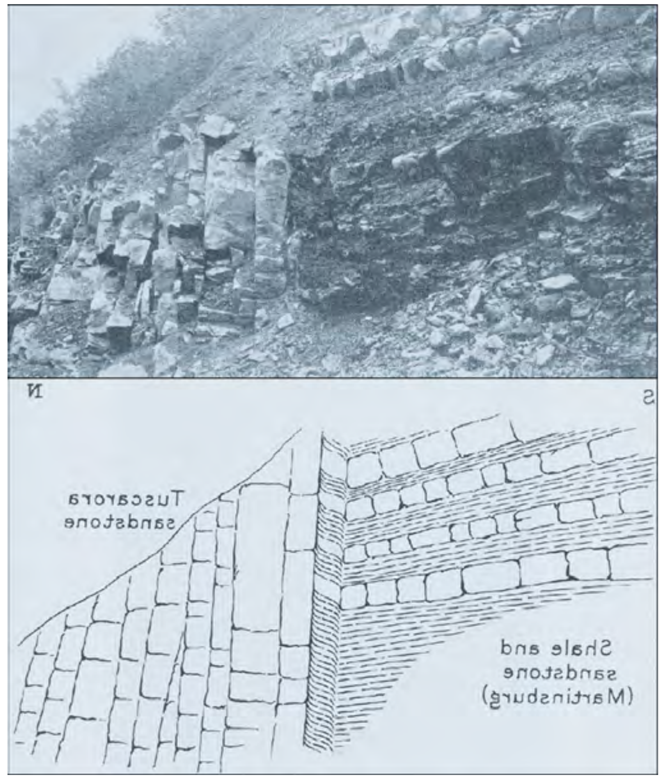

Figure 7. Closeup of the easternmost exposure of the unconformity along the Reading Railroad on the south side of the tracks. Stose (1930, Pl. 10) noted shearing at the contact, but considered it minor.

Willard and Cleaves (1939) concluded that the unconformable contact along the Reading Railroad had evidence for faulting.

Burtner et al. (1958) described the complex folding and faulting in the Clinton Formation on the east side of PA-61 (**see Day 1 Road Log, Figure 11 on p. ___**). He noted red bed sequences within the non-red sandstone-shale formation that were offset by normal faulting.

Hoskins, (in, Wood et al., 1963, p. 74-76), presented a strong case for faulting at the contact, including nearby demonstrable faults (Figure 8), considerable faulting in the overlying Clinton Formation along PA-61, bedding plane shearing in the Tuscarora at the contact, and the convenience of ductility contrasts at the contact. However, he did not rule out evidence for an unconformable relationship based on regional stratigraphic relationships.

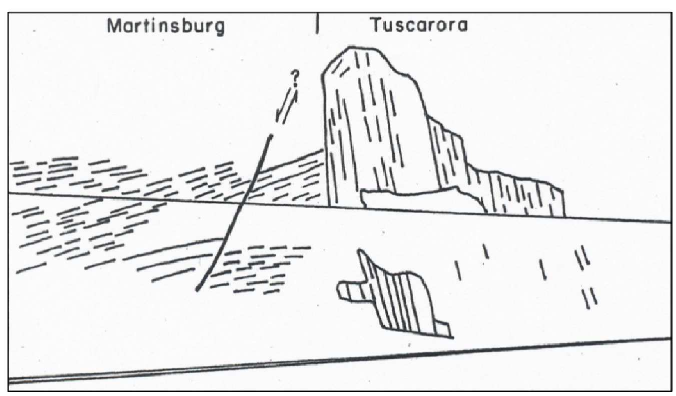

Figure 8. Sketch of the fault in the "Martinsburg" south of the contact with the Tuscarora at our Locality *D*, which Hoskins (1963) argued for predominant faulting accounting for the angular relation between the two formations. Note the similarity to Figure 6.

Stephens (1969) mapped the northeast-trending repetitive upright folds east of the Schuylkill River that offset

Blue Mountain to the east, but thought that the faults mentioned by Burtner et al. might be reverse faults that have been rotated by later deformation. The repetitive folds suggest they are shallow-=-the rocks do not plunge deeply to the northwest as they do farther to the west as shown by Wood and Kehn (1968). He also noted some of the contrasts between the Silurian and Ordovician rocks (Figure 16*C*). He described the rocks on Sharps Mountain and the Spitzenburg, and also wondered about why the river meandered along the outcrop of the Tuscarora Sandstone. He did find evidence for faulting at the contact.

Lash (1987, section B-B') presented a cross section 2 mi (3 km) northeast east of the SAchuylkill River showing the tight overturned folds in the Windsor Township Formation within 1 mi (1.6 km) of the open folds in the Tuscarora. No structures could be portrayed very close to Blue Mountain because of cover by talus.

Thirty years ago, on a curiosity venture, I investigated the "Martinsburg"/Tuscarora unconformity reported in the literature along the Pennsylvania Reading Railroad, and came upon two excellent exposures, the first 480 ft (northeast of locality *D* on this field trip, and the second an additional 660 ft (201 m) northeast of the first, seen in Figure 9. At the first, the Tuscarora's attitude is N71°E, 76°NW, while greywacke and siltstone in the "Martinsburg" was N4°W, 26°NW. A 2-5-in (6.4-cm) thick clay gouge separated the two units. The basal bed of the Tuscarora had down-dip slickensides, direction of movement could not be determined. The basal 1.5-ft (0.5-m) Tuscarora conglomeratic bed contained quartz pebbles as much as 1.5 in (3.8 cm) long, similar to the basal Tuscarora in this entire area. A joint face that trends N62°E, 77°NW has two sets of slickensides, one vertical and an earlier one plunging 10°NE, suggesting vertical, then strike-slip components of movement. Slickensides with a variety of movement directions were also seen in outcrops north and east of the Schuylkill River. This exposure has totally deteriorated due to slump and vegetation cover.

Figure 9. The Silurian-Ordovician contact along the Reading Railroad before it turns south towards Hamburg and just west of the Schuylkill River.

At the outcrop shown in Figure 9, The Tuscarora (the rib on the left) strikes N73°E, and dips 83° to the southeast. In contrast, the corresponding attitudes in the "Martinsburg" are N17°E, 20°SE. A poorly developed cleavage in a silty shale has an attitude of N62°E, 14°SE. The formational contact is covered in a rubble zone 4 ft (1.2 m) wide.

The two exposures described here was one of the driving forces for considering this year's Field Conference. Unfortunately, both exposures are no longer viable. The one in Figure 10 is overgrown, slumped, and right behind a row of train cars that have been in position for more than three years.

Location *A*. Bloomsburg Red Beds

The Bloomsburg Red Beds is the youngest of four formations that we will see at this stop. It consists of grayish red (10R 4/2) shale and siltstone and grayish red (5R4/2) fine-grained sandstone with some medium-grained sandstone. Shale beds range up to 3 ft (0.9 m) in thickness. Sandstone beds reach 2 ft (0.6 m) in thickness. Light olive gray (5Y6/1) reduction spots and irregular beds are scattered throughout. Mudcracks at a shale/sandstone interface (Figure 10A), and scour marks (Figure 10B) and load casts (Figure 10C) are found on sandstone bases. A few beds are fining upwards as shown by refracting cleavage, but most beds are sharply delimited.

Bedding strikes N71^{o}E with a near vertical dip, ranging between 80^{o}NW to 80^{o}SE (overturned). Cleavage is well developed in this steep limb of a syncline (Figure 11). It has the same strike as bedding. Cleavage development in the Bloomsburg is not universal is shaly and silty beds along PA 61 (see Figure 1). Cleavage is fairly common in many of the pelitic beds (see Figure 1), but in many outcrops a closely spaced joint set replaces that structural trend. For the most part, where well developed, it appears to be a typical slaty cleavage (described at Stop 2), but some laminated beds are crinkled by a slip cleavage (Figure 12).

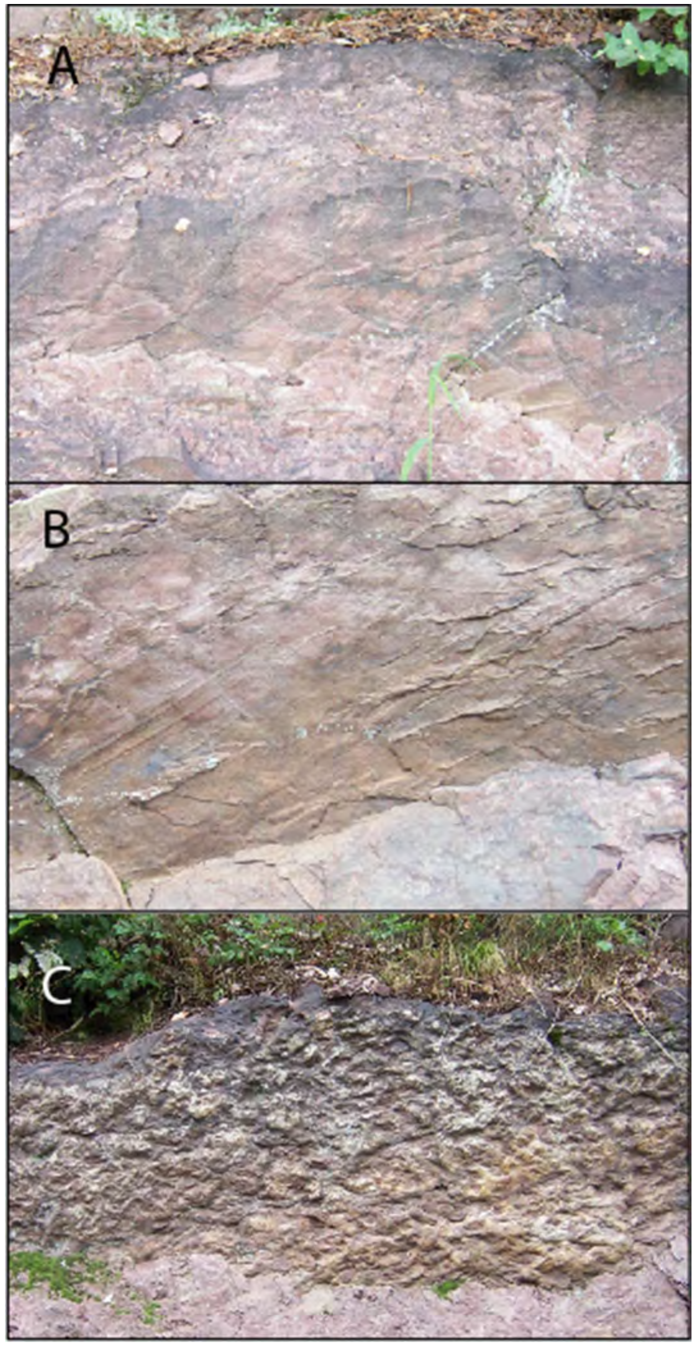

Figure 10. Sedimentary structures in the Bloomsburg Red Beds at Locality 1. A—Faint mudcracks at the base of a sandstone bed; B—linear scour marks, groove casts; C—load casts.

Location *B*. Clinton Formation

A 200-ft (61–m) long exposure of the sandstones and lesser shale of the Clinton Formation are exposed to the right (north) of where the stone steeps meet the rail-train. Cleavage is well developed in only a few of the shale beds (Figure 13). The steep northwest dipping cleavage suggests that the rocks were rotated after the cleavage developed.

Figure 11. Well-developed cleavage in shale between sandstone beds in the Bloomsburg Red Beds. Beds dip about 80°NW, cleavage dips 80°SE.

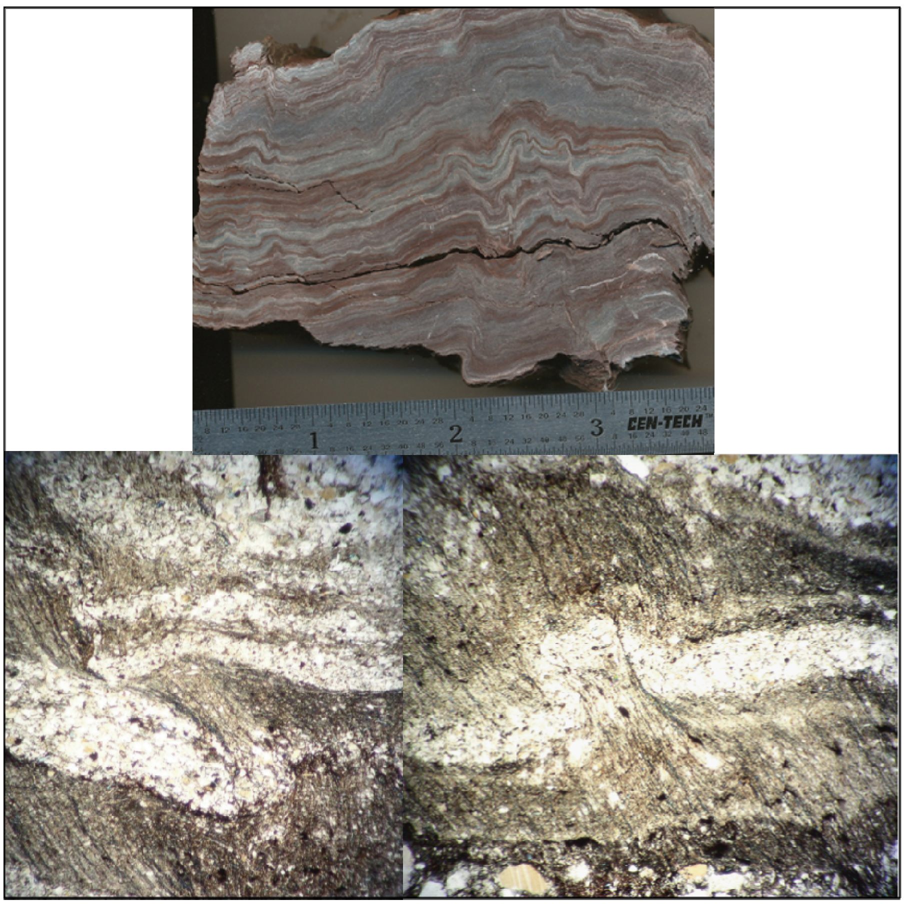

Figure 12. Scan of cut sample and thin-sections of laminated very fine sandstone, siltstone, and shale in the Bloomsburg Red Beds, along the off-ramp on the west side of PA 61 about 200 ft (61 m) north of the junction with PA 895. Crinkling resulted from shortening in the more resistant sandstone and pressure solution in the shale. Quartz grains in the microlithons are corroded on the maximum pressure edges. Some mice isaligned along the cleavage, probably due to mechanical rotation.

Figure 13. Steep northwest-dipping 85^{o} (dashed line) in one of the few shale beds at locality B.

Figure 14. Fold in sandstones of the Clinto Formation, view looking west. Steep (71^{o}) northwest limb of the fold arches over and cut off by a fault to the left. The northwest-trending joint at the top of the fold (inset) is contains near-vertical slickensides indicating that the northeast block moved down. This structure is on strike with the area of deformed rocks along PA 61 (Figure 15).

Location *C*. Clinton Structure

Peeking through the colluvial blanket 350 ft (107 m) south of the steps is a small faulted fold in sandstones of the Clinton Formation (Figure 14).

Location *D*. The *Unconformity*

Approxmately 150 ft (46 m) of orthoquartzites and fine conglomerates of the Tuscarora are in right-angle contact with shales and greywacke of the Windsor Township Formation. We have discussed the historical arguments for faulting at this angular unconformity, above. Like so many classical geological outcrops. This one is suffering the erosional effects of time. Figure 16 documents the changing appearance of the outcrop.

Figure 15. Deformation in the Clinton Formation along Pa 61. This is part of a 1,000-ft (305-m) long outcrop described by Burtner et al. (1958). Similar structures were seen in many places along PA 61. There is a crying need to map the Auburn quadrangle to understand the distribution and significance of these structures.

In 1982 the exposure was good enough to make the following observations: The basal tuscarora is a cross-bedded and channeled quartz-pebble conglomerate with pebbles up to about 1-in (2.5-cm) long, in beds 2 in (5 cm) to 3 ft (0.9 m) thick. There is a clay gouge as much as 8 in (20 cm) thick at the contact. A fault (white line) cut the graywackes along a 1-ft (0.3-m) wide shear zone. Slickensides indicate that the upper bed moved down to the southeast. The attitude of the

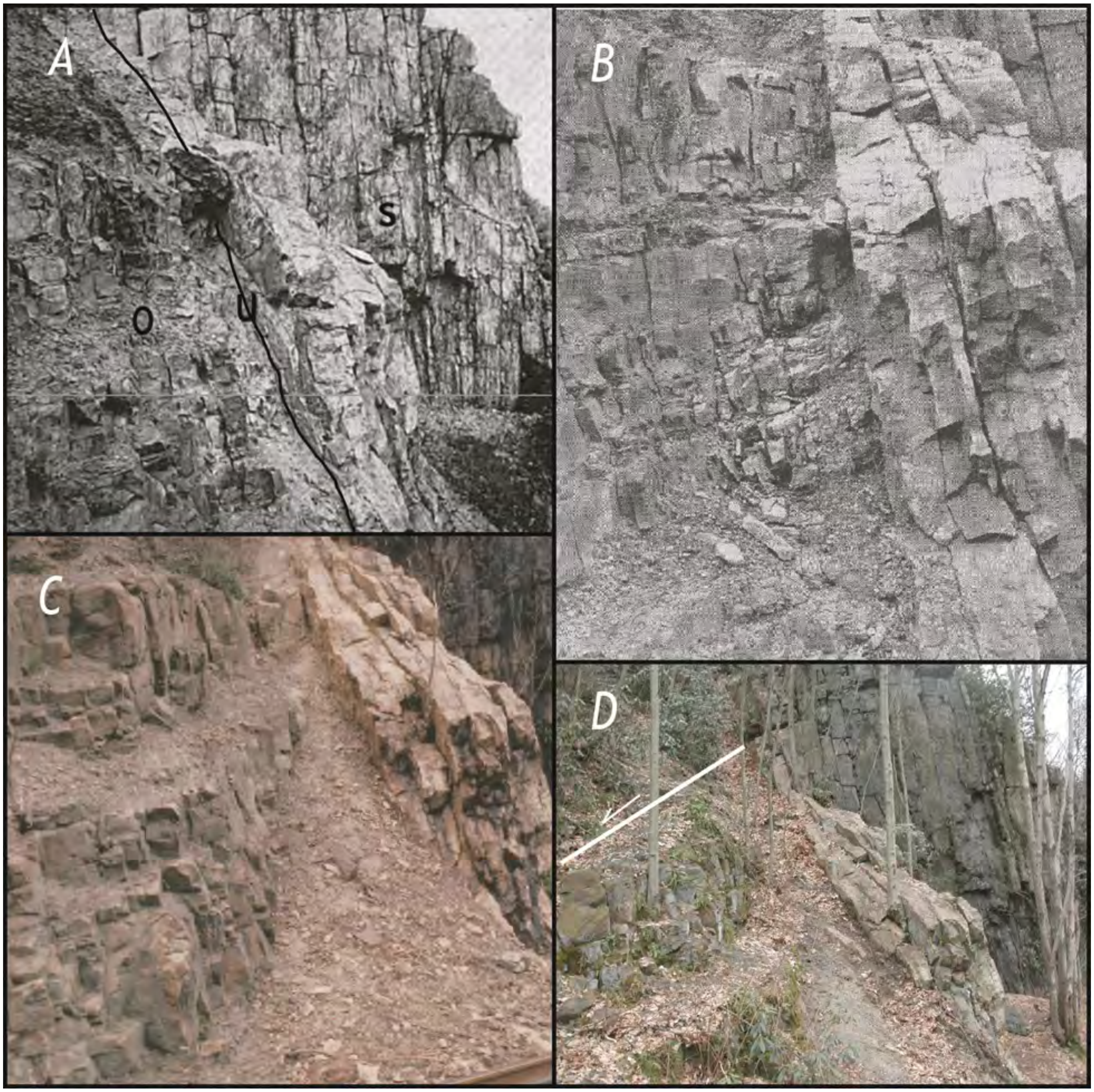

Figure 16. Appearance of the outcrop from pre-1925 to 1982. Your own photograph will take you up to date. A—From Miller, 1922: "Nearly horizontal Ordovician strata (0) separated by an unconformity U) from nearly vertical Silurian strata (S). The originally horizontal Ordovician strata were turned on end at the time of the late Ordovician (Taconic) Revolution, and, a free an interval of erosion followed by submergence under the sea, the Silurian strata were laid down horizon-tally upon them. At the time of the Appalachian Revolution the Silurian strata were turned on end while at the same time the Ordovician strata were shifted back to a nearly horizontal position. These rock, and their structures, once deeply buried, have been brought to light by post-Paleozoic erosion near Port Clinton, Pennsylvania. (Photo by N. H. Darton, U. S. Geological Survey.)"; B—Close-up of the "Martinsburg" dipping gently to the left and cut by closely spaced vertical fracture, from Stose (1930, pl 9); C—Sephens (1969, pl. 2) reports "The angular unconformity between the nearly horizontal Martinsburg Shale, which is cut by a string nearly vertical fracture cleavage, and the nearly vertical Tuscarora"; D—The exposure as seen by Epstein in 1982, described below.

Figure 17: Bedding-cleavage relations at distances from the unconformity. A—180 ft (55 m) south of the unconformity. Bedding dips 17°SE, cleavage dips 28° SE; B—950 ft (290 m) south of the unconformity, in the area of thick greywacke beds, some of which are as thick as four feet. Bedding dips 48°SE., cleavage dips 60°SE.

basal Shawangunk bed is N69°E, 77°NW, whereas the adjacent graywacke bed's is N14°E, 22°SE. Fifty ft (15 m) south of the unconformity bedding in the shale is N19°E, 19°SE. Except for a couple of small faults and folds for a distance of 1,800 ft (549 m) to the southeast, bedding attitudes slowly increase to about a 50° dip Figure 17).

Immediately to the north of the basal beds, there is an impressive quartz-slickensided fault surface (Figure 18). It's attitude is N23°W, 75°SW. The slicks plunge 63°, S71°E. The east block moved up. It does not appear to have offset the lower rib of quartzite to the immediate south. Have a look please, my bad knees keep me from climbing even that tiny slope.

Figure 18. Fault surface in the Tuscarora, just north of its base. Steps on slickensides show that the absent block facing the observer moved up..

Retrodeformation of the Unconformity

Assuming that faulting did not have a very significant effect on the orientation of the two formations, and assuming the standard assumption regarding angular unconformities (deposition of flat-lying beds (Windsor Township); folding and tilting; erosion forming a flat surface upon which the next layer of flat-lying sediment is deposited (Tuscarora); a second episode of folding (at least); and erosion exposing what we see today), then we should be allowed to tilt the Tuscarora back to horizontal. Figure 19 shows an attempt to do so.

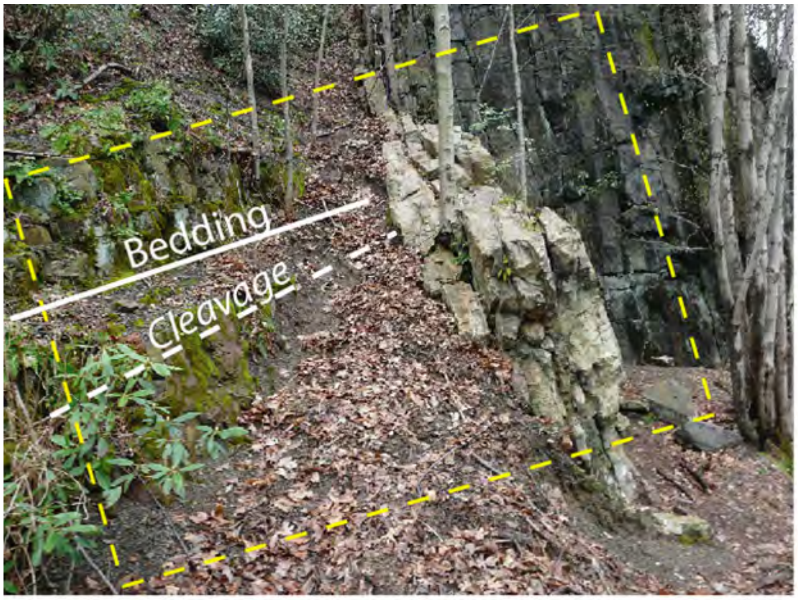

Figure 19. The present-day orientation at the Silurian-Ordovician boundary (left picture) rotated so that the Tuscarora is horizontal (right frame). It's a *PUZZLEMENT!*

Bedding in the Windsor Township Formation about 0.5 mi (0.8 km) south of the Tuscarora contact parallels the northeast structural grain (Figure 1). As the contact is approached, bedding in the Windsor Township strikes more northerly until in places it is nearly normal to the contact. Two interpretations of this relationship (or combinations, thereof) are possible. One is that the Windsor Township was folded during Taconic deformation prior to deposition of the Tuscarora. The other is that the beds are dragged into a fault along the contact as some of the authors mentioned above seem to indicate. Additionally, there is gouge and sheared shale 5 to 30 cm (2 to 12 in) thick at the contact in places with slickensides indicating an earlier northwest translation of the overlying Tuscarora, and a later set indicating left-lateral strike-slip movement. For this reason, a strike-slip component is shown on Figure 1.

Cleavage is present in many of the politic rocks of both Ordovician and Silurian age. While too few readings are available for a structural analysis of the cleavage orientations, as was done in Epstein and Lyttle, 1994, in the New Tripoli Quadrangle, 10 mi (16 km) to the northeast, some generalizations may be made. It is obvious that in the small area that we will visit in

Stop 1 that the dip of the Ordovician cleavage is generally less than that of the Silurian. The average dip of cleavage in Ordovician rocks shown in Figure 1 is 44^{o}SE., whereas it is 71^{o}SE in Silurian rocks. It is puzzling, however, that the cleavage in the Windsor Township reverts to a northeast strike at the contact and is not rotated as is the bedding. Locally, a northwest-dipping crenulation cleavage is developed at the contact. Another puzzling consideration is that if the contact is only an angular unconformity, and if we rotate the Tuscarora back to the horizontal, then the underlying Ordovician rocks would contain cleavage that dips very steeply to the northwest, a strange pre-Silurian orientation indeed. This is a common problem all along the sub-Tuscarora/Shawangunk contacts in eastern Pennsylvania, enough that the senior author (he gets 10% diner discounts) has tried to remain balanced in pre-Silurian time (Figure 20).

Figure 20. You fill in the caption.

Figure 21: View (looking upsection) of outcrop of Windsor Township formation along the rail trail.

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Location *E*. Turbidites of the Ordovician Windsor Township Formation

Approximately 655 ft (200 m) ESE along the rail trail from the unconformity, turbidite deposits of the Ordovician Windsor Township Formation are well exposed (Figure 21). These rocks average a strike of 015° and dip of 33° (right hand rule). The rocks consist of fine- to coarse-grained graywacke, light brownish gray siltstones, and olive gray fissile shales. Similar deposits across the Schuylkill River to the East (Figure 22) were visited during the 1984 Field Conference and were described by Lash et al. (1984, p. 124). The Eastern exposure visited in

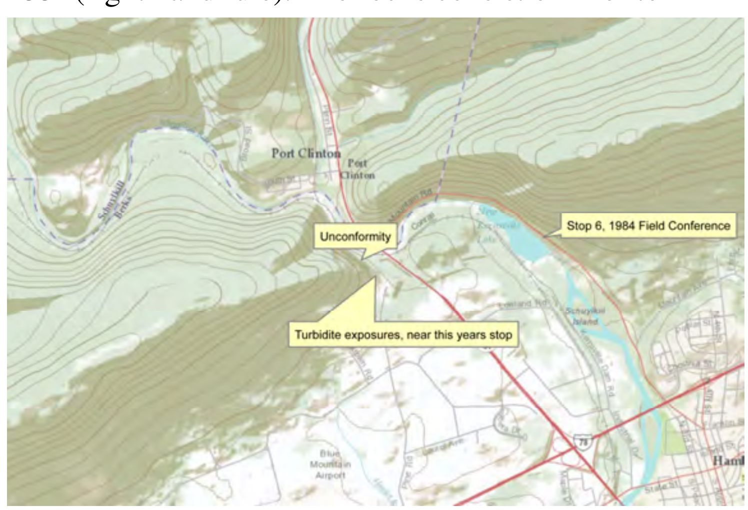

Figure 22: Location map of the Port Clinton area, showing the location of Stop 6 of the 1984 Field Conference, Stop 1 of the 2012 Field conference (the unconformity), and the location of the

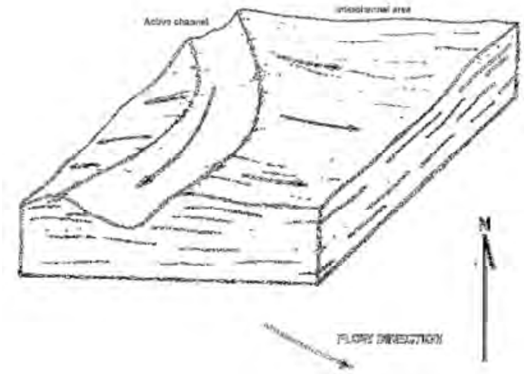

Figure 23: Initial state of sedimentation (modified slightly from Lash et al., 1984, p. 126, fig. 91A).

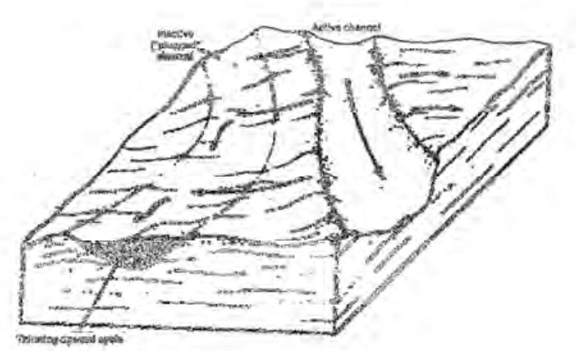

Figure 24: Abandonment of an active channel, resulting in thinning-upward sequences (modified slightly from Lash et al., 1984, p. 126, fig. 91B).

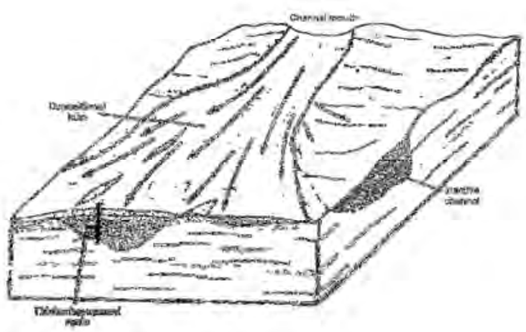

Figure 25: Return to thickening-upward sequence during the sedimentation of a depositional lobe (modified slightly from Lash et al., 1984, p. 126, fig. 91C).

1984 will be summarized first followed by a description of the Western exposure along the rail trail.

Stop 6, 1984 Field Conference

As described by Lash along the 1984 exposure, the rocks progress through a thinning-upward megasequence. The lower portion of this section is characterized by thick-bedded sandstone (beds up to 10 ft [3 m] thick), some of which feature rip-up clasts and minor channeling. The thickest of the sandstone beds is overlain by about 36 ft (11 m) of turbidite shale facies (Lash et al, 1984, fig. 90). Continuing up section, there is a noticeable decrease in bed thickness and sandstone:shale ratio. Lash interprets this thinning-upward trend as the abandonment of a submarine channel. The thick sandstones represent the plugging of a laterally migrating channel and the overlying siltstone and shale beds are interchannel deposits related to a newly formed adjacent channel. The thinning-upward sequence is followed by approximately 23 ft (7 m) of shale in a thickening-upward cycle, characteristic of prograding submarine lobes. The relationships between the channel and lobe deposits are characteristic of the sedimentation of a suprafan (Walker, 1978; Ricci-Lucchi, 1981). Above the lobe deposits are thick beds (about 30 ft [9 m]) of the shale facies. The thickness of these shale deposits indicates the rapid loss of sediment supply which could have resulted from a channel avulsion event upslope. Overlying the thick shale beds are turbidite sandstone facies, indicating a return to channel sedimentation.

The sedimentation patterns of the 1984 exposure (thinning-upward sequence, interchannel, followed by a thickening-upward sequence) are indicative of the deposition of a suprafan (Normark, 1978). The thinning-upward sequence represents the abandonment of an active channel (Figure 23). As the channel shifted laterally, the thinning-upward sequence is overlain by interchannel fines derived from the "new" adjacent channel (Figure 24). The presence of the "old" channel next to the "new" channel probably resulted in the overlying thickening-upward sequence as a result of the two channels merging to form a depositional lobe (Figure 25).

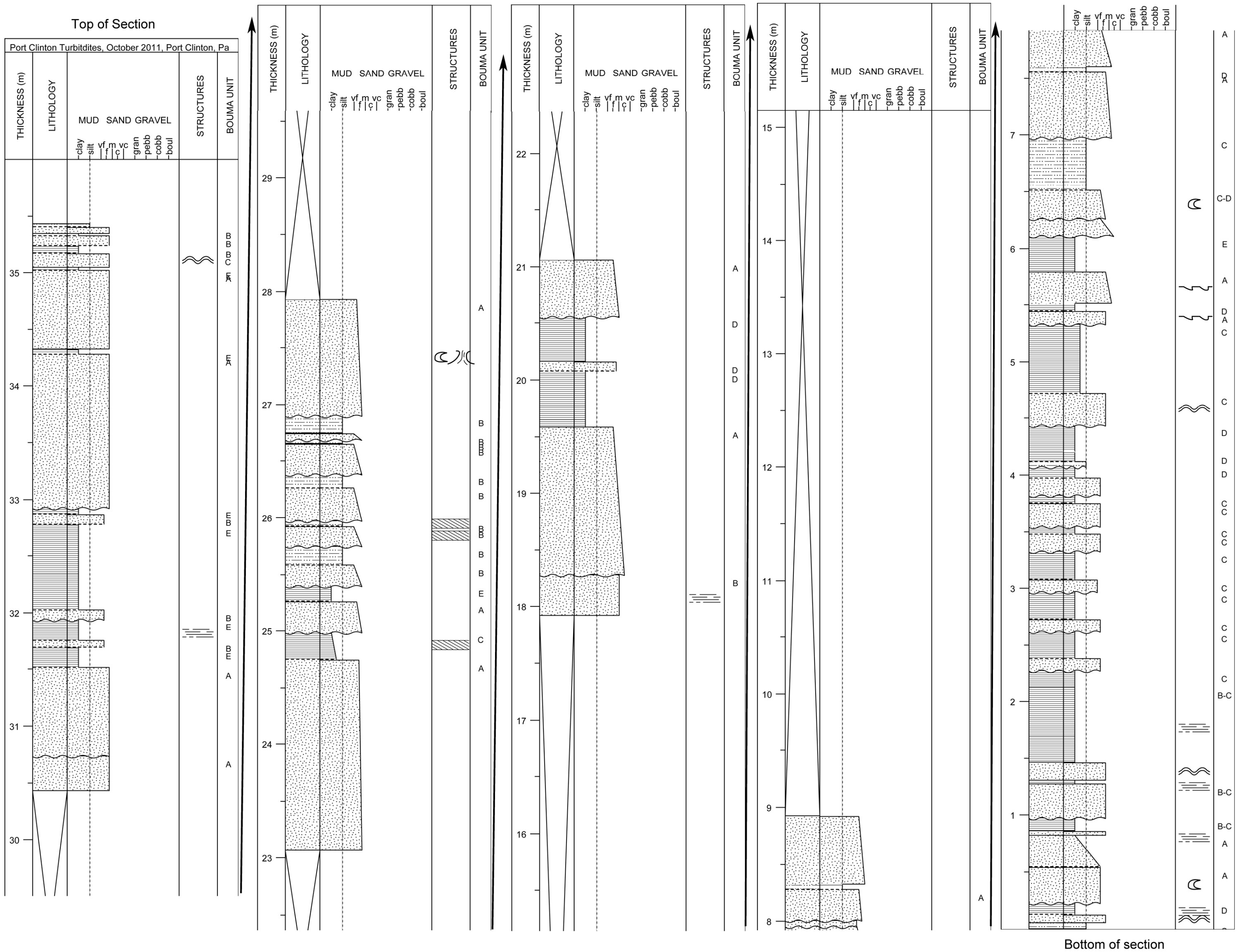

Figure 6: Measured section, south of Stop 1. See Figure 7 for legend.

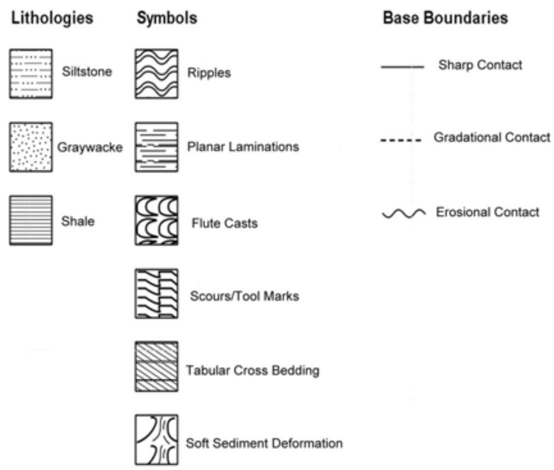

Figure 27: Key of symbols used in the measured section in Figure 6.

Figure 28: Lower portion of measured section. Shale beds are much thicker than graywacke beds here. Note the fault (Location N40.57180, W76.01917). Fault strikes

Figure 29: Upper portion of measured section. Graywacke beds are significantly thicker than shale beds. Notebook is placed on thickest

South of Stop 1, 2012 Field Conference

The turbidite deposits south of the unconformity along the rail trail are illustrated in a measured section (Figures 26 and 27). Approximately 117 ft (35.5 m) of section was measured, representing about half of the total length of the exposure here. At the bottom of the section (closest to the unconformity), graywacke beds are thin (thickest bed about 12 in [30 cm]), and shale beds are significantly thicker than graywacke beds, the thickest shale bed about 30 in (75 cm) (Figure 28). This implies hemipelagic sedimentation within an interchannel area. Moving upsection, graywacke beds become thicker and more abundant (Figure 29). The thickening of coarse-grained sediments implies the activation of a new channel. This section of the exposure records a thickening-upward sequence. This thickening-upward can be interpreted as reactivated sand sedimentation on top of interchannel shales and siltstones. Given two measured section in close proximity, both showing similar patterns of thinning-upward sequences followed by thickening-upward sequences, it is inferred that the Windsor Township Formation is characterized by this type of cyclic sedimentation, at least in this area of exposure.

In addition to the thickening-upward/thinning-upward sequences, partial Bouma sequences are easily identifiable at this exposure. Bouma units are defined on the basis of lithology and sedimentary structures present within a bed (Figure 30). Bouma A (T_A) units are massive, graded, coarse-grained deposits. Flute casts, tool mark, and other erosional features are found at the base of these beds (Figures 31 and 32). Bouma B (T_B) units consist of parallel -laminated, coarse to fine sands deposited under upper flow regimes. Bouma C (T_C) units

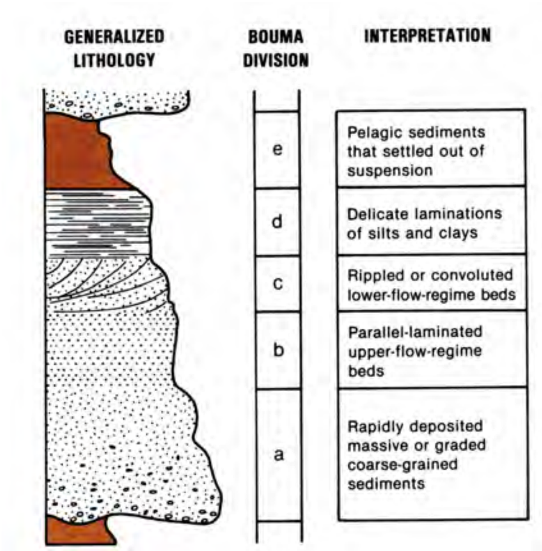

Figure 30: Idealized facies model for a turbidite sequence. From Harper, 1999.

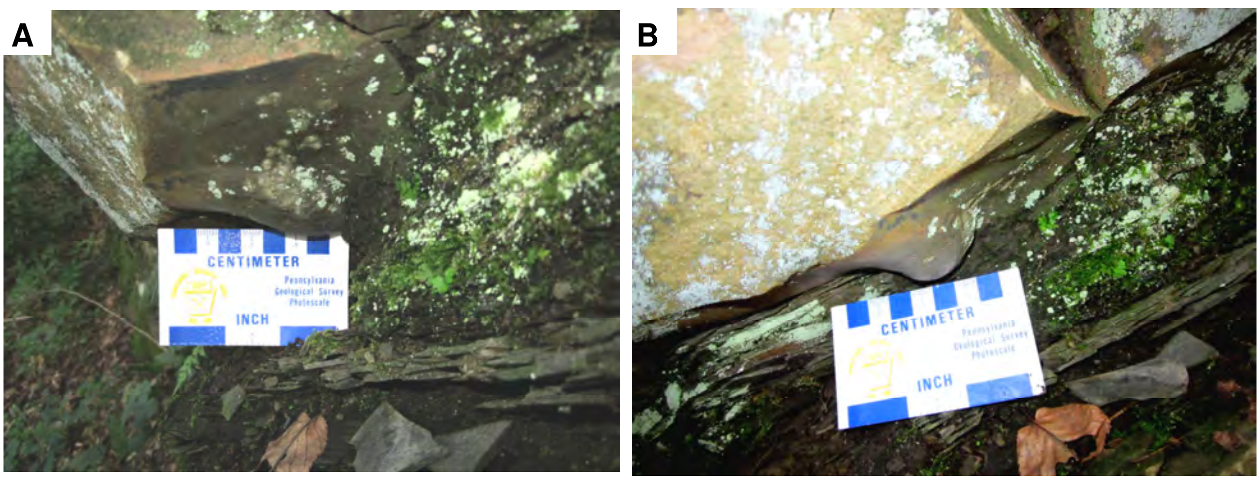

Figure 31: Photographs of flute cast in T_A bed. A – Flow direction is from the right to the left; B – Same as A, but with photo from the front. Flow direction out of the page.

Figure 32: Photograph of tool marks on the base of a T_A bed.

Figure 33: Photograph of ripple laminations in a T_C bed, showing a gradual transition from T--$_C$ to T_D finely laminated siltstones and shales.

contain cross- or ripple-laminated fine sands deposited under lower flow regimes (Figure 33). Parallel-laminated siltstones and shales are characteristic of Bouma D units (T_D). T_D beds indicate a decrease in energy in the turbidity flow allowing the fines to settle out of suspension. Bouma E units (T_E) consist of pelagic mud sedimentation, occurring after a turbidity flow has stopped.

Why Does the River Meander in Schuylkill Gap?

The orthoquartzites and conglomerates of the Tuscarora Sandstone and Shawangunk Formation invariably form the barrier in water gaps in Pennsylvania through which the host stream must traverse. Steep cliffs in these rocks are the result, such as Lehigh and Delaware water gaps (Stops 3 and 4). Not the case in this gap. Here, the Schuylkill River first encounters the Tuscarora, apparently flowed through it at one time judging from the topography 1,000 ft (305 m) to the south. It then flows back to the north and then flows southeast again through the Tuscarora. One possible explanation for the meander is that the Tuscarora is highly sheared at the gap site; many slickensided beds and joints in several orientations were seen. After initially breaching these quartzites, the river encountered the thick grawyackes in the Windsor Townshipo Formation (locality E), reversed course to flow north where it encountered the thick sandstone in the Clinton Formation, and then flowed southeast, again breaching the Tuscarora. At an earlier time the river may have continued to flow eastward following the col along the present trend of the railroad. Isn't geomorphic arm waving fun? Some more detailed field mapping would help.

This Quadrangle Needs To Be Mapped!

Little geologic mapping has been done in the Auburn 7.5-minute quadrangle, the local for Stop 1, nor in the adjacent Friedensburg quadrangle to the west. Stephens (1969) mapped the folds in the rocks east of PA 61. A geologic traverse north of Point Phillip along PA 61 for this field trip showed that the structure in the Bloomsburg Red Beds and Clinton Formation is a bit more complex than shown by Stephens. Faults are more abundant. For example, the outcrop of the Shawangunk at the north end of the geologic map (Figure 21) is faulted against the Clinton and possibly the Bloomsburg, and it extends upwards for an unknown distance, possibly at least halfway up the slope. Slickensides and disrupted beds are scattered throughout the traverse; their extent to the east is speculative. Slickensides indicating horizontal movement within the Shawangunk was noted on the east side of Schuylkill River and vertical slickensides are described at locality *D*. The deformational characteristics of the Silurian and younger rocks in the Auburn quadrangle appear to be significantly different than in areas to the east. This is one of the issues in the "Hamburg Triangle" (see the Structure section). Students—please note the encouragement for geologic mapping in the section "The Role of Geologic Mapping, a Call for Future Mappers" in the Structure Section of this field guide.

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ACKNOWLEDGEMENTS

Chris Oest thanks Jack Epstein and Jon Inners for their guidance, reviews and suggestions. Also, thanks to his classmates at Temple University, as the measured section would not be nearly as complete without sharing our data.

Yeah, I've heard that old grizzly legend about seven Indian girls carving the tower with their tomahawks while chasing a bear, too, but that's just silly superstition!

STOP 2: PENN BIG BED SLATE COMPANY QUARRY (MANHATTAN MINE); Stratigraphy, Structure, and Economic Geology; Pen Argyl Member of the Martinsburg Formation

Leader: Jack Epstein

The 32nd Field Conference of Pennsylvania Geologists first visited this quarry 45 years ago (Epstein and Epstein, 1967). The structure of the rocks has not changed since then (Figure 1), but the operation has progressed to the west. While access to the one other active and many abandoned slate quarries near Bangor, Pennsylvania, is limited because of company policy, and trespass laws, this one is still an excellent locality to compare the stratigraphic characteristics of the upper (Pen Argyl) Member of the Martinsburg Formation with those of the lower, thinner-bedded (Bushkill Member) farther south. Both members have produced commercial slate in the past, but only the Pen Argyl Member is presently active.

There are several vantage points that we may visit, depending on quarry operations and accessibility at the time. The view shown in Figure 1 is no longer available. The south wall of the quarry may be seen from a small pull-out near the office trailer in the large clear area in the north (Figure 3). We will most likely have a chance to see the quarry from the vantage point in Figure 4.

WARNING: AVOID DEATH-KEEP BACK FROM VERTICAL QUARRY WALLS!

Stratigraphy

The Martinsburg Formation in easternmost Pennsylvania exceeds 10,000 ft (3,048 m) in thickness and has been divided into three members. These are, from youngest to oldest, the Pen Argyl, Ramseyburg, and Bushkill members. The Ramseyburg contains abundant beds of greywacke perhaps 20% of the unit contains graywacke scattered throughout) and separates the other two members which are predominantly slate. Many beds in the Pen Argyl Member in this quarry exceed 10 ft (3 m) in thickness, although laminated slates are not uncommon. This is in sharp contrast with thicknesses of beds in the Bushkill Member which do not exceed 6 in (15 cm), as well as the interbedded slate and graywacke of the Ramseyburg Member to be seen at Stop 5 tomorrow. In the Pen Argyl medium-dark-gray to dark--gray evenly bedded slate generally grades up into thinner grayish-black carbonaceous slate. Laminae to beds of graywacke as much as 4 ft (1.2 m) thick may form the base of some of these cycles. Examples of graywacke, some with intraformational convolutions, may be seen on the dumps west of the mill. You will note that several hundred feet (scores of meters) of rock are exposed in a continuous section in this quarry alone. The total outcrop width of the Pen Argyl is about 13,000 ft (3,962 m) in this general area. Excellent exposures of the Pen Argyl are found along the Lehigh River, about 2.6 mi (4.2 km) to the northeast, and many folds similar to those in this quarry have been mapped. Few faults have been recognized. Thus, it is not surprising that the thickness of the Pen Argyl Member is estimated to be more than 5,000 ft (1,524 m). Petrographic characteristics of the Pen Argyl are given in Epstein et al. (1974).

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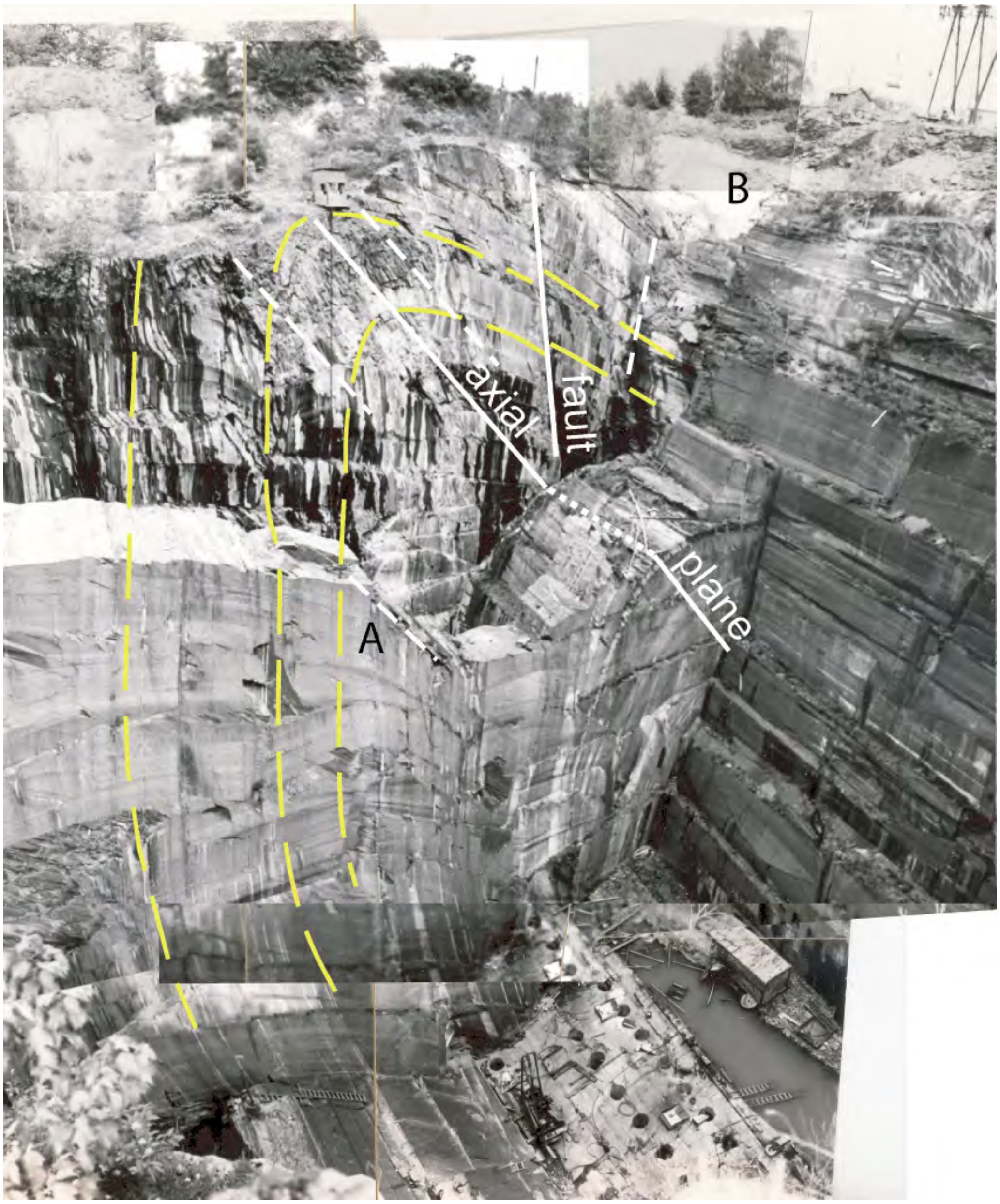

Figure 1. Overturned anticline in the Pen Argyl Member of the Martinsburg Formation in the quarry of the Penn Big Bed Slate Company, 2000 ft (610 m) north of Slatedale, Pa. Picture taken in 1980. View looking eastward. Bedding traces are shown by long-dashed yellow lines. Cleavage (short dashed white lines) dips steeply southward (to the right) and fans the fold. The quarry face in the center of the photo (at *A*) is perpendicular to the cleavage and bedding. A syncline (*B*) could be seen in the southeast corner of the quarry. A steeply dipping reverse fault is located in the upright limb of the fold. Figure 2 depicts the main structural features in the quarry. Overhead cables, with a breaking strength of 490 tons (445 metric tons) and supported by the derricks to the upper right, hoist blocks of slate out of the quarry. The smooth faces in the quarry have been cut with a wire saw (at *A* for example). Compare these with the rough dynamite-blasted beds just under the shed on top of the east wall. This direction of parting is termed the "grain". The shed is an old signalman's house. The signalman directed the hoisting operations upon vocal instructions from men in the quarry below, such as, *Hoist away matey, up your derrick, Jack*". The engine houses and mill are located to the south beyond the brink of the quarry. Three ft (0.9 m) wide calyx holes can be seen in the floor of the quarry. These are about 15 ft (4.5 m) deep and are sites where wire saw standards and sheaths are placed and between which the wire cuts the rock. The Pen Argyl is thick bedded here, and one bed, the Penn Big Bed, is 12 ft (4 m) thick in the limbs of the fold. The top of that bed is located just under the signalman's shed.

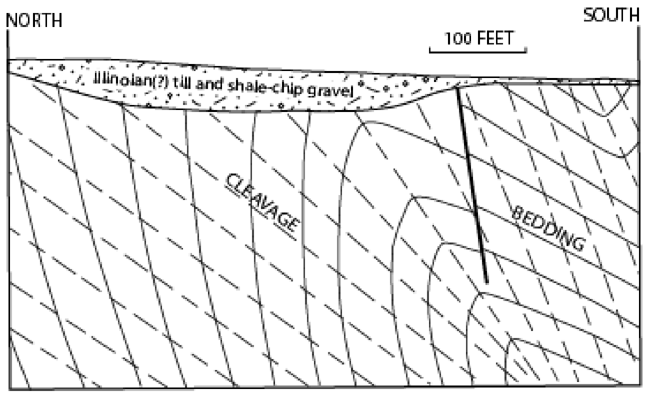

Figure 2 Diagrammatic cross section showing overturned folds, a reverse fault and fanning of cleavage in the Penn Big Bed Slate Company (Manhattan) quarry. Overburden, comprising till and shale residuum, thickens to the north in the quarry area.

Figure 3. The slate quarry looking south. The anticline on the east wall can be seen to the left. The locality of the view point is shown in Figure 4.

Figure 4. Panorama of quarry looking north. The quarry is divided into four sections: The presently active part is to the left (west). The hole directly ahead is presently water-filled. Two waste-filled abandoned sections are to the far right. A series of oval shapes above the red stain in the central area are 3-ft (0.9-m) wide calyx holes. These are now flooded and no longer visible. The faulted anticline is outlined to the right. The observation point for Figure 3 shown by the arrow.

Structure

The overturned anticline and syncline in this quarry are typical of the folds mapped in the Martinsburg Formation of the Lehigh Valley (see, for example, Miller et al., 1941, p. 413-415). Folding was dominantly passive and slaty cleavage is the prevailing secondary structure. The cleavage forms a fan with an angle of about 24^{o} (Figure 2). Abundant evidence indicates that the cleavage formed under conditions of low-grade regional metamorphism by processes involving pressure solution, new mineral growth and some mineral reorientation (see discussion of cleavage in Stops 3, 4, and 5).

Geology of Slate quarrying

Slate was first extracted in Pennsylvania as early as 1812 (Alderfer, 1953), and was widely quarried during the early half of the century (Figure 5). Since then more than 400 quarries have been opened in the slate belt in the Martinsburg Formation of Northampton and Lehigh Counties. At present, only three are active in Pennsylvania (Antonides, 1997). Vermont, Virginia, and Pennsylvania are the three largest producers of slate in the United States. Slate production figures in Pennsylvania are sparse, and are available from a self-reporting requirement through mining permits. For the last completed reporting year of 2005, production stands at 7,878 short tons (7,147 metric tons). Seven companies were active, including Penn Big Bend Slate Co. in eastern Pennsylvania. Employment in the mining side of this industry is reported as 16 persons working 8,071 hours. The slate belt in eastern Pennsylvania is located in the Martinsburg Formation just south of Blue-Kittatinny Mountain between the Delaware River on the east to several miles (kilometers) west of the Lehigh River, in Northampton and Lehigh Counties.

Figure. 5. This sign greets you near Bangor, Northampton County, PA showing the Welsh heritage in the Pennsylvania slate industry.

The Manhattan quarry of the Penn Big Bed Slate Company, the only active quarry in Lehigh County, began operations in 1916. When last visited by the Field Conference of Pennsylvania Geologists 28 years ago (Lash et al., 1984), the quarry was divided into two parts that are separated by a rib in the middle. The eastern section was about 350 ft (107 m) deep, and the central section, quarried in 1984, was more than 200 ft (61 m) deep. The area to the west, which contained an abandoned pit in 1984, is presently being quarried. The commercial history of the quarry and its operations can be obtained at **http://www.pennbigbedslate.com** (accesssed 9/16/2012).

The slate removed from the quarry is used for roofing tiles, sills, blackboards, floor tiles, aquaria bottoms, stair treads, fireplace facing, and turkey calls. In the past it was also used for billiard table tops. About 4,000 squares of roofing slate were produced in 1984. Presently, about 5,000 squares of roofing slate are produced.

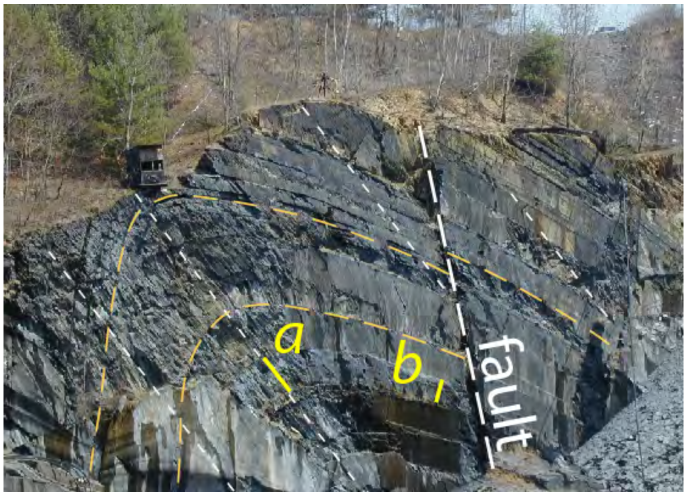

Figure 6. Close-up of anticline hinge area showing the difference in the length of a piece of slate that could be derived from the same bed in the hinge area (a) and on the limbs (b). In this case the length in the hinge is 180 percent greater than in the limb.

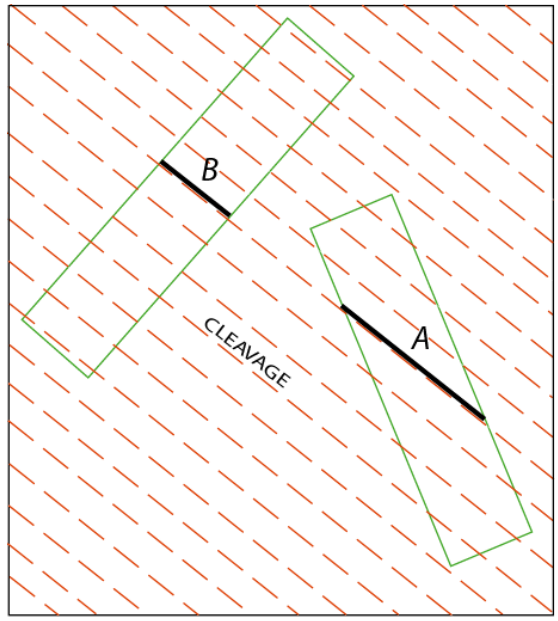

Figure 7. The length of a piece of slate that can be derived from a bed of given thickness (solid rectangle) is determined by the angle between bedding and slaty cleavage. Where bedding is at a low angle to cleavage (*A*) the length of the slate piece is much longer than where bedding is about perpendicular to cleavage (*B*); in this case it is twice as long.

Quarrying operations and profitability are controlled by the geologic setting of any slate quarry. Removing large quantities of "top" (weathered slate, colluvium, and till) might be prohibitively costly because stripping operations and extensive cribbing might be required. The thickening of overburden from about 8 ft (2.4 m) in the older western area to about 45 ft (14 m) to the north (see Figures 2 and 4) was not anticipated prior to opening the present active pit.

The shape and depth of the quarry is controlled by the steepness of bedding. For the most part, thick clear "runs" are followed down, to the near vertical beds in the north limb of the anticline. The deepest slate quarry in the United States, by the way, the collapsed Parsons quarry in Pen Argyl, Pa., 25 mi (40 km) to the northeast, is reported to have been about 900 ft (274 m) deep. It also followed vertical beds.

Cleavage is the feature that makes a rock a slate. It should be continuous through the rock, and it should not be curved or irregular ("curled"). Warped slaty cleavage is generally associated with a second-generation *crenulation* cleavage. Minor northwest-dipping crenulation cleavage was seen in the syncline in the southeast corner of the quarry. The length of a piece of slate that can be removed is determined by the thickness of a clear bed and the angle between bedding and cleavage. (Figures 6 and 7). If the angle between cleavage and bedding is high, the length of a piece of slate derived from that bed is relatively short. Conversely, if the angle between the two is low, the piece of clear slate is long. The thickest bed in the quarry, the Penn Big Bed, is 12 ft (3.7 m) thick (measured orthogonally) and is 21 ft (6 m) thick along the "split" (cleavage). The dip of cleavage is also important because it generally forms the floor of the quarry and may be inconveniently steep. In the Penn Big Bed quarry, cleavage averages about 55^{o}, and other fractures in the rock are used to form the quarry floor. The average dip of cleavage is gentler near the Delaware River in easternmost Pennsylvania.

Joints may facilitate quarrying if their orientation and spacing are favorable for the size of block being removed. If, however, the joints are too close together or are at low angles to each other, large blocks of slate cannot be obtained and the rock is worthless.

Grain ("sculp" of quarrymen) is important in removing slate from quarries because fractures readily form parallel to it during blasting or wedging (Figures 1, 9H), and the sides of many quarries therefore parallel the grain. This direction of splitting is believed to be controlled by the elongation of prismatic minerals, mainly quartz, in the direction of tectonic transport, approximately at right angles to cleavage and bedding, and generally in the down-dip direction of slaty cleavage.

Hazards associated with slate quarries are numerous. Drowning of swimmers and scuba divers has been reported in flooded quarries. A car was accidentally driven into a quarry just south of the Penn Big Bed quarry. Rockslides have occurred, especially along "rotten ribbons". (fault zones, Figure 8), killing and maiming workers below. These planes of weakness, where oriented in a direction that may facilitate sliding, also could be a concern for instability along highways. Many abandoned quarries have been used for dumping of trash, creating the possibility for ground water pollution.

Figure 8. Fault along bedding dipping to the left in quarry near Bangor, PA. Horizontal cleavage is dragged downwards to the right as fault is approached.

Most of the rock removed from the slate quarries in eastern Pennsylvania wind up on slate dumps that form conspicuous hills, or are dumped in adjacent abandoned holes. More than 80 percent of the rock removed from most Pennsylvania slate quarries is waste; the slate belt of eastern Pennsylvania is littered with these hills of waste.

Slate Quarry Practice, a Pictorial Journey*

Quarry methods, including the use of the calyx drill and wire saws, will be explained at the stop and in the following discussion. The mosaic of pictures in Figure 9 depicts general quarry operations for removing and milling slate in eastern Pennsylvania. For additional information about slate quarry operations, refer to Behre (1933), Stickler et al. (1951), Epstein (1974), and Berkheiser (1984).

Operations in slate quarries are labor intensive. The work is hard and dangerous. The quarries are steep sided and deep, requiring the workers to be hoisted down in *buckets* (Figure 9A). The slate is worked in sloping rhombic blocks, depending upon the geometry of cleavage, bedding, and joints (Figure 9B), cut using a variety of methods. Dynamite blasting produced much waste, and in 1926 the wire saw was introduced which greatly reduced the amount of waste. The saw consists of a ¼- in (0.6 cm) steel cable, connected through pulleys to a motor at the top of the quarry, and traveling in an endless belt over the slate. It is charged with sand as an abrasive, connected through a sheave to a standard (Figures 9C, D) and slowly lowered

*Photos 23-27 from Penn Big Bed Slate Company website, **http://www.pennbigbedslate.com** (Accessed 9/17/2012)

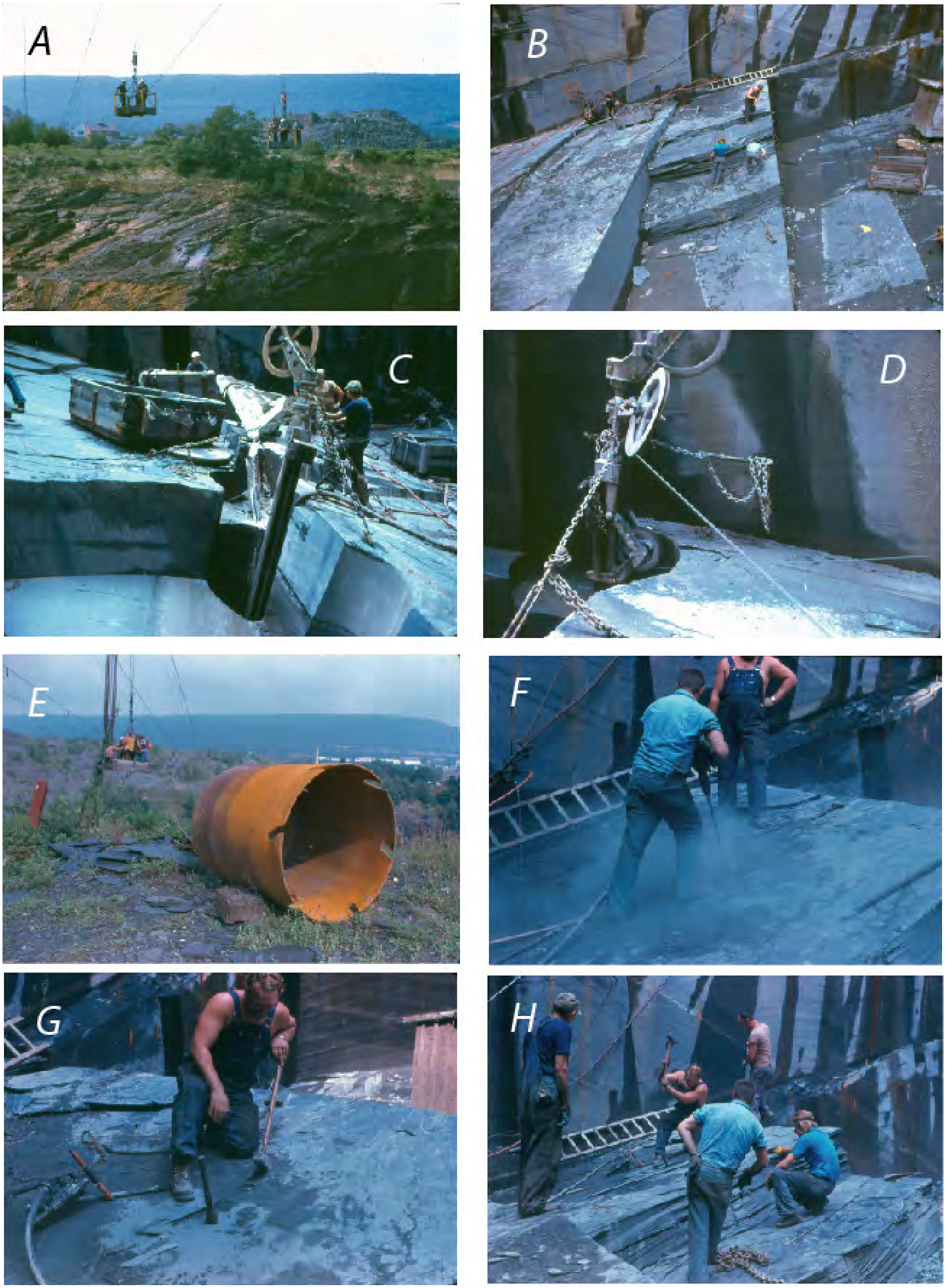
A
B
C
D
E
F
G
H

Figure 9. Photos showing the various stages of slate mining, removal, milling and disposal at the Manhattan quarry of the Penn Big bed Slate Company.

into 3-ft (0.9-m) hole that was previously cored with a calyx drill (Figure 9E). Large blocks are separated by drilling a hole (Figure 9F), inserting a wedge (Figure 9G), pounding away with a sledge (Figure 9H), until the rock cracks along the *grain* (*sculp* or *scallop* of quarrymen). The grain is a direction of weakness in the slate, at right angles to the cleavage, produced by linear alignment of prismatic grains in the direction of tectonic transport, the "a" direction of structural geologists. It is not visible in the rock and becomes apparent only after the rock is split. This fracture is then used to separate the block of slate with a pry bar and a suitable sized block is pried loose along cleavage (Figure 9I). Joints may also be used to separate blocks of rock where they are suitably oriented. The block is then enveloped with a chain (Figure 9J), and lifted from the quarry floor (Figure 9K). The block is hoisted to the top of the quarry (Figures 9L, M) by the crane operator, who receives signals thorough bell ringing from the team down in the quarry. These blocks may weigh as much as eight tons. It is then lowered onto a rail cart (Figure 9N) and brought into the mill (Figure 9O) where it is sorted for quality, cut into various products (Figures 9P), trimmed, and stored in the mill or an outside yard (Figure 9Q). The slate is not immune to the weather—it can be damaged by freezing during winter months. It must also be kept wet to facilitate splitting. For roofing shingles, blocks that measure 16 to 24 in (41 to 61 cm) by 10 to 16 in (25 to 41 cm), are manually split to standard thickness between 3/16" to ¼". The splitter uses a wide-blade chisel to separate the pieces along cleavage (Figure 9R). The waste pieces are thrown into a nearby dump. Nail holes are punched in the shingles with a machine operated by a treadle (Figure 9S). Slate roofs are fire proof and can last for 50 to 100 years before needing replacement. Slate shingles have been manufactured by the present owners of this quarry since it was acquired in 1934. More than 50 percent of the slate removed from the Manhattan quarry is waste and winds up being dumped into an old abandoned quarry south of the mill (Figure 9T).

Glossary

The following are terms that have been applied to fine-grained sediments, predominantly with clay and silt, and which have been applied to some of the rocks seen on this field trip (modified from Gary et al., 1972).

Argillite: compact rock, derived from mudstone (claystone or siltstone) or shale, that has undergone a some-what higher degree of induration than is present in mudstone or shale but that is less clearly laminated than, and without the fissility (either parallel to bedding or otherwise) of, shale, or that lacks the cleavage distinctive of slate. May have undergone weak metamorphism.

Claystone : an indurated rock in which clay predominates over silt lacking the fine lamination or fissility of shale whose constituent particles have diameters less than 0.01 mm. May be less indurated than shale.

Mudstone: A fine-grained, blocky or massive indurated mud in which the proportions of clay and silt are approximately the same and having the texture and com-position, but lacking the fine lamination or fissility, of shale; a nonfissile mud shale. A general term that includes clay, silt, claystone, siltstone, shale. and argillite, and which should be used only when the amounts of clay and silt are not known. Useful term when it is desirable to characterize the whole family of finer-grained sedimentary rocks (as distinguished from sands-tones, conglomerates. and limestones).

Pelite A mudstone, or calcareous sediment composed of clay, minute particles of quartz, or rock flour. Equivalent to the term, *lutite.*

Shale A fine-grained, indurated, thinly laminated or fissile claystone, siltstone, or mudstone, characterized by finely stratified structure (fissility) that is approximately parallel to the bedding (along which the rock breaks readily into thin layers) and that is commonly most conspicuous on weathered surfaces. Shale is less firm than argillite and slate. The term "shale" has been loosely applied to fine-grained rocks lacking these characteristics, and has been applied to almost any indurated clayey rock.

Siltstone An indurated silt having the texture and composition, but lacking the fine lamination or fissility, of shale; a massive *mudstone* in which the silt predominates over clay.

Slate Fine-grained rock formed by low-grade metamorphism possessing slaty cleavage which is the property of a rock to be split along a pervasive, closely spaced parallel foliation formed by the reorientation of platy minerals away form the original bedding in a direction per-pendicular to the direction of tectonic compression.

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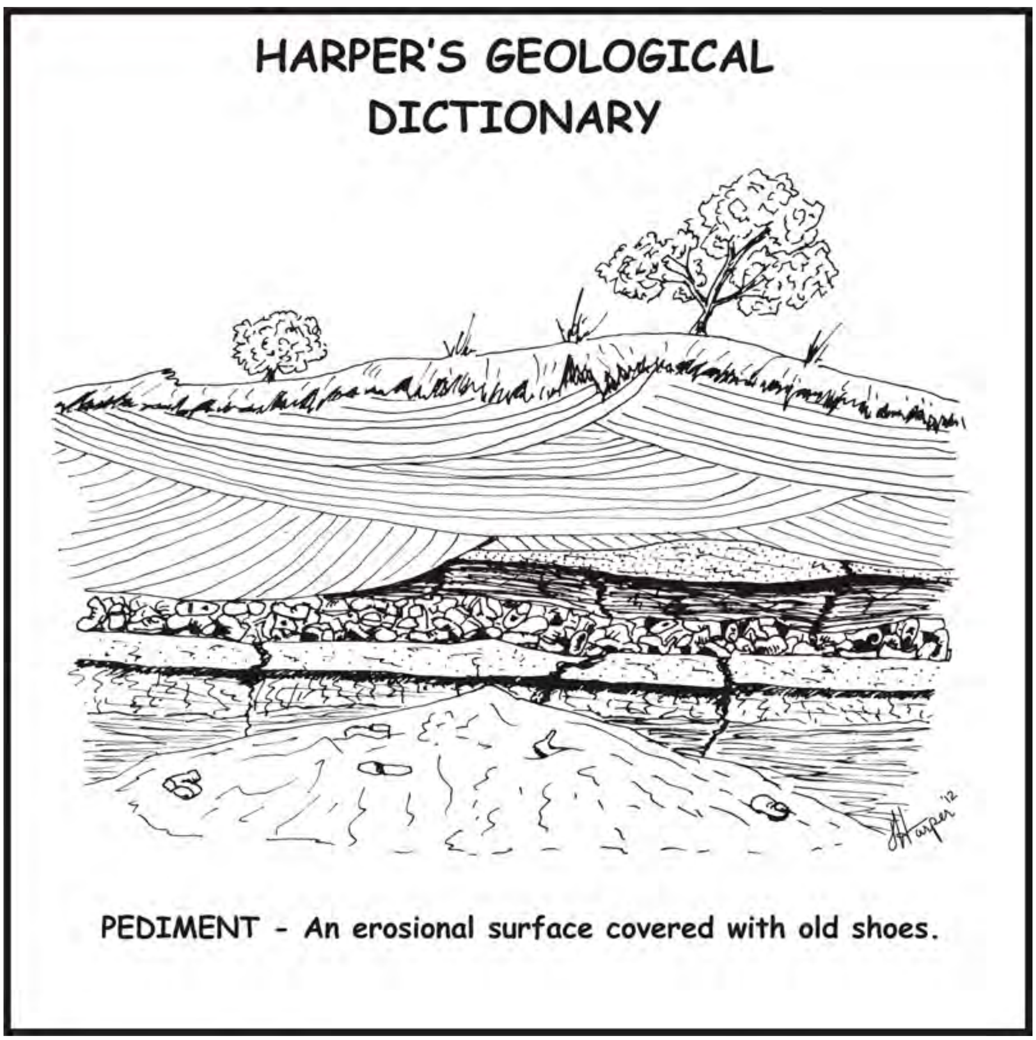


STOP 3 AND LUNCH: LEHIGH GAP

Martinsburg-Shawangunk Contact; A Cleavage Story; Pennsylvania Turnpike Tunnel; A Superfund Site; Rockfall Mitigation

Leader: Jack B. Epstein

Lehigh and Schuylkill Gaps are the only two places east of the Schuylkill River in Pennsylvania where the unconformable contact between Ordovician and Silurian rocks **is** exposed. Here, the exposures allow for an understanding of the effects of two orogenies in eastern Pennsylvania—the Taconic and Alleghenian. The different rocks in the two formations have also deformed differently, causing potential for rockfalls in the more massive Shawangunk Formation. The area is also the locus of a superfund site, due to contamination by zinc smelting in the valley to the north.

The area has lost much of its vegetation since 1912, when New Jersey Zinc opened a

Figure 1. Two views looking south of Lehigh Gap from atop a sand pit in the Palmerton Sandstone of Devonian age, approximately 1.5 mi (2.4 km) from Stop 3. The top panorama shows deforestation with smoke from the New Jersey Zinc smelting plant to the right (west) during 1972. The lower photo is the same scene more than 71 years ago (from Miller et al., 1941, p. 121). Town of Palmerton in valley to left.

smelter plant in the town of Palmerton, a little more than one mile to the north (Figure 1). The beauty of the gap before that must have matched that of Delaware Water Gap, our next stop. One hundred and sixty seven years ago, I. Daniel Rupp (1845) described the "stupendous work of nature" of the gap when he wrote:

> "*Die Lecha Wusser-Huft,* i.e. the *Lehigh Water Gap,* in the Kittatinny, or Blue mountain . . . is so named from the river Lehigh, which steals its way through the *Gap,* prominently walled on both sides, forms a sublime object of

Epstein, J.B., 2012, Stop 3: Lehigh Gap, *in* Harper, J. A., ed., Journey along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and southeastern New York. Guidebook, 77th Annual Field Conference of Pennsylvania Geologists, Shawnee on Delaware, PA, p. 248-271.

admiration, and presents to the observant spectator, one of the most picturesque prospects in east Pennsylvania. At almost every season of the year, the diversified defile is exceedingly attractive. The writer visited this place in September, 1844. In ascending the eastern bank some hundred feet, the scene heightens in grandeur, and the stream – the beautiful . . . rippled waters of the Lehigh river, add much, nay every thing, to make it impressive beyond oblivion. Though it is seemingly a rugged stream here, yet as you follow it in its course, through a fertile region of country, receiving tributaries of different seizes, until itself is a considerable river, before it reaches its silvery recipient, the Delaware. It is in all its ways, as well as at the Gap, where it rolls majestically over a rupic bed, and reflecting a sombre shade of the impending mountains, a grand stream.

"Ascending the eastern height, the traveller is amply rewarded for the exertion of climbing from rock to rock, in scaling the pine covered side of the mountain, by the rich and extensive prospect which the eye then commands. At his feet roll the waters of the majestic stream—on the opposite side is a towering ridge, near the summit of which appears, right opposite, emerging from the surrounding woods, a lonely pile of rocks, whimsically called, "*Die Teufel's Kanzel,*" i.e. "*The Devil's Pulpit,*" which indignantly suffers but a few blasted pines to shade its sullen brow. At a distance an extensive country, variegated with woods and farms, watered by the meandering Lehigh, and ridge retiring behind ridge, till lost in the faint tints of the horizon, all bursts upon the sight, and fill the mind with sublime ideas of the greatness of the Creator. The shattered rocks, thrown together in wild confusion, and the strata of rounded stones, which are to be met with in passing through the Gap, have given rise to the supposition that the Lehigh, being obstructed in its course by the Blue mountain, was formerly dammed up into a lake, which at length bursting the barrier, formed the chasm now called the Lehigh Gap. The learned have not agreed, as yet, in the decision of this mooted point."

"A learned writer says: 'It is common to speak of such passes as being formed by the rivers, which are often supposed to have burst their barriers, and thus to have shaped their own channels. This may have happened in some peculiar cases, and there are doubtless many instances where the lakes, of which many must have been left at the retiring both of the primeval and of the diluvial ocean, have worn or burst away their barriers, especially when composed, as they must often have been, of loose materials. But with respect to most rocky passes of rivers through mountains, there appears no reason whatever to believe that the waters have torn asunder the solid strata. A more resistless, energy must have been requisite for such an effect; and we must therefore conclude that the rivers have, in most instances, merely flowed on through the lowest and least obstructed passages. Their channels they have doubtless deepened and modified, often to an astonishing degree but they have rarely formed them through solid rocks.'—Silliman."

At this stop we will examine the lithologic makeup and structure of the two exposed formations, decipher the orogenic history of these rocks, and discuss slope instability and its mitigation. Figure 2 shows the main features to be seen at this stop.

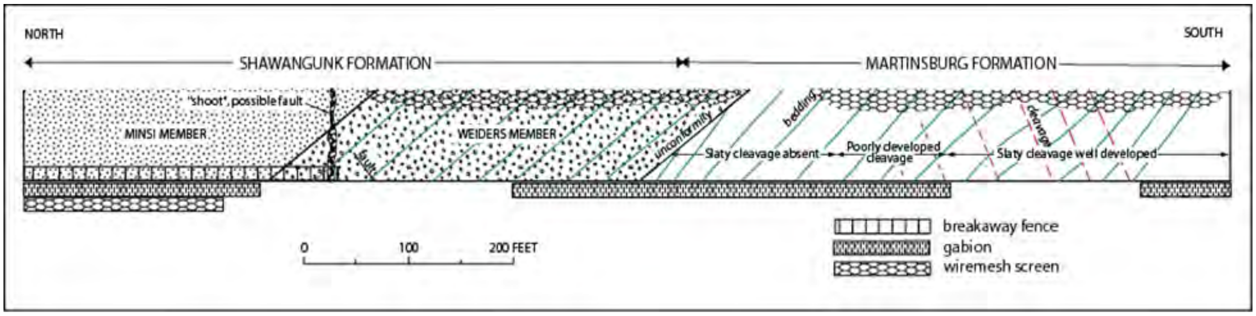


Figure 2. Geologic and engineering features seen along the abandoned railroad track at Lehigh Gap. See Figure 7 for details in the Martinsburg Formation.

Stratigraphy

Lithologic descriptions of the two formations in the Lehigh Gap area are given in Table 1. The shales (with slaty cleavage at the south end of the exposure; therefore should be termed "slates") and graywackes of the Martinsburg are in sharp contrast with the sandstones and conglomerates of the Shawangunk. The sharp contact and difference in bedding dip between the two formations, and the very different environments of deposition under which they accumulated, indicate an angular unconformity with a large hiatus, possibly between 10-25 million years. The contact is a folded and faulted unconformity. The Martinsburg at Lehigh Gap is weathered and leached of calcium carbonate, in contrast with the fresh rocks seen at Stop 2 today.

The Martinsburg sediments were deposited in a rapidly subsiding flysch-turbidite basin formed during Middle Ordovician continental-volcanic arc plate collision. The source for the Martinsburg was to the southeast and the sediments covered a foundered Cambrian and Ordovician east-facing carbonate bank. Basin deepening actually began during deposition of the muddy carbonate rocks of the underlying Jacksonburg Limestone. The thin-bedded graded sequences of siltstone, siliceous slate, and carbonaceous slate of the lowest (Bushkill) Member of the Martinsburg are probably distal turbidites and pelagic sediments of a deep-sea submarine plain that were later overrun by thicker turbidites and submarine fan deposits of the middle Ramseyburg Member. The deepest part of the basin appears to be in the area of this field trip because the Martinsburg is thickest here. Many of the turbidites in the Ramseyburg were undoubtedly triggered by seismic events related to Ordovician tectonism in the source area. These events may have become less severe during Pen Argyl time, so that much thicker pelagic muds were deposited, as seen at the Penn Big Bed slate quarry, Stop 2.

Rapid shallowing of the Ordovician basin was accompanied by tectonic uplift during Taconic mountain building which peaked with emergence of the area during the Late Ordovician. This period of orogenic activity, regional folding and uplift was followed by deposition of a thick coarse clastic wedge, the Weiders Member of the Shawangunk Formation. The contact between the Shawangunk and Martinsburg is a regional angular unconformity. The discordance in dip is not more than 15^{o}, between the area just east of Stop 1, through New jersey, to Stop 10, a distance slightly more than 100 mi (161 km) to the northeast. Beyond these two limits, the angular discordance between Silurian and Ordovician rocks approaches 90^{o} in places, such as at Stop 1.

The sandstones and conglomerates of the Weiders and Minsi Members of the Shawangunk Formation are interpreted to be fluvial in origin and are overlain by a transitional marine-

Table 1. Description of rock units in Blue Mountain at and in the vicinity of Lehigh Gap. Modified from Epstein and Epstein (1969).

Age	Formation	Member (Thickness, in feet)	Description
SILURIAN	SHAWANGUNK	Lizard Creek (1,225)	Medium-gray to greenish-gray very fine to medium-grained thin- to thick-bedded quartzite containing a few intervals of dark-grayish-red-purple fine-grained partly silty and shaly hematitic quartzite. Grayish-orange to lightolive-gray shale, silty shale, and siltstone with some grayish-red-purple beds. Medium-gray to greenish-gray very fine to medium-grained, thin- to thick-bedded, laminated to planar-bedded and cross bedded, evenly to unevenly bedded, rippled and flaser-bedded sandstone containing burrows and a few intervals of dark-grayish-red-purple fine-grained partly argillaceous hematitic sandstone interbedded and interlaminated with grayish-orange to light-olive-gray and minor grayish-red-purple, evenly to unevenly laminated, flaser-bedded, burrowed shale, silty shale, and siltstone. Upper half contains scattered beds and lenses of collophane (carbonate fluorapatite), siderite, and chlorite nodules, quartz pebbles, siltstone and shale intraclasts, and ***Lingula*** fragments. Upper contact with Bloomsburg red Beds gradational.
		Minsi (225)	Medium-light-gray and greenish-gray, medium- to very coarse grained partly conglomeratic (with quartz pebbles as much as 2 in. long and clay galls as much as 7 in. across); crossbedded to planar-bedded quartzite and very light-gray to medium-light-gray and greenish-gray, predominantly medium-grained quartzite. Upper contact gradational.
		Weiders (190)	Light-gray to medium-dark-gray and light olive-gray medium- to coarse-grained crossbedded and planar-bedded, limonitic, pyritic, unevenly to. moderately evenly bedded thin- to thick-bedded quartzite, conglomeratic quartzite, and quartz-, chert-, and shale-pebble conglomerate (quartz pebbles as much as 2 in. long). About 7 percent dark-gray irregularly bedded laminated locally mud-cracked argillite. Upper contact gradational.
ORDOVICIAN	Martinsburg	Pen Argyl (3,000-6,000)	Dark-gray to grayish-black, thick- to thinbedded, evenly bedded claystone slate, rhythmically intercalated with beds of quartzose slate or sub graywacke and carbonaceous slate. Some beds more than 20 feet thick. Upper contact abrupt and unconformable.
		Ramseyburg (about 2,800)	Medium- to dark-gray claystone slate alternating with beds of light- to medium-gray, thin- to thick-bedded graywacke and graywacke siltstone. Graywacke composes about 20-30 percent of unit. Upper contact with Pen Argyl Member gradational.
		Bushkill (about 4,000)	Greenish-gray to medium-gray crossbedded and planar-bedded medium- to thick-bedded quartz-, chert-, quartzite-, argillite-pebble conglomerate (quartz pebbles as much as 6 in. long), with clay galls up to 8 in. across. Medium-dark-gray medium- to very coarse grained conglomeratic quartzite and a few beds of greenish-gray argillite. Upper contact gradational.

Rocks seen at Stop 3 (bracketing the Weiders Member and the top of the Pen Argyl Member)

continental facies (the Lizard Creek Member, which can be seen farther north along the abandoned railroad track and in Delaware Water Gap, Stop 4). The fluvial sediments are characterized by rapid alternations of polymictic conglomerate (Figure 3) with quartz pebbles more than 6 in (15 cm) long in places, conglomeratic sandstone, and sandstone (cemented with silica to form quartzite), and subordinate siltstone and shale (Figure 4). The large clasts, planar

Figure 3. Polymictic conglomerate boulder of the Weiders Member of the Shawangunk Formation at barrier in the parking lot. Whence came the pebbles?

Figure 4. Planar-bedded conglomerate near the top of the Weiders Member of the Shawangunk Formation behind the breakaway fence, Lehigh Gap. Rounded to subangular white quartz and dark-gray chert pebbles and cobbles are as much as 3 in (7.6 cm) long.

bedding and cross bedding indicate rapid flow conditions. Cross-bed trends are generally unidirectional to the northwest. The minor shales and siltstones are thin, and at least one at Delaware Water Gap, 28 mi (45 km) to the northeast, is mudcracked, indicating subaerial exposure (which may be seen at mileage 5.3, Day 2 Road Log; also Epstein and Epstein, 1969, fig. 8D). These sedimentological features indicate that deposition was by steep braided streams with high competency and erratic fluctuations in current flow and channel depth. Rapid runoff was undoubtedly aided by lack of vegetation cover during the Silurian. The finer sediments are relicts of any that may have been deposited in overbank and backwater areas – most of these were flushed away downstream to be deposited in the marine and transitional environment represented by the Lizard Creek Member.

One of the most vexing sedimentological problems in the folded Appalachians is the source of debris for many of the thick clastic wedges in the Paleozoic succession. The Shawangunk Formation of Silurian age, with its abundant quartz sand and quartz pebbles (Figures 3 and 4), is one example. It overlies a thick lower Paleozoic section of slate and carbonate rocks of the Great Valley, and Precambrian metasedimentary rocks, amphibolite, marble, and granitic rocks in the Reading Prong. A comparison of the mineralogy of these rocks does not make the rocks beneath the Shawangunk an enticing source for the Shawangunk. It is possible that pre-Silurian structural shuffling may have brought a source terrane in juxtaposition with the Shawangunk depositional basin that was more quartz rich than the rocks presently south of the Shawangunk outcrop belt. An added puzzlement is that the quartz pebbles in the Shawangunk are of vein-quartz origin (contain chlorite inclusions). The Shawangunk in easternmost Pennsylvania is about 1,500 ft (457 m) thick. A *huge* thickness of rock containing abundant quartz veins would have to have been present to the southeast to supply those pebbles. A *PUZZLEMENT!*

The Lizard Creek Member contains many rock types, some unique, and a variety of sedimentary structures that suggest that the streams represented by the lower members of the Shawangunk flowed into a complex transitional (continental-marine) environment, including tidal flats, tidal channels, barrier bars and beaches, estuarine, and shallow neritic. Sedimentologic details of the Shawangunk are presented by Epstein and Epstein (1972). As the source highlands were eroded, the braided streams of the Shawangunk gave way to gentler streams of the overlying Bloomsburg Red Beds. The following Upper Silurian and Lower Devonian rocks were deposited mostly under marine conditions and were superseded by continental rocks of the Catskill Formation during the orogenic pulse of the Acadian orogeny.

The contact between the conglomerate unit and overlying lower quartzite-conglomerate unit may be seen about 250 ft (76 km) north of the Shawangunk-Martinsburg contact. The planar-bedded conglomerates and crossbedded sandstones seen in the lower Shawangunk is indicative of fluviatile sediments deposited by streams of great competency, high gradient, and low sinuosity. These streams flowed to the northwest off the highlands uplifted during the Taconic orogeny. A few miles to the south, a partly dissected Illinoian(?) outwash terrace along the east side of Lehigh River can be seen from this stop.

Quartz, chert, and quartzite pebbles in the basal beds of the Shawangunk, in places more than 5 in (13 cm) long, indicate that the Martinsburg was breached during Silurian time and that underlying stratigraphic units were exposed and supplied the pebbles (possibly chert from the Ordovician Beekmantown Group, quartzite from the Cambrian Hardyston Quartzite, and vein quartz from Precambrian rocks). The sharp lithologic break at the contact brings together rocks of vastly different origin--deep-water shales and turbidite sandstones of the Martinsburg are overlain by fluviatile-terrestrial deposits of the Shawangunk. Within the basal Shawangunk no fragments of shale from the underlying Martinsburg contain slaty cleavage that may have been produced during Taconic deformation. Rather, any cleavage that may be present conforms to the attitude of the regional cleavage in post-Ordovician rocks. The obvious conclusion is that no Taconic cleavage can be recognized in pebbles within Silurian rocks. Additionally, in a few localities folds have been mapped along the unconformity in eastern Pennsylvania. The fold axes pass from the Shawangunk into the Martinsburg Formation without deflection, showing that the folds are post-Taconic in age. Cleavage in the Martinsburg is parallel to the axial planes of the folds (as at Stop 5), or fans the folds (except for the arching of cleavage as described below), again showing that the cleavage is post-Taconic in age. Additionally, whole-rock age spectra of mudstone and slate samples at Lehigh Gap supports a late Paleozoic (Alleghanian) age for the formation of the cleavage in the Martinsburg (Wintsch et al., 1996).

Structure

Lehigh Gap was first visited by the Field Conference of Pennsylvania Geologists in 1932 (Miller et al., 1932). A cross section was shown (Figure 5) that shows about a 45^{o} discordance between the Shawangunk and Martinsburg Formations.

Lehigh Tunnel through Blue Mountain are projected into the cross section. “X” marks the locality with bedding slippage in the Bloomsburg Red Beds discussed in that section. The bedrock structure near the Lehigh River is shown in Figure 6. A syncline-anticline pair occur in the Shawangunk Formation in Blue Mountain at Lehigh Gap. These die out rapidly to the west and are not seen here at the Lehigh Tunnel (see Figure 28, right). The Martinsburg and Shawangunk Formations are well exposed along the abandoned railroad in the gap. Detailed structural relations are shown in Figure 7. Southeast-dipping slaty cleavage is well developed in the Martinsburg, 200 ft (61 m) (stratigraphically) below the contact (Figures 7A and B). The cleavage disappears gradually 120 ft (37 m) below the contact (Figures 7C, D, and E) and bedding-plane slickensides become prominent. Steps on the slickensides indicate northward movement of the overlying beds (Figures 8 and 9). The uppermost 8 in (20 cm) of the Martinsburg is heavily slickensided and contains fault gouge and breccia with internal

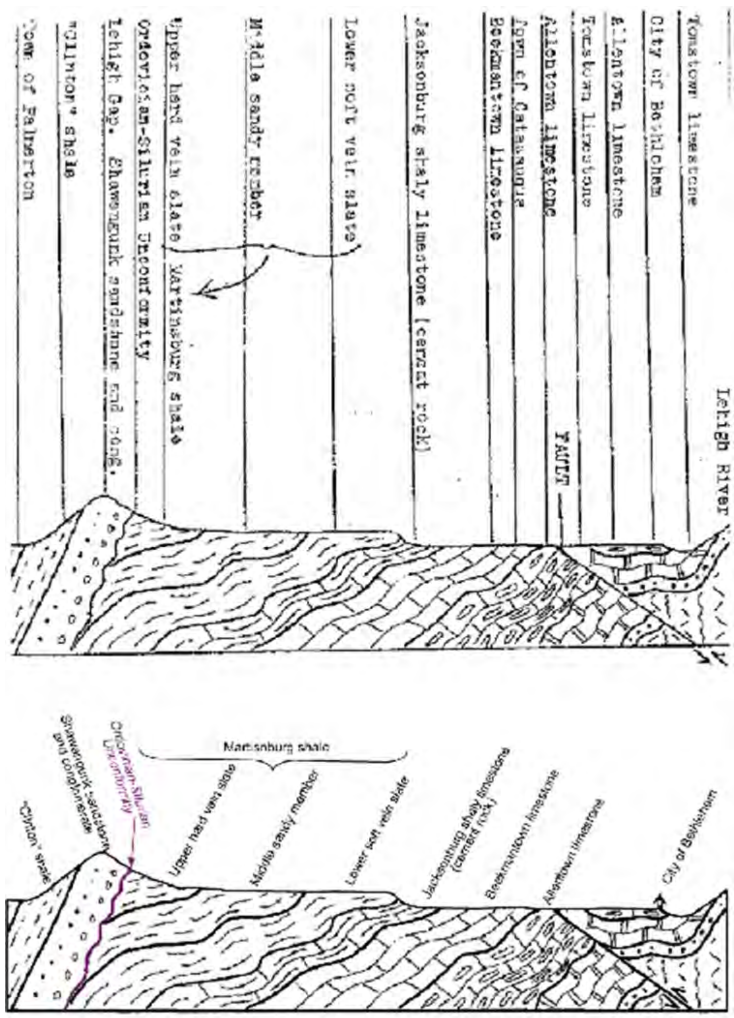


Figure 5. Cross section through Lehigh Gap showing the angular divergence between the Shawangunk and Martinsburg Formations to be about 45°.

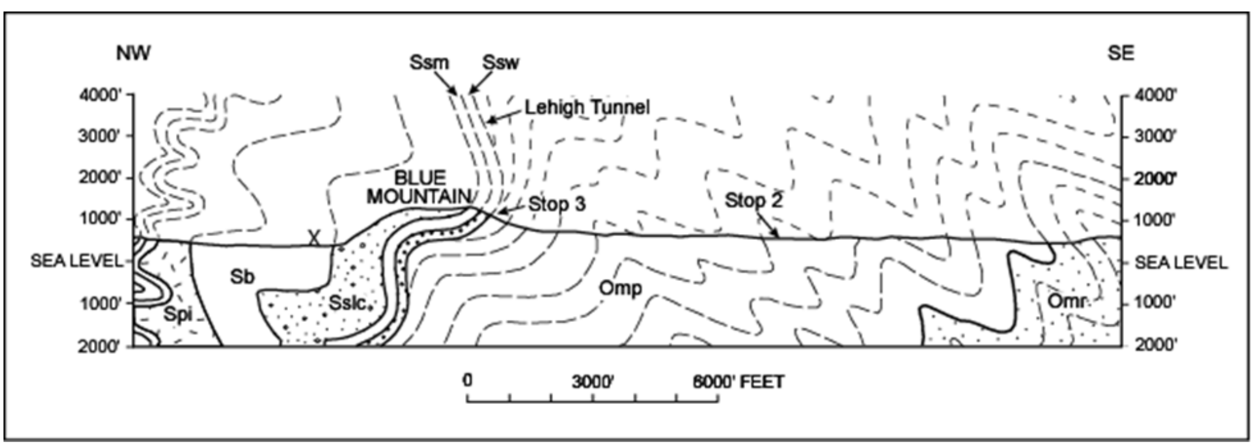


Figure 6. Geologic section 2,000 ft (610 m) east of Stop 3, Lehigh Gap. Spi, Poxono Island Formation; Sb, Bloomsburg Red Beds; Sslc, Lizard Creek Member of Shawangunk Formation; Ssm, Minsi Member of Shawangunk Formation; Ssw, Weiders Member of Shawangunk Formation; Omp, Pen Argyl Member of Martinsburg Formation; Omr, Ramseyburg Member of Martinsburg Formation. Units above Spi are Upper Silurian and Lower Devonian rocks. Approximate structural position of Stops 2 and 4 and the Pennsylvania Turnpike.

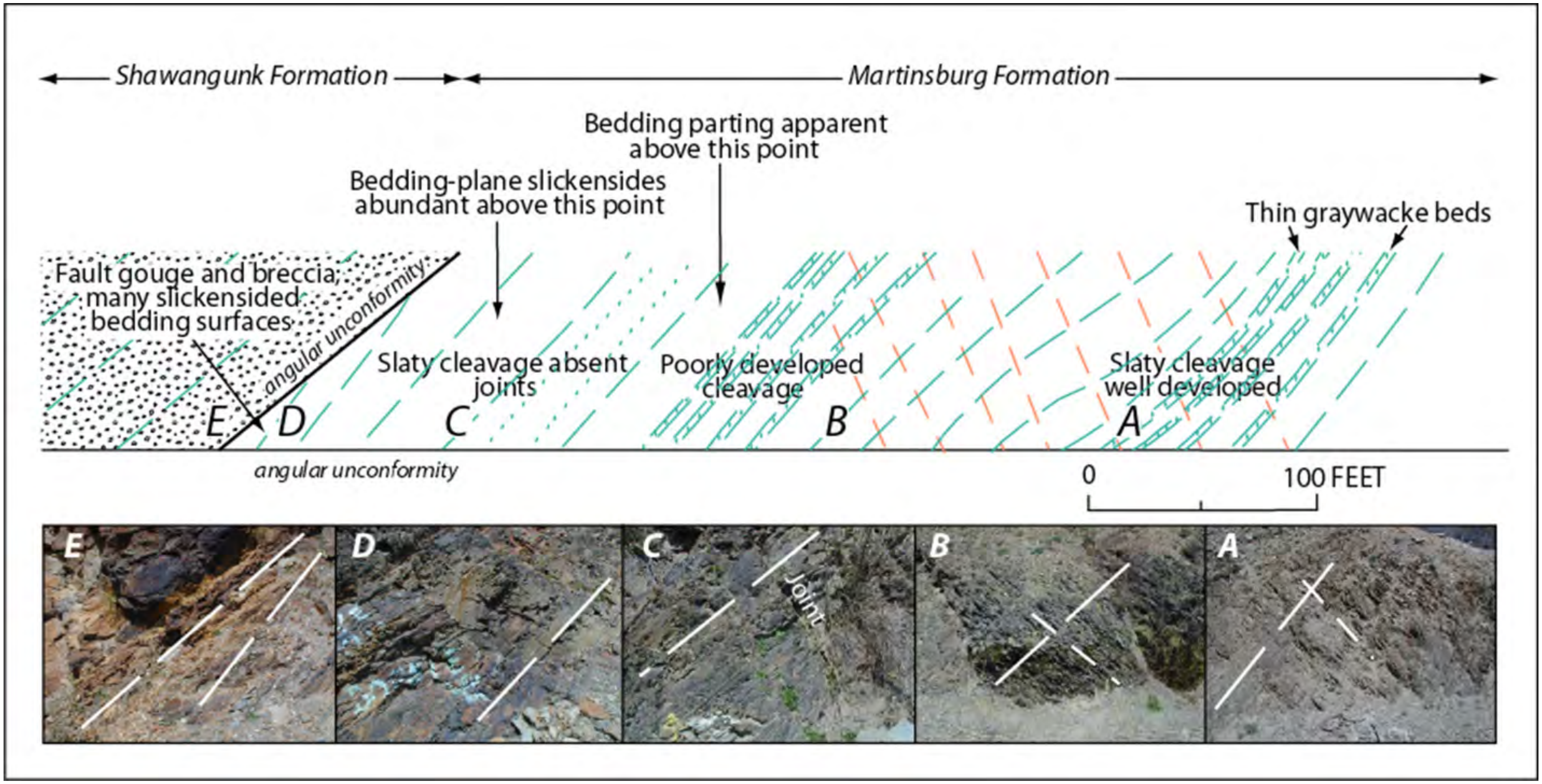


Figure 7. Diagrammatic geologic section through the Martinsburg-Shawangunk contact at Lehigh Gap, Stop 3, showing the dying out of the prominent slaty cleavage and increased development of bedding parting in the Martinsburg as the unconformable contact is approached. Bedding, long-dashed lines; cleavage, short dashed lines.

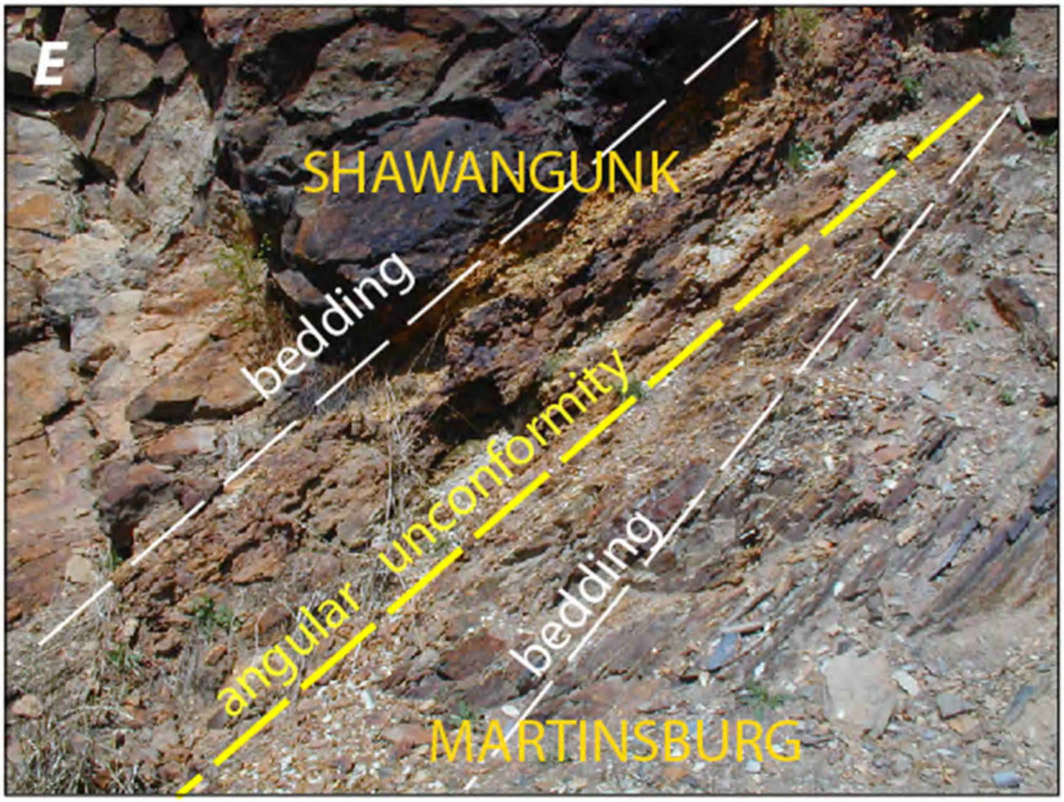


Figure 8 Closeup of Martinsburg-Shawangunk contact (also Figure 7E**). Note the absence of cleavage in the Martinsburg Formation.**

Figure 9: Bedding plane slickensides in the Martinsburg about 10 ft (3 m) below the contact with the Shawangunk formation. Pen points in direction of movement to the lower left.

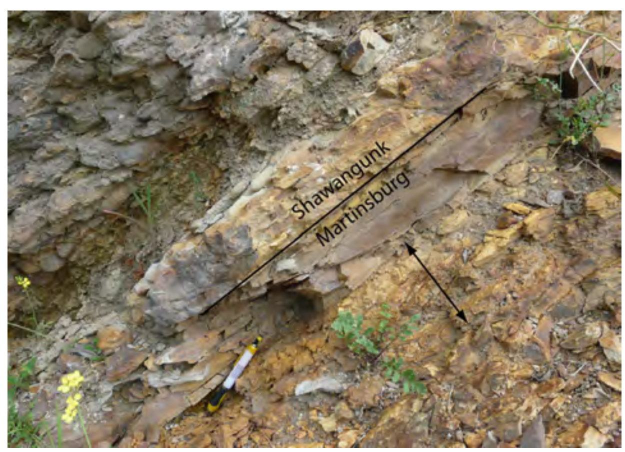


Figure 10. Shear zone about 8 in (20 cm) thick (arrow) underlying about 2 in (5 cm) of unsheared Martinsburg that is in contact with the overlying Shawangunk Formation. From bottom to top the zone consists of slickensided quartz and sheared slate (2 to 3 in [5 to 7 cm] thick), fault gouge of Martinsburg fragments as much as 2 in (5 cm) long in a clay matrix (2 in [5 cm] thick) , and breccia (3 to 4 in [7 to 10 cm] thick). Is this the Blue Mountain decollement?

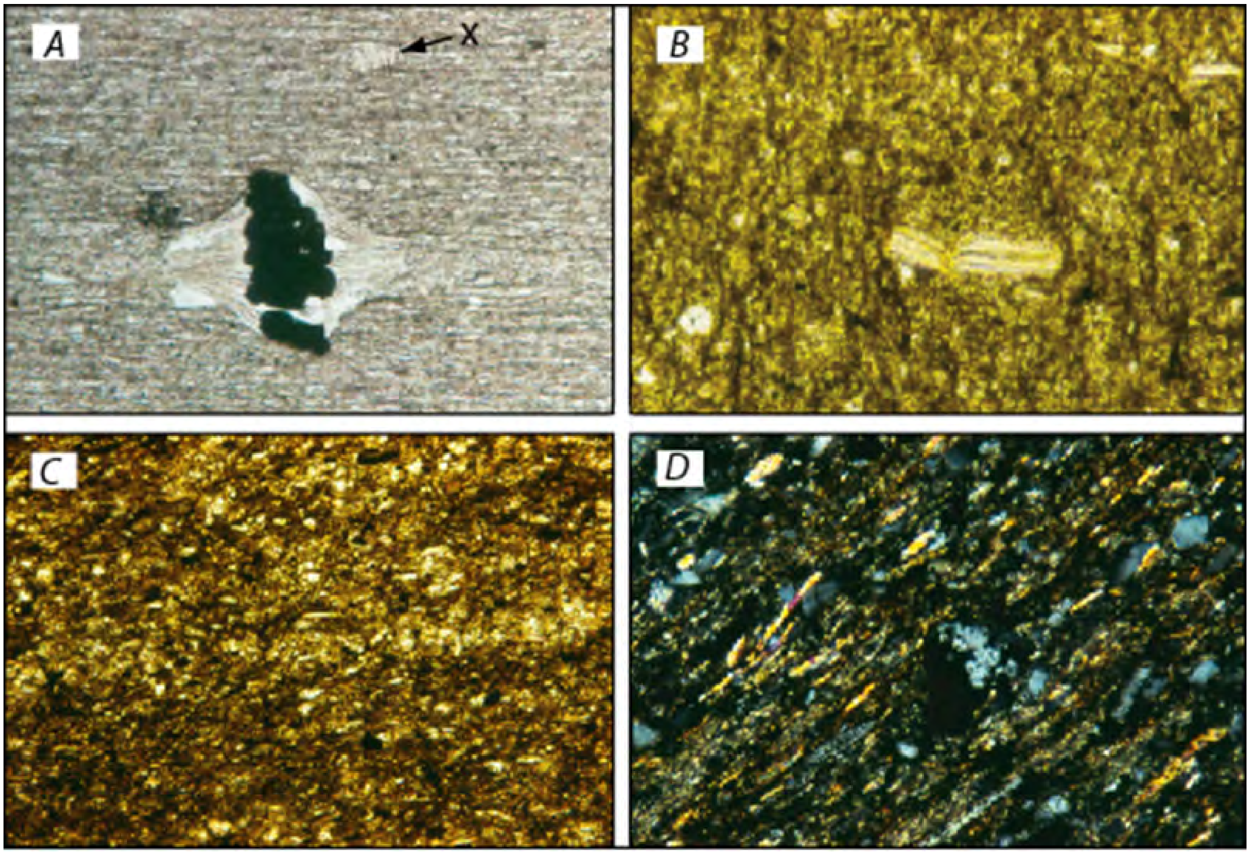


Figure 11.. Photomicrographs showing the slate to shale transition at Lehigh Gap and fissility in a typical shale. A - Slate from abandoned slate quarry about one mile south of Lehigh Gap. Slaty cleavage (dark folia) is horizontal; bedding is vertical and represented by alignment of black pyrite framboids. The cleavage folia are residual remnants of carbonaceous material due to dissolution of more soluble quartz and calcite. The growth of mica and chlorite around the framboids indicate the amount of solution that has taken place. New grains of intergrown chlorite and muscovite scattered throughout, as at x; B - Poorly developed cleavage (vertical in figure) about 120 ft (37 m) south of the Martinsburg-Shawangunk contact. Bedding is horizontal shown by the alignment of grains of mica. Note the "cutting" and warping of the large grain of mica by the cleavage; C - Sample about 10 ft (3 m) south of the Martinsburg-Shawangunk contact showing absence of slaty cleavage and horizontal bedding shown by thin quartz-rich beds and alignment of micas; D - Sample of a typical fissile shale with micas parallel to bedding and tilted to the left. Precambrian Nonesuch Shale, northern Michigan.

structures also indicating northwest movement of overriding beds (see Figure 10).

Not only is the dying out of cleavage obvious in the outcrop along the abandoned railroad, it is obvious under microscopic examination as well. In Figures 11A, B, and C, the decreasing mineral alignment forming the cleavage is apparent as the contact with the Shawangunk is approached. The mineral alignment that forms in bedding that has not been metamorphosed, should not be confused with cleavage (Figure 11D).

Slaty cleavage is a secondary structure, dependent upon microscopic mineral dissolution, growth, and reorientation, that allows a rock to be split along closely spaced planes, as we saw at Stop 2. Most pelitic rocks in this part of eastern Pennsylvania, regardless of age, have this secondary foliation. Microscopic and field relations of the cleaved rocks suggest that slaty cleavage formed by pressure solution of more soluble minerals along anastomosing folia, leaving behind a residuum of carbonaceous matter and iron oxides. This was accompanied by mechanical reorientation of platy and elongate minerals and by some new mineral growth.

Elongation of quartz and its removal from cleavage folia resulted from corrosion by pressure solution perpendicular to the cleavage direction. The cleavage folia are separated by more quartz-rich areas in which reorientation of platy minerals and dimensional alignment of prismatic minerals has not taken place, or is not as well developed.

Intensity of deformation in all Paleozoic rocks increases westward in easternmost Pennsylvania. Whereas slate extraction occurs only in the Martinsburg Formation along the Delaware River, commercial slates appear higher in the section near Lehigh Gap, where slate has been extracted from the Mahantango Formation of Devonian age, although now those operations have ceased (see Day 1 Road Log, Figure 19).

A second-generation "slip" cleavage is locally developed. It crenulates the earlier-formed slaty cleavage. Transposition of minerals into this new cleavage plane and new mineral growth are common, and in this respect it is similar to slaty cleavage. Commensurate with the increased development of slaty cleavage westward in northeastern Pennsylvania, slip cleavage appears higher in the Martinsburg, and in the Lehigh Gap area it is found in overlying formations, paralleling the increased development of the earlier slaty cleavage in younger units. Two cleavages (one a slip cleavage) occur in a 2-in (5-cm) thick argillite bed in the Shawangunk Formation about 50 ft (15 m) north of the contact (Figure 12). This exposure may have been decimated by the recent rockfall mitigation clean-up.

Figure 12. Two-in (5-cm) thick argillite bed in the Weiders Member of the Shawangunk Formation with slaty cleavage (medium-dash-line) and a later slip cleavage (short-dash line). The first cleavage may have formed in response to interbed shear with overrid-ing beds moving to the north (arrows) as suggested by bedding-plane slickensides. Pen points down in the direction of movement.

The dying-out of cleavage as the contact with the Shawangunk is approached is interpreted as a pressure-shadow (strain) mechanism (Epstein and Epstein, 1967,1969). In many places in eastern Pennsylvania, where small folds in interbedded fine-grained cleaved rocks adjacent to more competent rocks which are less cleaved, the slaty cleavage diverges around synclinal troughs and is either poorly developed or absent in the pressure-shadow area next to the trough (Figure 13A). This relationship is the same on a larger scale (Figure 13B), explaining the dying out of cleavage near the Martinsburg-Shawangunk contact here at Lehigh Gap (Figure 13B1). The steeper cleavage along the Pennsylvania Turnpike (Stop 6) (Figure 13B2), and the arching of cleavage 25 miles to the east at Delaware Water Gap (Figure 13B3) is also explained by this mechanism.

Blue Mountain Decollement: Is it real?

The folding in Paleozoic rocks in eastern Pennsylvania is disharmonic due to lithic variations within each unit (Epstein and Epstein, 1967; Epstein et al., 1974). These groups of rocks, called lithotectonic units, such as the Martinsburg Formation, the Shawangunk Formation and Bloomsburg Red Beds, and a multitude of thinner units of Upper Silurian to

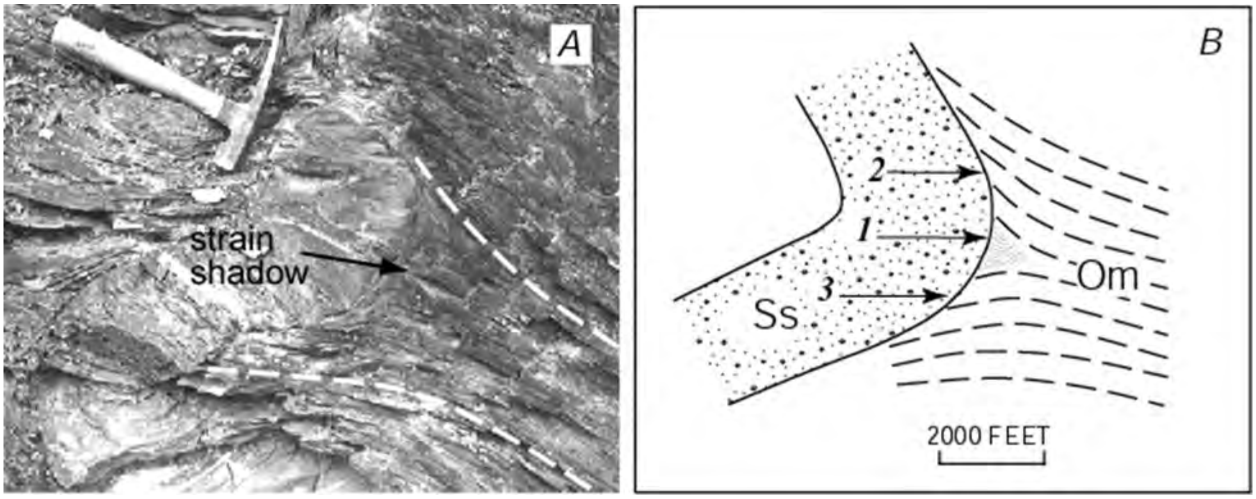


Figure 13. Strain shadows and arching of slaty cleavage in interbedded rocks at different scales and of different competencies. A - flattened folds near the base of Martinsburg Formation (Bushkill Member) along US Route 46, 1.8 mi (2.9 km) northeast of Belvidere, NJ, near the Delaware River. Cleavage (dashed line) in pelite diverges around the syncline in the more competent micaceous fine-grained dolomite and is less well developed in the strain shadow at the trough of the fold; B - generalized cross section showing trough of syncline in the competent Shawangunk Formation (Ss) and structural relations of cleavage in the Martinsburg Formation (Om) near the contact. The dying out of cleavage (1) is seen at Lehigh Gap at this stop. The steepening of the southeast-dipping cleavage (2) can be seen at the south portal of the Pennsylvania Turnpike 2 mi (3 km) to the southwest. The northwest arching of cleavage (3) is perfectly developed in the Delaware Water Gap area, 25 mi (40 km) to the northeast, to be seen at Stop 4, next.

Lower Devonian age, have different fold characteristics, including size and geometry of folds. The difference in shortening between adjacent lithotectonic units is believed to have been taken up in incompetent rocks along bounding discontinuities or decollements. Movement of overriding plates on the decollements was to the northwest, as interpreted from fold geometry and minor structural features. The Blue Mountain decollement is interpreted to separate rocks of the Martinsburg and Shawangunk Formations., such as the exposures here at Lehigh Gap along the abandoned Lehigh and New England Railroad grade (Figure 10). Here, the decollement is a zone about 8 in (20 cm) thick underlying about 2 in (5 cm) of unsheared Martinsburg that is in contact with the overlying Shawangunk Formation. It consists of slickensided rock, fragmental gouge, and breccias.

In the slickensided bed, northwest movement of overriding beds is indicated by small drag folds and faults (Figure 14) and by microscarps or steps on the slickensided surfaces. Relations between the slickensides, drag folds, and cleavage indicate that the cleavage developed synchronously with movement on the decollement. Because the movement is intimately associated with the position of the overriding Shawangunk, and because the dying out of the cleavage in the Martinsburg is regionally associated with proximity to the Shawangunk, the Shawangunk must have already been deposited before the cleavage formed. Therefore, the cleavage formation cannot be a Taconic (Ordovician) event, but must have been post Silurian in age, at least.

The sheared rocks in the decollement are weathered dark-yellowish orange (10YR5/6), reddish brown (10R3/4), and grayish red (5R4/2). They apparently were a zone for the movement of ground water. X-ray analysis of the fault gouge shows the clay-sized particles to

Figure 14. Negative print of thin section from 2- to 3-in (5- to 10-cm) thick slickensided interval in Blue Mountain decollement, 8 in(20 cm) below contact of Martinsburg and Shawangunk Formations at Lehigh Gap. Northwest is to the left. Dark laminae are folded and faulted quartz slickensides. The drag folds are overturned to the northwest and displacement of upper plates on small faults is to the northwest, corroborating the movement indicated by steps on slickensides. Long dashes are traces of slaty cleavage; short dashes are traces of slip cleavage. Absence of slaty cleavage in strain shadow at trough of fold (at A) and arching of cleavage of folded northwest limb of the fold suggest that cleavage developed synchronously with and slightly earlier than the folding but during the same deformation. Pelitic material is either intruded through the quartz slickensides at a steeper angle to cleavage in the surrounding shale and parallel to the axial planes of the folds (at B), or it is residuum due to pressure solution in the axes of the folds. Note divergent fanning of cleavage on either side of the fold trough. From Epstein et al., 1974, p. 248.

be

Figure 15. Fault in sandstones and conglomerates of the Shawangunk. Arrows indicate movement directions. The rocks here were coated with soot from trains long departed.

quartz, muscovite, and kaolinite. The kaolinite apparently developed by weathering at the expense of chlorite, which is present in unweathered Martinsburg rock.

A small normal fault may be seen in the Shawangunk about 250 ft (76 m) north of the contact with the Martinsburg (Figure 15).

Bedding Slippage, Wedging, And Telescoping In The Bloomsburg Red Beds

Not only are there bedding-plane slippage in the Martinsburg, but they are common in the Shawangunk and especially in the Bloomsburg Red Beds. If you look about 0.75 mi (1.2 km) to the northwest , you will see steeply dipping to vertical on the northwest limb of an overturned anticline (see Figure 6). The Bloomsburg Red Beds of Middle Silurian age is 3,500 ft (1,067 m) in the Lehigh Valley and consists of many fining-upward cycles comprising crossbedded sandstones with mud clasts at the base, rippled to unevenly bedded shaly siltstones and sandstones in the middle, and indistinctly mudcracked and bioturbated shaly siltstones, locally with dolomite concretions, at the top (Figure 16). These are interpreted as meandering stream deposits of a low alluvial coastal plain. At this locality, 900 ft (274 m) of red beds are exposed; the total thickness of the Bloomsburg is estimated to be 1,500 ft (457 m).

The bottom of many of the sandstones are slickensided and direction of steps indicate that the overriding beds moved down to the northwest (Figure 17). Wedges (mini “ramps”) and rotated cleavage corroborate this sense of movement (Figure 18). Figure 19 illustrates the

Figure 16. Bloomsburg Red Beds exposed in 1970 south of Palmerton, Pa. Fining-upward cycles of basal fine- to medium-grained sandstone (lighter color) grade up through siltstone into mudstone.

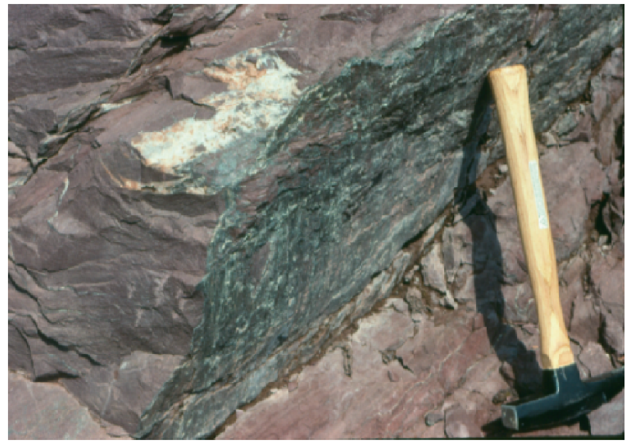


Figure 17. Green (chloritic) slickensides on basal sandstone bedding plane with steps showing movement of overriding beds down to the northwest (left).

Figure 18. Bedding-plane fault (long dashed line), rotated bedding wedge (solid line) and rotated cleavage (short dashed line) showing northwest downward translation of overriding beds.

movement sense on these structures. There are a very few wedges which indicate a reverse sense of movement, up to the southwest. The predominant translation to the northwest is similar to movement seen in the Martinsburg at its unconformable contact with the Shawangunk in Lehigh Gap (see Figure 8).

In the exposed section, 128 planes of bedding slippage were counted, so that the total number of such planes in the entire formation is certainly greater. The net telescoping could be thousands of feet (hundreds of meters) of total northwest translation from the bottom of the bedding-

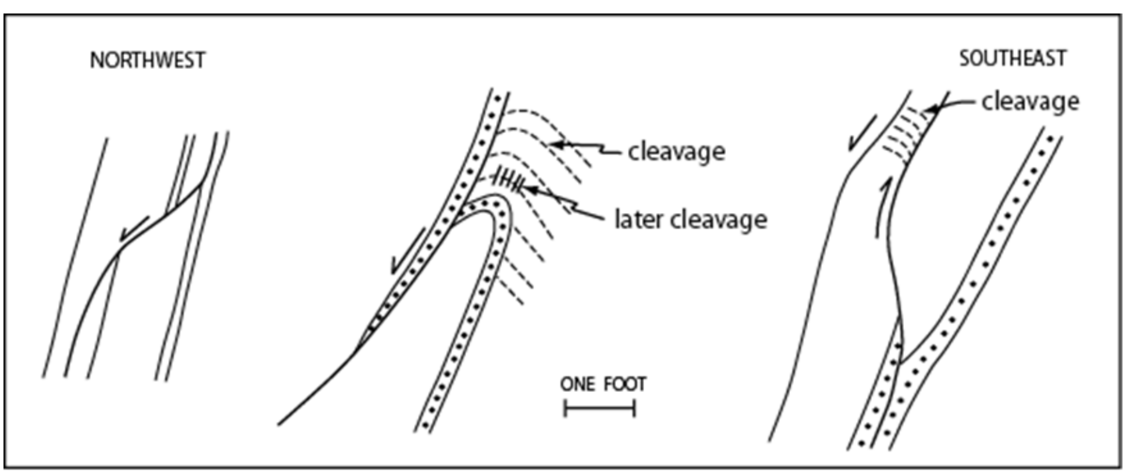


Figure 19. Diagrammatic sketches of wedges, bedding-slip faults, and rotated cleavage in the Bloomsburg Red Beds immediately south of Palmerton, Pa.

Figure 20. View of the Shawangunk-Martinsburg contact at the lonely tree in right picture (from Willard, 1938). It was built in1912, leaving a pinnacle of hard rock on the west (left) side, overlooking the road below (http://www.gingerb.com/lehigh_gap_station.htm; accessed 9/19/2012). That pinnacle was removed sometime before 1967 when the bridge was dismantled.

deck-of-cards to the top. In about all instances the overriding beds have moved down-dip or up -dip to the northwest.

Rockfall Hazard At Lehigh Gap

New Jersey Zinc Corporation began smelting zinc at Palmerton in 1898 and terminated that industry in 1981. Forest denudation caused by drifting plumbs laden with Cadmium zinc, lead, and sulphur dioxide exasperated slope stability. Attempts to mitigate the slope instability, two engineering projects have recently been initiated.

Collapse of blocks of boulders from the Shanagunk Formation that precariously is aligned with the cantilevered four lane highway PA 248 has caused a major problems for drivers below. One engineering project was initiated to minimize the hazard. The railroad and a trestle bridge that crossed the Lehigh River, was built by the Lehigh and New England Railroad Company in 1912. It was abandoned and later was removed in 1967 (Figure 20).

Rock fences, wire netting, and steel rope were used to mitigate the rockfall within the ouctcrop area of the Minsi member of the Shawangunk formation, 200 ft (61 m) north of the Ordovician-Silurian contact (Figure 21).

Figure 21. Rock fence installed in the contact area between the Minsi and Weiders Members of the Shawangunk Formation , about 200 ft (61 m) north of the Ordovician-Silurian contact. This is an area of abundant loose talus blocks, possibly within an area of faulting (Porto and Petrasic, 1996, fig. 23).

The Appalachian Trail traverses the northern slope of Blue Mountain at Lehigh Gap. In 2010 the National Park Service responded to the need for abating continuing contamination and the rockfall hazard at Lehigh Gap, initiated an engineering project funded under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, also known as Superfund; **http://www.nps.gov/appa/parkmgmt/upload/May-2010-LehighGapProject-FactSheet.pdf)** . A variety of engineering techniques were used, including draped wire mesh, rockfall

Figure 22. Wire mesh drapes cover much of the south slope of Blue Mountain in Lehigh Gap. Arrows points to Ordovician-Silurian contact. View taken across the Lehigh River from the Lehigh Gap Nature Center.

Figure 23. Much of the Shawangunk is covered in wire mesh drapes. Part of the Martinsburg in the foreground is also covered to prevent shale-chip spalling onto the roadbed.

protection fences, rock bolts, and others (Smerekanicz, 2011). Much of the slope above the unconformity is cloaked in wire mesh (Figures 22 and 23)

Bedrock instability is favored by a variety of fractures and parting planes in bedrock, such as joints, bedding, and cleavage. The relation of slope to the orientation of these fractures, as well as the type of geologic material, is important in determining the potential for failure. The orientation of joints, which controls the direction that the sandstones and conglomerates break at Lehigh Gap, has created actual and potential slope instability. Joints are a natural consequence of folding of rocks; they generally form in distinct sets, especially in the hard competent rocks in the Shawangunk Formation.

Figure 24 shows the general orientation of longitudinal and cross joints in eastern Pennsylvania. The longitudinal joints strike (trend) northeast and the cross joints are approximately perpendicular to them, aligned through the topography at right angles. The cross joints are planes of weakness which are sought out by streams to carve their valleys. Water gaps, such as Lehigh Gap, form in localities of abundant fractures. Folds are produced by compression as crustal plates collide. Longitudinal joints form at right angles to the direction of maximum compressive stress and are generally smooth, whereas cross joints are pulled apart by tension and are more irregular. The confining pressure against cross joints may be lessened by rapid erosion of rock along streams or by the excavation of rock, such as during highway construction. This may cause rock masses to move outward and become a rockfall hazard, as has happened here along PA 248 in Lehigh Gap.

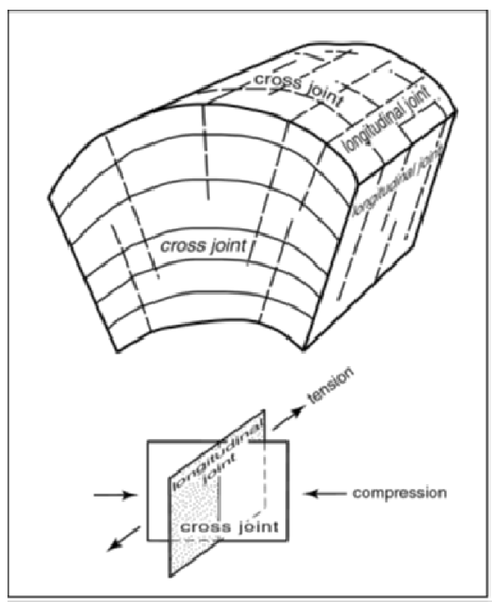


Figure 24. Diagram showing orientation of longitudinal and cross joints in folded rocks typical of the Appalachian Valley and Ridge province.

PA 248 is cantilevered between two railroads as it enters the Lehigh Gap (Figure 25A), one to the west near the Lehigh River, and the other on the slope 90 ft (27 m) above, abandoned a few years after the highway was completed in 1960. Individual falling rocks and slumping of shale and slate along the upper railroad grade were a recurring problem, although not as serious as the potential of rockfalls initiated along cross joints immediately above the highway. The rocks of the Martinsburg Formation break the rock into small fragments controlled by bedding, cleavage, and joints, leading to spalling from the steep face above the railroad grade. Gabions were erected to prevent this material from falling on the road below (Figure 2), and more recently rock bolts and mesh sheeting were installed, as described bove.

The cross joints are irregular to roughly planar (Figure 25B, C, and D). A diagram showing the trend of joints in sandstone and conglomerate of the lower Shawangunk Formation is shown in Figure 26. Longitudinal joints parallel the trend of the mountain, averaging about N68°E, and the cross joints trend about N20°W. The abandoned railroad and the highway below parallel the cross joint trend. The joints break the Shawangunk into blocks as much as

Figure 25. Rockfall hazard due to cross fractures along PA 248 and abandoned railroad grade in Lehigh Gap. A - Northbound lane of the highway, as it appeared in 2000, is cantilevered above the southbound lane beneath the contact between the Shawangunk Formation (Ss) and Martinsburg Formation (Om). The location of the highway was constrained by a railroad along the Lehigh River to the left and a railroad, now abandoned, above. A wire-meshed gabion (arrows) lines the edge of the railroad grade to protect against falling rocks; B - Cross joints in the Shawangunk Formation (arrow) opening parallel to the abandoned railroad grade, Lehigh River below; C - View of cross joints from highway below. Some of the rock has been removed subsequent to taking this picture in 1990; D - Cross joints in the Shawangunk Formation parallel the highway below.

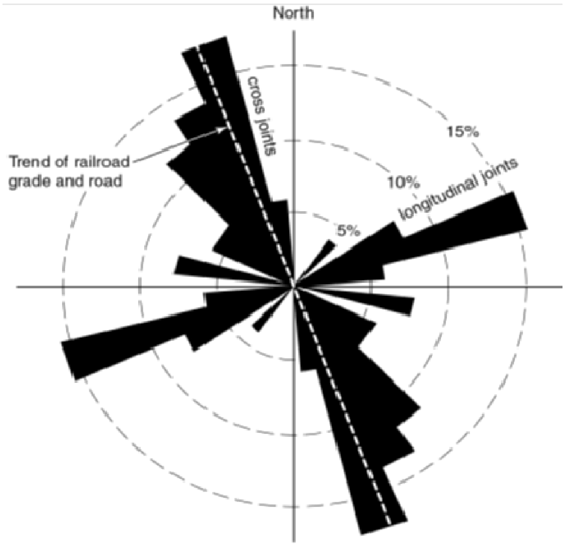


Figure 26 Rose diagram showing strike of 52 joints at Lehigh Gap, 29 mi (47 km) southwest of Delaware Water Gap. Dashed line shows trend of the abandoned railroad grade above PA 248.

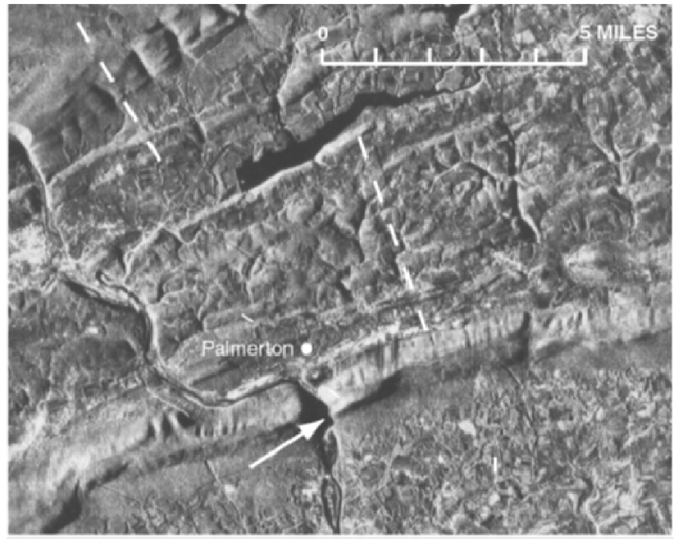


Figure 27. Radar image of the Lehigh Gap area showing location of the rockfall hazard along PA 248 south of Palmerton, PA (arrow) and fracture control of many of the NNW-trending lineaments (dashed line). From Newark, NJ; PA; NY radar mosaic.

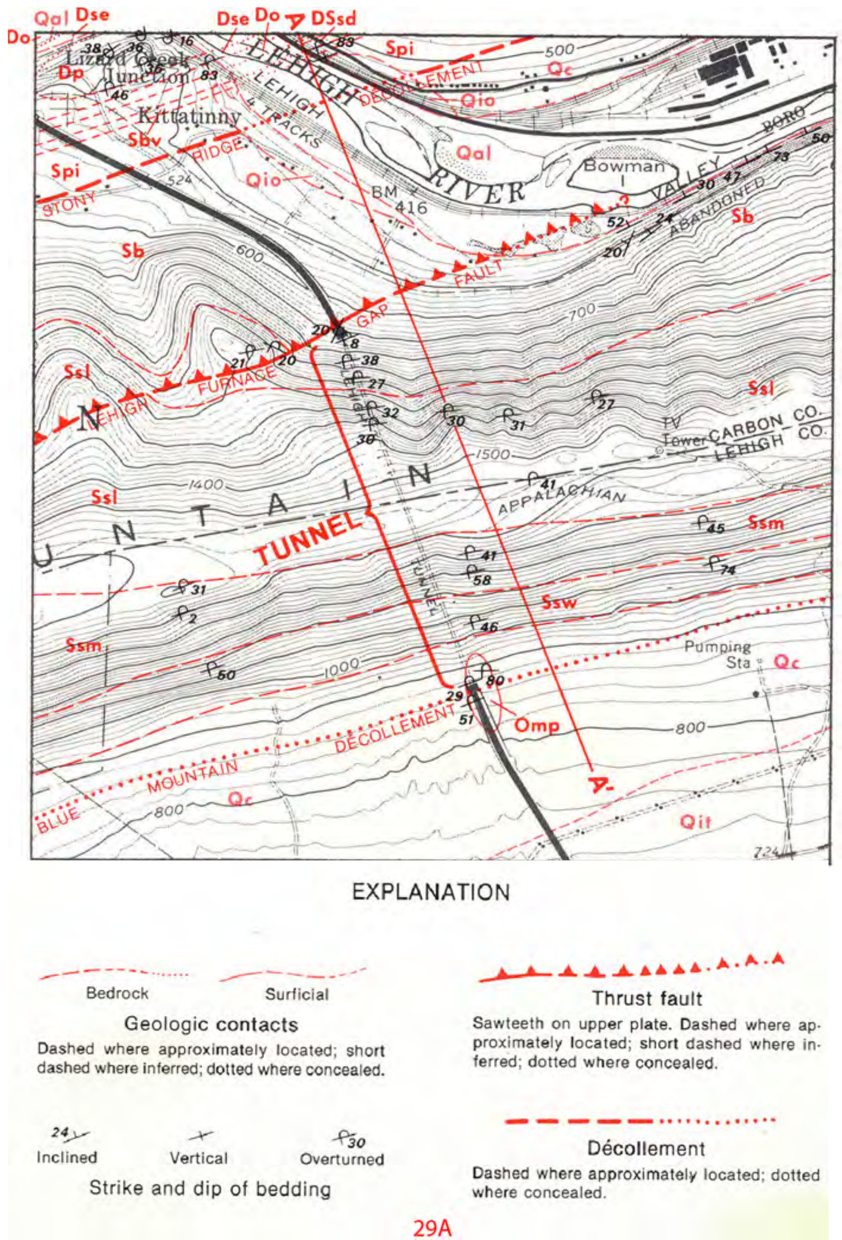
10 ft (3 m) long, each weighing many tons. Outward movement from these fractures were noted in 1989, and, because of the potential for these rocks falling on the highway below and because the site is adjacent to the Appalachian National Scenic Trail, the National Park Service requested the Federal Highway Administration to analyze mitigation procedures. These are discuss above.

The cross fractures recorded at Lehigh Gap are exactly similar to those in the larger surrounding area (Epstein et al., 1974, p. 271). Figure 27 is a radar image of the region in which many lineaments define the cross-fractures. Many streams, gullies on mountain fronts, and sections of the Lehigh River, including that at Lehigh Gap, are controlled by these cross fractures. An appreciation of these structures and their orientation in relation to roads and other constructions is important to avoid potential future slope instability problems.

Geology of the Second Lehigh Tunnel Through Blue Mountain Northeast Extension of the Pennsylvania Turnpike

(Modified from Epstein and Buis, 1991)

The Northeast Extension of the Pennsylvania Turnpike (Pennsylvania Route 9) is a major traffic artery in eastern Pennsylvania, extending for 110 mi (177 km) from the Pennsylvania Turnpike (Interstate Highway 276) near Philadelphia northward to Scranton. Prior to construction of the second tunnel in 1991, the four-lane highway narrowed to two lanes as it approached Blue Mountain, a nearly 1,000-ft (305-m) high ridge at the boundary of Lehigh and Carbon Counties, about 13 mi (21 km) north of Allentown and 1 mi (1.6 km) southwest of Palmerton. This constriction was the cause of miles- (kilometers-) long traffic jams, especially during the summer months, when vacationers visit the Pocono Mountains. In February 1989, construction began on the second two-lane tunnel immediately west of the original. Prior to opening, the tunnel had a projected cost of $37.8 million and required the excavation of an



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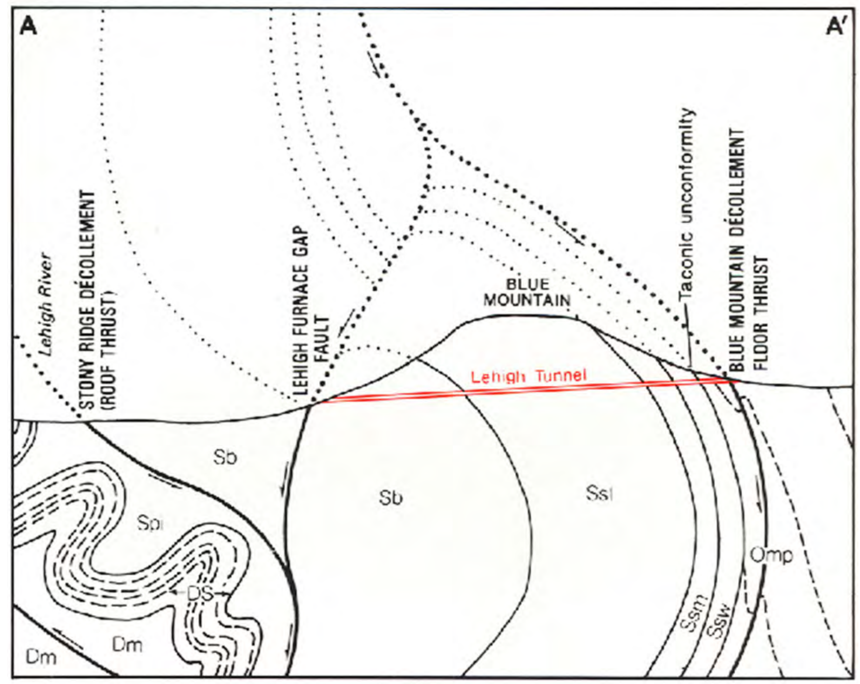

29B

Figure 28. Geologic map and cross section at the site of the Lehigh Tunnel (modified from Epstein et al., 1974). Left—Bedrock geologic map; Right—Geologic cross section. Dashed lines in cross section show bedding within stratigraphic units; dotted lines show contacts projected above ground. Omp, Pen Argyl Member of the Martinsburg Formation; Ssw, Weiders Member of the Shawangunk Formation; Ssm, Minsi Member of the Shawangunk Formation; Ssl, Lizard Creek Member of the Shawangunk Formation; Sb, Bloomsburg Red Beds; Spi, Poxono Island Formation; DS, various units of Late Silurian and Early Devonian age; Dm, Marcellus Formation; Qit, pre-Illinoian till; Qio, pre-Illinoian outwash; Qc, colluvium; Oal, alluvium.

estimated 200,000 yd^3 (152,911 m^3) of material from Blue Mountain. It was completed and opened for traffic in fall 1991.

Blue Mountain is part of a nearly continuous ridge that forms a natural barrier to the north and west of the Great Valley physiographic section through Pennsylvania from New Jersey into Maryland and beyond. At the tunnel site, slates and graywackes of the Martinsburg Formation are present at the south portal, succeeded northward by Silurian quartzites, conglomerates, and shales of the Shawangunk Formation and then by red and green sandstones, siltstones, and shales of the Bloomsburg Red Beds. These are further succeeded northward by a variety of Silurian and Devonian strata (Figure 28, left). These rocks were complexly deformed during the late Paleozoic Alleghanian orogeny. The Martinsburg Formation was also affected by earlier Taconic (Ordovician) deformation and is separated from the younger Shawangunk Formation by an angular unconformity of regional extent. The orogenic episodes created folds, faults, cleavage, joints, surfaces of movement with slickenlines, and a variety of fractures filled with secondary quartz, calcite, and chlorite in the various units. At the unconformity in the tunnel, the Martinsburg is overturned and dips 35^o to the southeast, whereas the Shawangunk dips more steeply by 10^o and is also overturned to the southeast. No displacement has taken place at this contact or in adjacent rocks, as is evidenced at the contact exposed at Lehigh Gap, 2 mi (3 km) to the northeast (see Stop 5). At the north portal, the rocks of the Bloomsburg Red Beds have been rotated past 180^o so that they are overturned and dip to the northwest, as does the cleavage (Figure 28, right; Epstein and Epstein, 1969; Epstein et al., 1974).

A topographic bench at an altitude of 1,100 ft (335 m) on the north slope of the mountain, 0.4 mi (0.7 km) west of cross section A-A', marks the position of an imbricate thrust fault at which the overriding beds have been moved up to the northwest and subsequently folded so that the hanging wall is presently down to the northwest. The structure, the Lehigh Furnace Gap fault (Figure 28, right), was shown in cross section by Epstein et al. (1974) to cut bedding at very high angles. However, because the fault lies at a very low angle to the structural grain (Figure 28, left), the fault is reinterpreted to be an imbricate fault that ramps up from a thrust subparallel to bedding in the Martinsburg Formation (Figure 28, right). Several similar ramps have been mapped in the New Tripoli and New Ringgold quadrangles to the west, and the entire fault system in the Shawangunk Formation and Bloomsburg Red Beds is now interpreted as a duplex. The ramps join the floor thrust in the Martinsburg with a roof thrust in the Bloomsburg, as depicted in Figure 28, right. The roof thrust is not exposed, but it is interpreted to be present in the upper part of the Bloomsburg concealed beneath the valley of the Lehigh River.

The new Lehigh Tunnel passed through a fault zone, which is believed to be the floor thrust in the Martinsburg, about 350 ft (107 m) south of the contact with the Shawangunk Formation and 90 ft (27 m) north of the portal entrance in January, 1990. This zone is about 27 ft (8 m) wide and contains intensely sheared and rotated rocks with abundant quartz veins (Figure 29). The rocks are heavily slickensided (Figure 30), movement directional trends on the slickensides are variable. The contact between the shear zone and non-sheared rock is fairly abrupt (Figures 30 and 31). Cleavage is absent outside the shear zone and the rock breaks readily along bedding surfaces. Because the rocks in the shear zone broke along the irregular fractures, a backhoe-mounted jack hammer was used to clear irregularites prior to installing shotcrete.

If time permits, the group can examine the shear zone on the surface behind the maintenance building (see Figure 32).

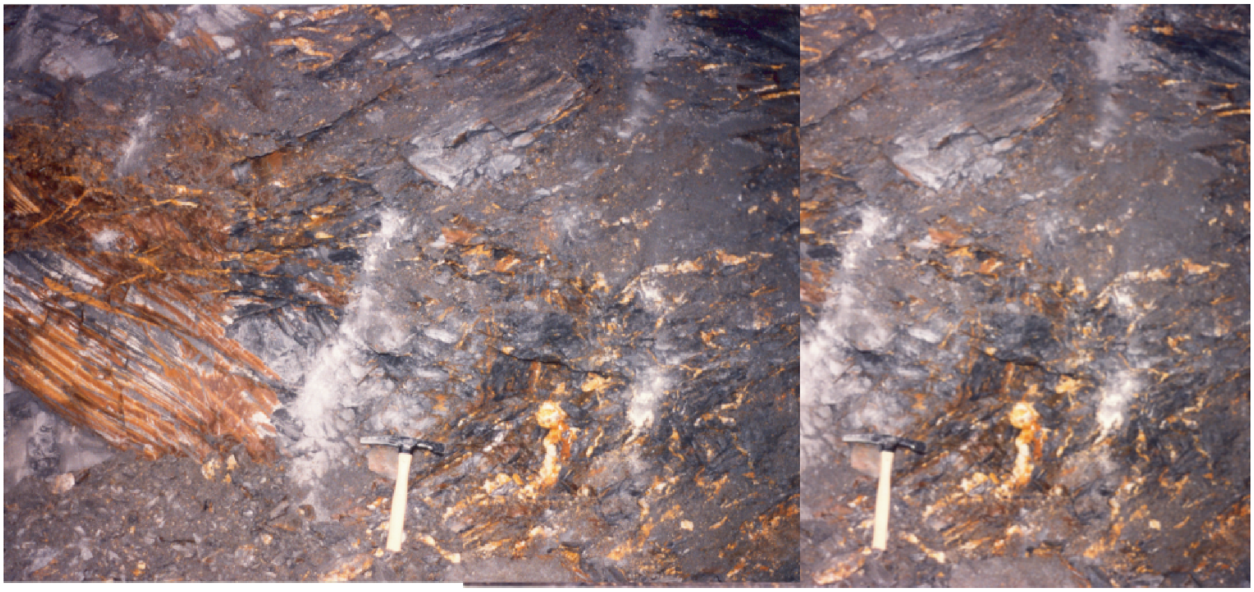

Figure 29. Stereo pair of part of the 27-ft (8-m) wide shear zone in the Martinsburg Formation showing rotated blocks of rock and abundant variously oriented quartz veins.

Figure 30. Close-up of slickensides in the Martinsburg shear zone.

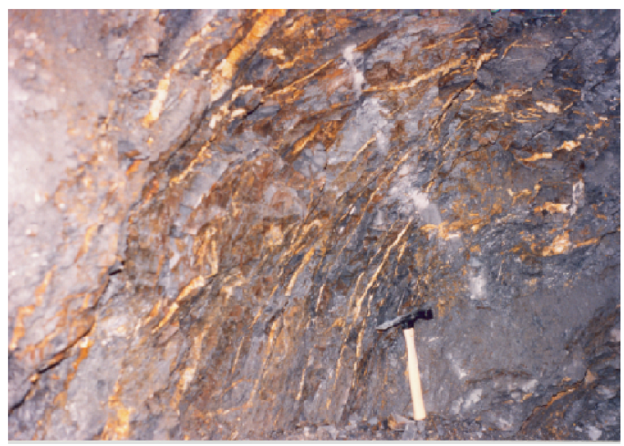

Figure 31. Fairly abrupt southernmost contact between Martinsburg pelite on the upper left with the 27-ft (8-m) wide quartz-veined shear zone, 90 ft (27 m) north of the south portal entrance.

Figure 32. Closeup between shear zone and bedded pelite of the Martinsburg Formation.

If this shear zone is, in fact, the floor thrust of a duplex, it must extend for many miles (kilometers) to the northeast and southwest, parallel to the south slope of Blue Mountain. However, it has only been seen in the tunnel; elsewhere the strata that would contain it are buried by thick colluvium and glacial deposits. The floor and roof thrusts may coincide with detachments that have been interpreted to separate lithoteconic units of differing structural characteristics – the Blue Mountain decollement and Stony Ridge decollement, respectively (Figure 28, right).

Welded wire fabric and spilling pipes at the top are part of the "shotcrete" canopy used to reinforce the tunnel crown and protect the tunnel opening, especially in the fault zone (Figure 33). The fault zone in the Martinsburg is exposed above the tunnel portal, preserving some of the structures seen in the tunnel, now all buried behind shotcrete (Figure 34).

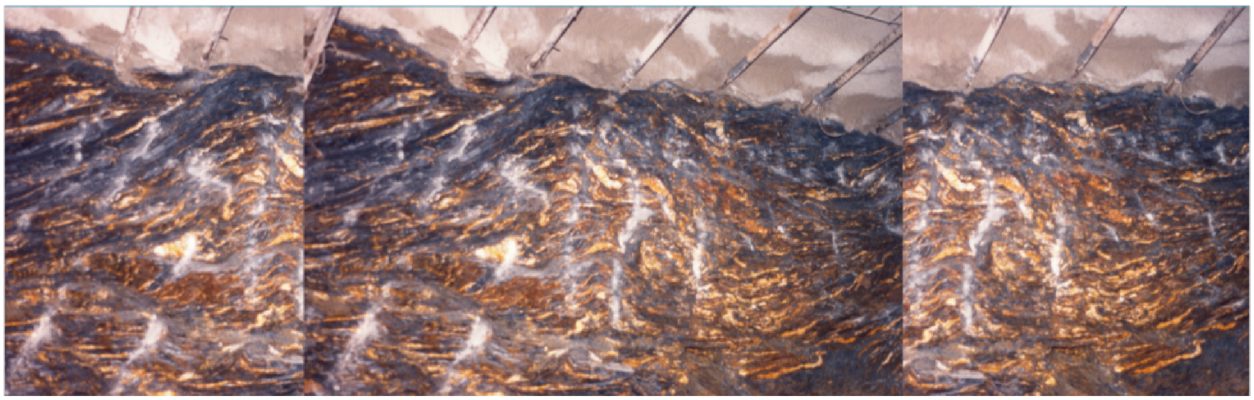

Figure 33. Stereo triplet showing shear zone in the Martinsburg Formation exposed in the second Lehigh Tunnel on January 24, 1990, believed to be the floor thrust of a duplex in the Shawangunk Formation and Bloomsburg Red Beds.

The geologic structures found in Blue Mountain created a variety of problems for tunnel construction. An innovative European engineering technique, the New Austrian Tunneling Method (NATM), was used to cut through these rocks. NATM differs from other tunneling techniques in several ways. The tunnels are lined with strengthening material, including rock bolts, welded wire mesh, and lattice girders, immediately after a few feet are excavated, and covered with pneumatically emplaced concrete, or "shotcrete" (Associated Pennsylvania Constructors, 1989). The advantage of this technique is that the rock mass surrounding the tunnel becomes self supporting, so the need for conventional steel support beams is eliminated, thus reducing the costs of construction significantly. Because of this process, the final cross-sectional shape of the tunnel is elliptical, rather than the conventional parallel-sided horseshoe shape (Figure 35).

Figure 34. Shear zone exposed behind the south maintenance building showing disrupted bedding, variable directions of slickensides, and abundant quartz veins.

As part of NATM procedures, continuous pressure and convergency readings must be taken during the tunneling to monitor rock

Figure 35. A - South portal of the second Lehigh Tunnel excavated in the Martinsburg Formation, glacial drift, and colluvium. Bedrock dips approximately 40° and is overturned to the southeast; B - North portal excavated in the Bloomsburg Red beds. Bedding is overturned and nearly recumbent. Note the elliptical shape of the tunnel bore, a diagnostic feature of the New Austrian Tunneling Method.

behavior. These readings gauge the amount of support needed at any particular location in the tunnel. Overall, the Martinsburg Formation has required the most support and the Shawangunk Formation the least. However, variations in local rock characteristics have prevented setting definite support limits for each rock unit.

Excavation of the tunnel proceeded from both sides of the mountain and was guided by laser beams positioned by satellite telemetry. The tunnel "holed through" on June 13, 1990, and Ken Pukita, the project manager, noted that the two laser beams coming in from opposite ends of the tunnel were off by only a couple of inches.

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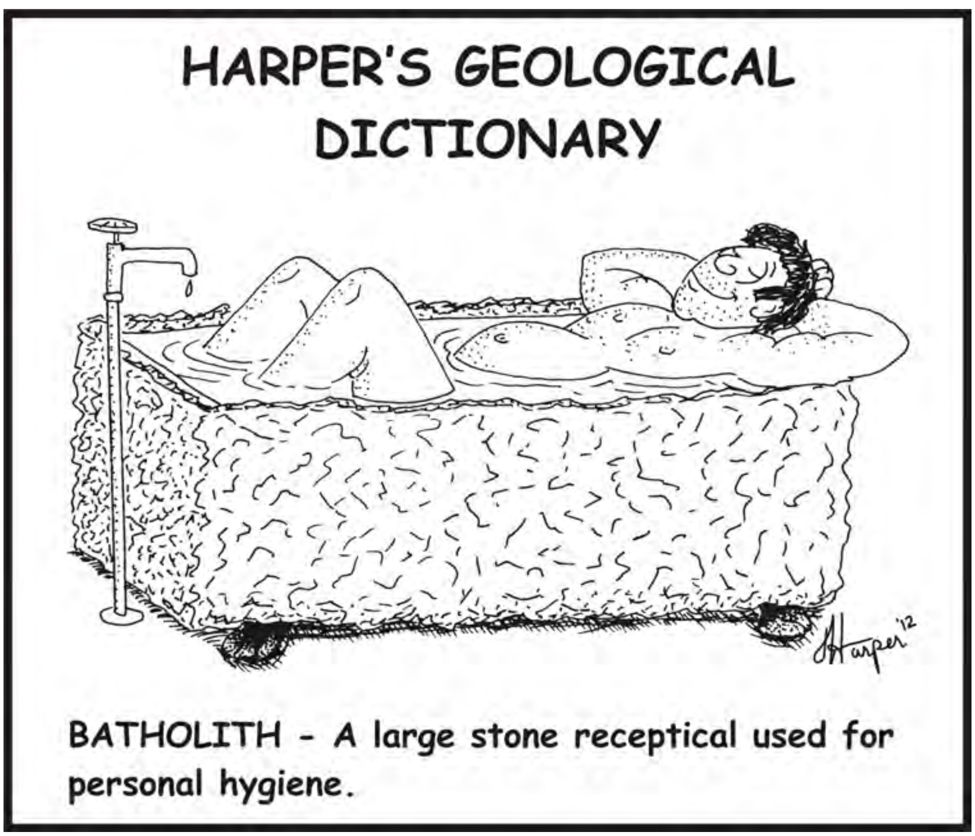

STOP 4: DELAWARE WATER GAP

Point Of Gap Overlook; Structure, Stratigraphy, Glacial Geology, Geomorphology

Leader: Jack Epstein

The Delaware River is the longest free-flowing river in the eastern United States. Its branches begin north of Hancock, NY, winding south through Delaware Water Gap National Recreation (DEWA) area (Figure 1), flowing past Trenton, NJ, at tide water, and ending in Delaware Bay, a distance of 410 mi (660 km) to the south shore of New Jersey, at Cape May. The river has witnessed many dramatic human events and has been the site of numerous geologic controversies. At this stop we will discuss aspects of structural geology (including timing of deformation and origin of slaty cleavage), stratigraphy, glacial geology, paleontology, and environmental issues that have been in both the regional and national geologic spotlight. Without detailed mapping by both State and Federal geologists, many of the conclusions presented here could not have been possible.

Figure 1. Entrance to Delaware Water Gap as viewed from atop Kittatinny Mountain; Pennsylvania on the right, New Jersey on the left. The Delaware River flows through the constricted gap behind the view, and as it widens into the valley beyond and its velocity lessens, it deposits a streamlined bar, Arrow Island. Between the mountain, held up by quartzites of the Silurian Shawangunk Formation, and the Precambrian metamorphic rocks of the New Jersey Highlands in the distance, lies Paulins Kill Valley, underlain by Cambrian and Ordovician limestone and slate. Coarse gravels in a Wisconsinan outwash terrace lines both sides of the valley south of the gap.

The scenic allure of DEWA draws people from several major population centers, totaling more than 30 million people within the heart of the northeast United States urban corridor and is presently the sixth most heavily visited NPS facility in the country. It includes a scenic and mostly undeveloped 40-mi (64-km) stretch of the Delaware River between Port Jervis, New York, and the world-famous Delaware Water Gap in New Jersey and Pennsylvania (Figure 2). It straddles the Pocono Plateau on the northwest, underlain by gently inclined Devonian sandstones and shales, and complexly folded Ordovician to

Figure 2. View, looking eastward of Delaware Water Gap showing The difference in height of Mt. Tammany and Mt. Minsi, related to the arching of Mt. Minsi as discussed below. Location of Resort Point (Stop 4A) and Stop 4 (hidden behind Mt. Minsi) are shown. National Park Service photograph partly annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

Epstein, Jack, 2012, Stop 4: Delaware Water Gap, *in* Harper, J. A., ed., Journey along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and southeastern New York: Guidebook, 77th Annual Field Conference of Pennsylvania Geologists, Shawnee on Delaware, PA, p. 272-291.

Devonian rocks of the Valley and Ridge to the southeast. The stratigraphic sequence spans about 65 million years, not counting the more recent Pleistocene and younger sediments. Wisconsinan glacial erosion and deposition resulted in a varied scenery. The present Delaware River has cut through a silt and sand terrace that was occupied by American Indians about 11,000 years ago. The application of our geologic efforts emphasizes scientific interpretation, land-use planning and management, points of scientific interest to be enhanced or protected (paleontologic, structural, geomorphic, stratigraphic, glacial, economic resources), landslide susceptibility, facility location and trail design, the park's GIS data base, scientific interpretation for both park personnel and the public, preparation of geologic exhibits, and general-interest publications including nature trail guides. Results of geologic investigations efforts can be effectively utilized by the Park Service only by making our data readily available and avoiding jargon. One of the geologic field guides prepared for the 2001 Field Conference may be used as a pre-trip for this session.

Stratigraphy

Delaware Water Gap owes its notoriety to the depth to which the river has cut through Kittatinny Mountain. Exposures of 3,000 ft (914 m) of Silurian clastic rocks are nearly continuous; the entire Shawangunk Formation, with its three members, and most of the Bloomsburg Red Beds are visible (Figure 3). To the west, in central Pennsylvania, the Shawangunk merges into the Tuscarora Sandstone below and the Clinton Formation above, seen at Stop 1. To the east, in New York State, as seen from the heights of High Point at Stop 8, the Shawangunk thins and just beyond it disappears. Eastward, the Bloomsburg likewise pinches out. The Bloomsburg has been erroneously called the High Falls Shale in the past. The High Falls of New York State is actually a facies of the Poxono Island Formation which overlies the Bloomsburg. Immediately below the Shawangunk is the Martinsburg Formation (Epstein, 1993). The following are details from the 2001 field Conference (Epstein, 2001).

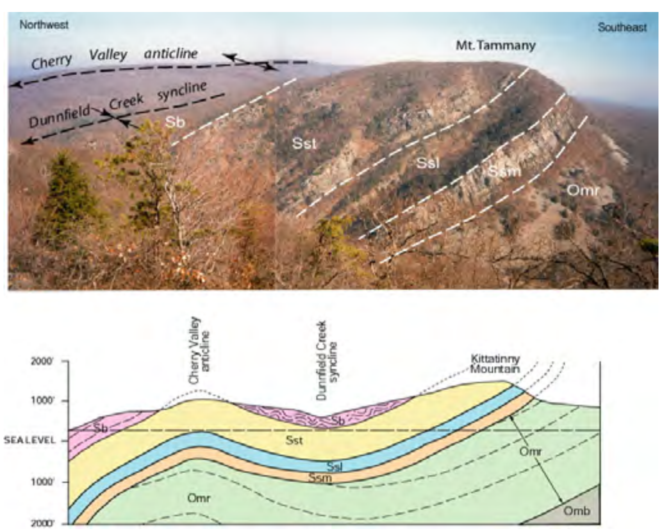

Figure 3. Delaware Water Gap in New Jersey as viewed from atop Kittatinny Mountain (Mt. Minsi) on the Pennsylvania side. Omb, Bushkill Member of the Martinsburg Formation; Omr, Ramseyburg Member of the Martinsburg Formation; Ssm, Minsi Member of the Shawangunk Formation; Ssl, Lizard Creek Member of the Shawangunk Formation; Sst, Tammany Member of the Shawangunk Formation; Sb, Bloomsburg Red Beds. Small-scale folds in the Bloomsburg are located only in the Dunnfield Creek syncline. The angular discordance at the Ss-Om Taconic contact is about one degree as seen during highway construction

The Martinsburg is more than 15,000 ft (4,572 m) thick in eastern Pennsylvania, consisting of three members: a lower Bushkill Member of thin-bedded slates, middle Ramseyburg Member with abundant greywacke packets, and an upper Pen Argyl Member with medium- to thick-bedded slate and some greywacke (Drake and Epstein, 1967). These sediments were deposited in a rapidly subsiding flysch-turbidite basin (Van Houten, 1954) formed during Middle Ordovician continental plate collision. The highland source for the Martinsburg was “Appalachia” to the southeast, and the sediments covered a foundered Cambrian and Ordovician east-facing carbonate bank. The graywackes were probably deposited in submarine channels and were triggered by earthquakes during the Ordovician. The contact between the Pen Argyl and Ramseyburg Members disappears under the Shawangunk just within the confines of Delaware Water Gap National Recreation Area 1 mi (1.6 km) west of Delaware Water Gap (Epstein, 1973). The Pen Argyl does not reappear in New Jersey to the northwest. Several small slate quarries and prospects in the Ramseyburg Member, all long since abandoned, are found within the DEWA boundaries (Epstein, 1974a). The deepening of the Ordovician basin in which the Martinsburg detritus was deposited was followed by tectonic uplift reflecting intense Taconic mountain building, which peaked with emergence of the area during the Late Ordovician. This period of orogenic activity and regional uplift was followed by deposition of a thick clastic wedge, the lowest unit of which consists of coarse terrestrial deposits of the Shawangunk Formation. The contact between the Shawangunk and Martinsburg is a regional angular unconformity. The discordance in dip is not more than 15^{o} in northeastern Pennsylvania, New Jersey, and southeastern New York (Epstein and Lyttle, 1987).

The Shawangunk was divided into three members at the gap (Epstein and Epstein, 1972). The upper and lower conglomeratic-sandstone members, the Minsi and Tammany are believed to be fluvial in origin and are interposed by a transitional marine-continental facies (the Lizard Creek Member). The fluvial sediments are characterized by alternations of polymictic conglomerate with quartz pebbles more than 2 in (5 cm) long, conglomeratic sandstone, and sandstone (cemented with silica to form quartzite), and subordinate siltstone and shale. The bedforms (planar beds and cross-bedding) indicate rapid flow conditions. Cross-bed trends are generally unidirectional to the northwest. The minor shale and siltstone beds are thin, and at least one is mudcracked, indicating subaerial exposure. These mudcracks may be seen at mileage at the south entrance to Delaware Water Gap along I-80 in New Jersey side by looking up about 50 ft (15 m) at an overhanging ledge (Epstein and Epstein, 1969, fig. 8D). These features indicate that deposition was by steep braided streams flowing toward the northwest with high competency and erratic fluctuations in current flow and channel depth. Rapid runoff was undoubtedly aided by lack of vegetation cover during the Silurian. The finer sediments present are believed to be relicts of overbank and backwater deposits. Most of these were flushed away downstream to be deposited in the marine and transitional environment represented by the Lizard Creek Member of the Shawangunk Formation.

The Lizard Creek Member contains a variety of rock types, and a quantity of sedimentary structures that suggest that the streams represented by the other members of the Shawangunk flowed into a complex transitional (continental-marine) environment, including tidal flats, tidal channels, barrier bars and beaches, estuarine, and shallow neritic. These are generally energetic environments, and many structures, including flaser bedding (ripple lensing), uneven bedding, rapid alternations of grain size, and deformed and reworked rock fragments and fossils support this. Many of the sandstones in the Lizard Creek are supermature, laminated, rippled, and contain heavy minerals concentrated in laminae. These are believed to be beach or bar deposits associated with the tidal flats.

The outcrop pattern of the Shawangunk Formation and the coarseness of some of the sediments, suggest that they were deposited on a coastal plain of alluviation with a source to the southeast and a marine basin to the northwest. Erosion of the source area was intense and the climate, based on study of the mineralogy of the rocks, was warm and at least semi-arid. The source was composed predominantly of sedimentary and low-grade metamorphic rocks with exceptionally abundant quartz veins and small local areas of gneiss and granite. As the source highlands were eroded, the steep braided streams of the Shawangunk gave way to more gentle-gradient streams of the Bloomsburg Red Beds.

The rocks in the Bloomsburg are in well- to poorly-defined upward fining cycles that are characteristic of meandering streams. The cycles are as much as 13 ft (4 m) thick and ideally consist of a basal cross-bedded to planar-bedded sandstone that truncates finer rocks below. These sandstones were deposited in stream channels and point bars through lateral accretion as the stream meandered. Red shale clasts, as much as 3 in (8 cm) long were derived from caving of surrounding mud banks. The sandstones grade up into laminated finer sandstone and siltstone with small-scale ripples indicating decreasing flow conditions. These are interpreted as levee and crevasse-splay deposits. Next are finer overbank and floodplain deposits containing irregular carbonate concretions. Burrowing suggests a low-energy tranquil environment; mudcracks indicate periods of desiccation. The concretions are probably caliche precipitated by evaporation at the surface. Fish scales in a few beds (seen near the toll booth along I-80 as it crosses southward into New Jersey) suggest marine transgressions onto the low-lying fluvial plains, perhaps in a tidal-flat environment.

The source for the Bloomsburg differed from that of the Shawangunk Formation because the red beds required the presence of iron-rich minerals, suggesting an igneous or metamorphic source. Evidently, the source area was eroded down into deeper Precambrian rocks.

Upper Silurian and Lower Devonian rocks younger than the Bloomsburg Red Beds hold up Godfrey Ridge just north of the Delaware River, which can be seen as we travel each day leaving our headquarters from Shawnee. These younger rocks span the complete range of sedimentary types, and reflect an equally complex series of depositional environments, including shallow marine shelf, supratidal and intertidal flats, barrier bars, and many neritic zones. Fossils are plentiful in many of the units.

Structural Geology: The View From the Gap

Field mapping in rocks of Ordovician to Devonian age in the Valley and Ridge province of northwestern New Jersey and neighboring eastern Pennsylvania indicates that rocks of differing lithology and competency have different styles of deformation. Folding is thus disharmonic (Figure 4). Type and amplitude of folds are controlled by lithic variations within each lithotectonic unit. The lithotectonic units, their lithologies, thicknesses, and styles of deformation are listed in Epstein and Epstein (1969) and are repeated in Table 1. Folding and intensity of deformation decreases from eastern Pennsylvania, across the Delaware Water Gap, through New Jersey, and into New York. In general, folding diminishes northeastward from overturned and faulted folds to northwest-dipping monoclines with superimposed gentle folds in the northeast. Slaty cleavage is found in all rocks, but decreases in intensity both to the northwest across strike and northeast along strike. Detailed field studies allow us to decipher the age(s) of the cleavage and determine the nature of the Taconic unconformity between the Shawangunk and Martinsburg Formations.

Three periods of mountain building are recognized in the Valley and Ridge rocks of eastern Pennsylvania and northern New Jersey: the Taconic, Acadian, and Alleghanian

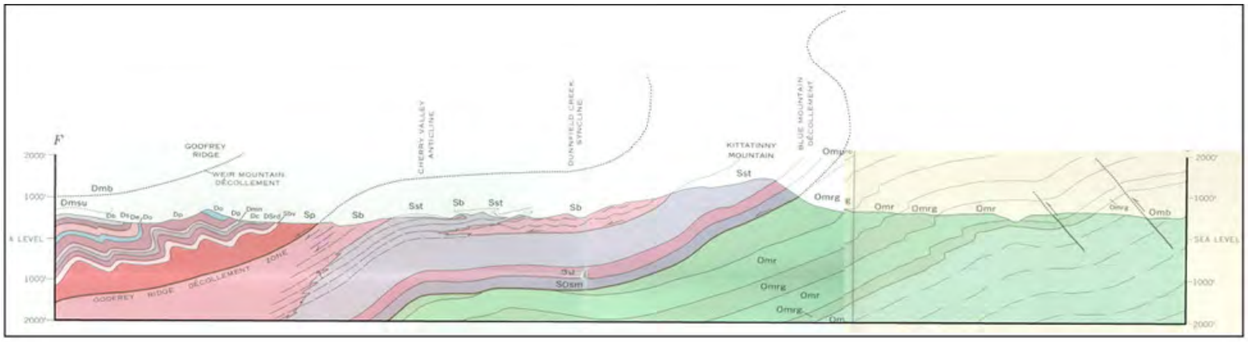

Figure. 4. Cross section in the Delaware Water Gap area (from Epstein, 1973, and Drake et al., 1969) showing the disharmonic relations between rocks of differing ages and lithic types. The contact between the Martinsburg Formation of Ordovician age and the Silurian Shawangunk Formation marks the Taconic unconformity. Omp—Pen Argyl Member of the Martinsburg Formation (disappears under the Shawangunk about 1 mi (1.6 km) west of the gap); Dmb through Sp—Devonian through Upper Silurian rocks; Sb—Bloomsburg Red Beds; Sst—Tammany Member of the Shawangunk Formation; Ssl—Lizard Creek Member of the Shawangunk Formation; Ssm—Minsi Member of the Shawangunk Formation; Omr—Ramseyburg Member of the Martinsburg Formation; Omrg—graywacke zones in the Ramseyburg Member; Omb—Bushkill Member of the Martinsburg Formation.

Table 1. Lithotectonic units in the Delaware Water Gap area.

Lithotectonic unit	**Age of lithotectonic unit and stratigraphic sequence**	**Lithologic characteristics**	**Style of folding**	**Average size of folds**
4	Upper and Middle Devonian Marcellus shale and younger rocks	10,000+ feet of sandstone, conglomerate, siltstone,and shale	Nearly symmetrical, concentric, predominantly flexural slip	Northwest-tilting, non-folded in DEWA, folding intensifies to southwest
3	Middle Devonian to Upper Silurian Buttermilk Falls Limestone to upper part of the Poxono Island Formation.	Up to 1,500 feet of limestone, shale, siltstone, sandstone and dolomite. Formations 3-180 feet thick.	Asymmetric, concentric, and similar, flexural slip and flow, passive slip and flow. Cascade folds in DEWA and flaps (antiformal synclines to the west	Wavelenths 1,000-1,500 feet, amplitudes about 250 feet.
2	Upper to Lower Silurian lower part of the Poxono Island Formation, Bloomsburg Red Beds and Shawangunk Formation	3,100 feet of sandstone, siltstone, shale, and conglomerate; fining uopwards.	Assymetric, concentric; flexural slip with minor passive slip and flow. Extensive bedding slip and wedging in the Bloomsburg.	Wavelengths about 5,000 feet; amplitudes average about 2,000 feet.
1	Upper and Middle Ordovician Martinsburg Formation	About 12,000 feet of thick sequences of slate and greywacke.	Assymetric, smilar, mainly passive flow and slip; flexural slip near unconformable. contact with Shawangunk	Wavelengths 1,000-3,000 feet; amplitudes 4,00-2,000 feet. Imbricate thrusts with possible displacement in miles south of DEA.

This is the DELAWARE WATER GAP.
You are in a water gap, the pass in a mountain range through which a stream flows. Here, where Indian trails once bordered the river, early settlers founded resorts which by the 1850's were the summering places for vacationaers, artists, and nature lovers. Still an attraction for travelers, the Gap and surroundings are now part of the Delaware Water Gap National Recreation Area.

The Rocks Across the River
These great rock layers were once level deposits of mud and sand on the bed of an ancient sea. Hardened by time and pressure, then pushed above the level of the sea by forces within the earth, they buckled under lateral pressures, into folds and massive ridges. These layers you see now tilting into the sky once vaulted in a great continuous arc coming down many miles to the southeast.

As the land rose, the river sliced downward through it and laid bare the tilted and folded layers. Now, erosion has removed most of these arching layers, leaving only the remnant toes, one here, one many miles to the southeast. Still the wearing away continues as the river widens its bed and rocks fall from the cliff, adding to the talus at its base.

Figure 5. A three-part metal plaque located in the kiosk at Stop 1 during the late 1960's interpreted the geologic structure of the rocks in Delaware Water Gap as part of a broad regional anticline. This exhibit is now gone and is reproduced here. An alternative interpretation is shown in Figure 6.

orogenies. Structural evidence for the Acadian is lacking, but uplift (i.e., orogenesis) is documented by the clastic rocks of middle Devonian and later age rocks present beneath the Delaware River and to the north in the Pocono Plateau. Separating the structural effects of the Taconic from the Alleghanian has been controversial, especially the age of the cleavages that penetrate the pelitic rocks in the Delaware Water Gap area

Shortly after the DEWA was established in 1965, an exhibit in the kiosk at the south end of the parking lot (the assembly site for this field conference) presented an interpretation of the structure in the gap. The plaques have since disappeared from the site as well as from most memories. Figure 5 brings back those memories.

This structural interpretation alludes to the fact that the Green Pond Conglomerate, the correlative of the Shawangunk, is exposed about 30 mi (48 km) to the east in New Jersey. Hence, a way was needed to bring the rocks of the Shawangunk at Delaware Water Gap down again to mate with the Green Pond rocks and a broad regional anticline was invoked. Satellitic folds that verge to the southeast would indicate that such an anticline does indeed lie to the southeast (Figure 6A). On the contrary, mapping along strike and down the plunge of the folds

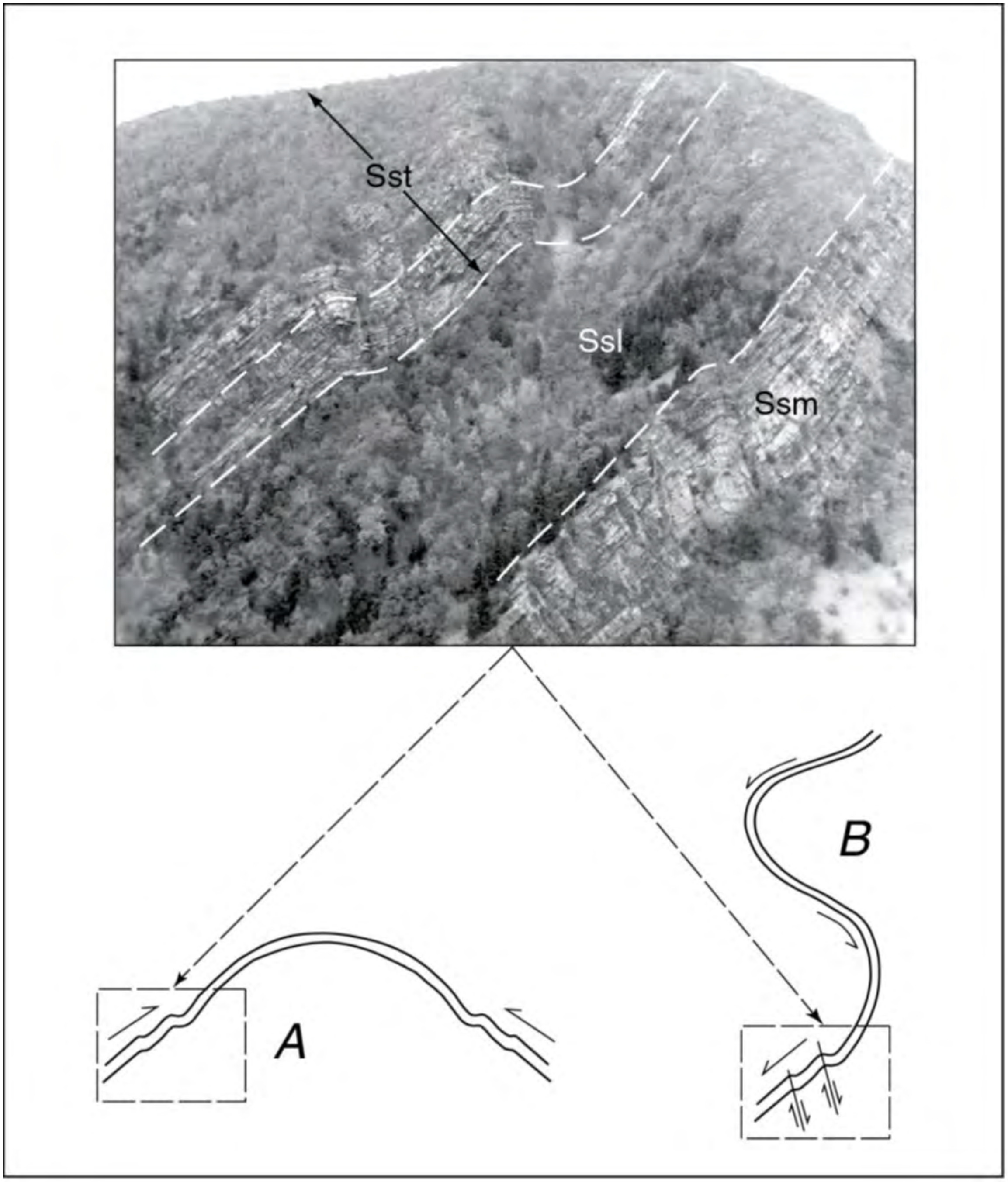

Figure 6. Satellitic folds in the Shawangunk Formation in Delaware Water Gap, New Jersey (Ssm, Minsi Member; Ssl, Lizard Creek Member; Sst, Tammany Member). A—Interpretation of an anticlinal crest to the southeast as shown in Figure 5 with "drag folds", due to interbed shear, verging towards the anticlinal crest; B—Interpretation of an overturned syncline to the southeast as determined by down-plunge reconstruction. The satellitic folds are antithetic to northwest shear of overriding beds as determined by bedding-plane slickensides.

to the southwest on Kittatinny Mountain (Epstein, 1973), shows that an overturned syncline extends upwards from the rocks at Delaware Water Gap (Figure 6B). Because the terrain south of Kittatinny Mountain is replete with thrust faults, the structural relations between it and the Green Pond area is certainly much more complex than a simple regional anticline.

The Story of Slaty Cleavage: Diagenic vs. Metamorphic Origin of Slaty Cleavage

Slaty cleavage is the property of a rock that allows it to be split into very thin slabs of slate. It is controlled by parallelism of platy minerals in the rock. For many years geologists did not argue that slaty cleavage was formed during folding, the stress having rearranged the orientation of minerals, particularly micas, parallel to the cleavage direction. It generally is considered a metamorphic process, occurring during elevated temperature and pressure. Slaty cleavage is especially well developed in the Martinsburg Formation, where it has been quarried for slate in New Jersey and eastern Pennsylvania since it was discovered about 1808.

The Martinsburg Formation is exposed in continuous outcrops along US 46 south of Columbia, NJ. Here, about 5 mi (8 km) south of Delaware Water Gap, about 1.5 mi (2.4 km) south of mileage 9.7 of the Day 2 Road Log, there is an outcrop of interbedded graywacke and slate in the Ramseyburg Member of the Martinsburg Formation on the east side of US 46. Based on interpretation of a sandstone dike intruded down from a graywacke bed and into the cleavage of the underlying slate (Figure 7), Maxwell (1962) concluded that the slaty cleavage in the Martinsburg Formation in the Delaware Water Gap area was produced by tectonic dewatering during the Taconic orogeny, and that the cleavage was the result of only slight tectonic stress on pelitic sediments with high pore-water pressures. The slate that was produced, therefore, is not a metamorphic rock, but is rather a product of diagenesis. As a consequence, Maxwell concluded that the Taconic orogeny was minor in comparison to the later more intense Alleghanian orogeny, during which time a metamorphic fracture cleavage was produced in the Martinsburg and younger rocks. Maxwell's thoughts served the geologic profession very well because they stimulated a flood of papers on the origin of slaty cleavage (a recent search of the GeoRef geologic data base for articles after 1965 resulted in 595 hits for *slaty cleavage*).

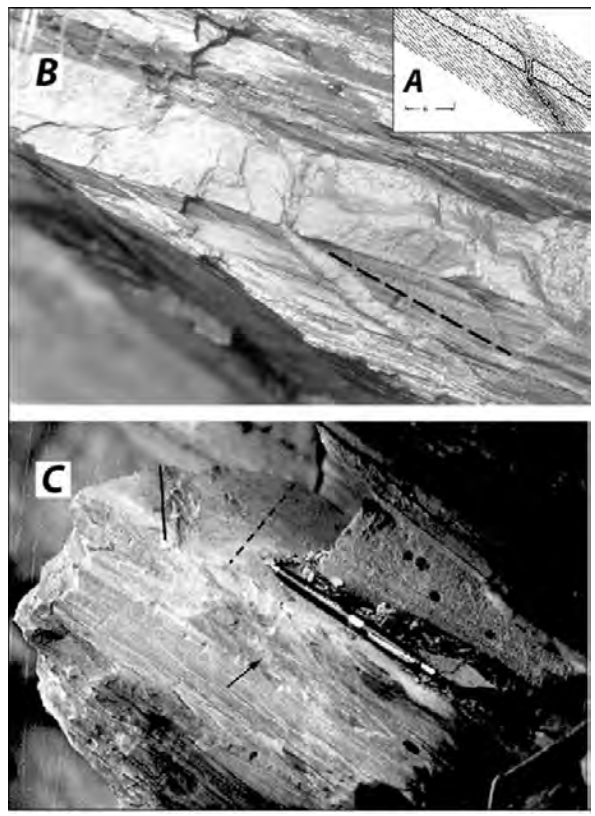

Figure 7. Sandstone dikes in the Martinsburg Formation along US Route 46 south of Delaware Water Gap. A—Dike illustrated by Maxwell, 1962, his Fig. 4; B—Actual dike shown in A and #1 in Figure 8. Cleavage (dashed line) dips 8° less than the dike. Mud from the overlying bed replaced the evacuated sand and formed a mud dike in the graywacke. A poorly developed cleavage in the graywacke is about 10° steeper than the mud dike; C—Another sandstone dike at this locality (#2 of Figure 8). Arrow points to dike in section; dashed line is the intersection of bedding and cleavage (IBC). Solid line shows trace of dike on bedding at a significant angle to the IBC.

Figure 7A is the line drawing of the dike Maxwell discovered that stimulated his interpretation for a non-metamorphic origin of slaty cleavage. He reasoned that high pore pressures in the sand beds caused the fluid expulsion of sandstone dikes parallel to already-formed slaty cleavage in the water-bearing muds. Figure 7B is the actual dike shown in Figure 7A. Note that the dike is not parallel to the slaty

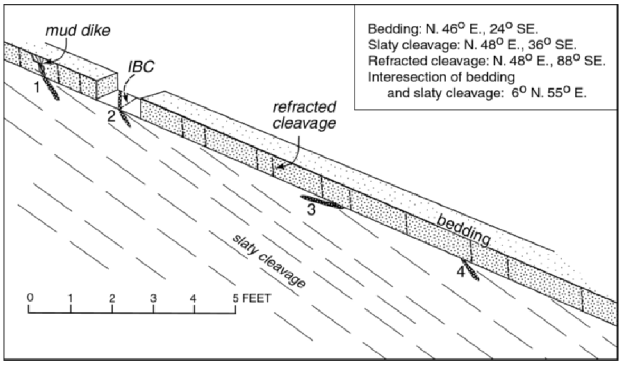

Figure 8. Sandstone dikes extending down from a graywacke bed into slate in the Ramseyburg Member of the Martinsburg Formation, along US 46, 5 mi (8 km) south of Delaware Water Gap. North is to the left. 1—Sandstone dike shown in Figure 7B and portrayed by Maxwell (1962, p. 287). The dike does not parallel cleavage (dips 8° steeper than cleavage). A mud dike extends into the graywacke bed and dips 10° less than the refracted cleavage; 2—Sandstone dike dips 5° steeper than cleavage and is shown in Figure 7C. The strike of the dike (N28°E) is more northerly than the strike of cleavage. This difference is reflected in the divergence of the trend of the intersection of bedding and cleavage (IBC) with the trend of the intersection of the dike and bedding; 3—This sandstone dike differs from the others in that it dips more gently than slaty cleavage. Figure 9 shows the details. The strike of this dike is also more northerly than the strike of cleavage (N25°E) and it dips 10° more steeply than cleavage; 4—The strike of this dike is also more northerly than the strike of cleavage (N25°E) and it dips 10° more steeply than cleavage.

cleavage. Additionally, at the outcrop there are several other dikes extending down from the parent bed (Figure 8). None of these parallel the cleavage. They vary considerably in dip, dip direction, and strike. In one case (dike #2, Figure 7C) the strike of the dike on the graywacke-bedding surface does not parallel the strike of cleavage on the bedding surface (the intersection of bedding and cleavage; *IBC*). A thin section of one of the dikes (the specimen was loose and about ready to fall when collected in 1970) is shown in Figure 9. Note the lack of parallelism between the dike and slaty cleavage. Clearly, the supposed parallelism between sandstone dikes and slaty cleavage, which formed the basis for the non-metamorphic origin of cleavage, is incorrect. Field relations also show that variation in cleavage development in the younger rocks is controlled by lithologic differences and not age differences.

Epstein and Epstein (1967) and Epstein (1974b, who else?) concluded that the dominant northwest-verging folds and related regional slaty cleavage were produced during the Alleghanian orogeny and are superimposed upon Taconic structures in pre-Silurian rocks. The regional slaty cleavage formed after the rocks were indurated at, or just below, conditions of low-grade metamorphism. Estrangement of the effects of the two orogenies is still the subject of considerable debate. The following are conclusions regarding the dominant regional slaty cleavage in eastern Pennsylvania and northern New Jersey (ok—add southeastern New York here too). Some of this will be discussed further at Stop 10.

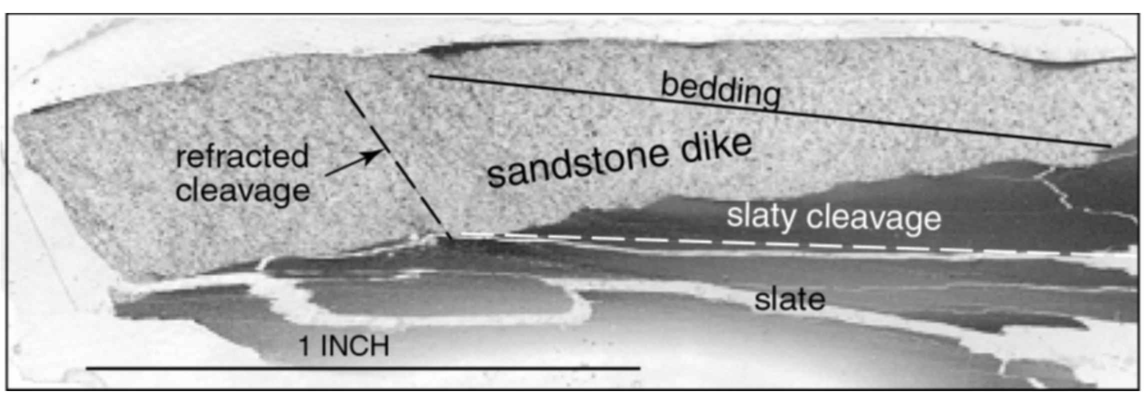

Figure 9. Scanned thin section of sandstone dike # 3 shown in Figure 8. The dike dips to the southeast (to the right) 4° less than bedding and slaty cleavage dips 9° more than the dip of the dike. Irregular fracture at word "slate" is pull apart in thin section.

1. The Martinsburg was competent enough to deform by flexural slip prior to passive deformation that produced the cleavage. This is shown by abundant bedding-plane slickensides that are cut by cleavage, negating the hypothesis that the cleavage was imposed on a water-bearing pelite.
2. The mica in Martinsburg slate is 2M muscovite as shown by X-ray analyses. This, along with chlorite porphyroblasts in the rock, shows that the slate is a product of metamorphism. This is also corroborated by high length-width ratios of quartz grains, the result of pressure-solution.
3. An Alleghanian age for the regional slaty cleavage is supported by $^{40}Ar/^{39}Ar$ whole-rock dating of the Martinsburg Formation at Lehigh Gap, 30 mi (48 km) southwest of Delaware Water Gap (Wintsch et al., 1996).
4. Slaty cleavage is not confined to the Martinsburg. All post-Ordovician pelitic units contain cleavage. Rocks in the Mahantango Formation have been quarried for slate near Aquashicola, PA, a fact noted many years ago by Dale et al. (1914, p. 108) and Behre (1933, p. 119; see Figure 19, first day's road log).
5. In some exposures of the Martinsburg, a later slip cleavage has nearly obliterated the earlier slaty cleavage. This second cleavage has nearly perfect mineral alignment along which the rock can be split into thin laminae. If transposition had been more complete, a perfectly respectable slate would have resulted as suggested by Broughton (1946, p. 13) where he examined the slate along US 46 in New Jersey.
6. Within the basal Shawangunk no fragments of pelitic rock from the underlying Martinsburg contain slaty cleavage that may have been produced during Taconic deformation. Rather, any cleavage that is present in these pebbles conforms to the attitude of the Alleghanian regional cleavage found throughout the Shawangunk and younger rocks. The obvious conclusion is that no Taconic cleavage can be recognized in pebbles within Silurian rocks.
7. At several localities folds have been mapped in the Shawangunk and Martinsburg along the unconformity, such as at Yards Creek (discussed below) and High Point, New Jersey (Monteverde et al., 2001; Stop 8). The fold axes pass from the Shawangunk into the Martinsburg Formation without deflection, showing that the folds are post-Taconic in age. Cleavage in the Martinsburg is parallel to the axial planes of the folds, or fans the folds (except for the arching of cleavage as described below), again showing that the cleavage is post-Taconic in age.
8. The dying-out of cleavage in the Martinsburg as the contact with the Shawnagunk is approached, implying a pressure-shadow effect due to the position of the very competent beds in the Shawangunk Formation, is discussed at Stops 3, 5, 9, and 10).
9. Examination of xenoliths of baked Martinsburg rocks have no cleavage in them (see discussion at Stop 7).

The cleavage in the Martinsburg immediately south of the gap dips to the northwest (Epstein, 1973). This interrupts the generally southeast-dipping regional cleavage and is part of a broad cleavage arch. This cleavage arch is discussed below and will demonstrate a post-Silurian age for the cleavage. It is not due to Alleghanian folding of a Taconic cleavage.

The Arching of Cleavage and Its Implications

The slaty cleavage bears a geometric relationship to the folds in which it is found, fanning the folds by either opening or closing towards the anticlinal crest. At Delaware Water Gap, and at other localities near the contact with the competent rocks of the Shawangunk Formation, the slaty cleavage is arched in a manner different from the usual geometric relation to the local fold it which it normally finds itself. Figure 10 is a generalized geologic map of the Delaware Water Gap area. Note that about 2,000 ft (610 m) south of the Martinsburg-Shawangunk contact the cleavage dips to the southeast, but turns to the northwest as the contact is approached. Drake et al. (1960) and Maxwell (1962) attributed this arching of the slaty cleavage to refolding of a Taconic foliation during the later Appalachian orogeny. However, the form of this cleavage fold in the Martinsburg is not reflected upwards into the overlying rocks. The contact between the Martinsburg and Shawangunk Formations is exposed at about a dozen localities between southeastern New York and Lehigh Gap, PA, a distance of more than 100 mi (107 km). On the basis of observations at these localities and from data gathered during mapping along the contact, it is concluded that the arching of cleavage at Delaware Water Gap is due a strain-shadow mechanism in the trough of a syncline in the Shawangunk as shown in Figure 11 and initially described by Epstein and Epstein (1967 and 1969).

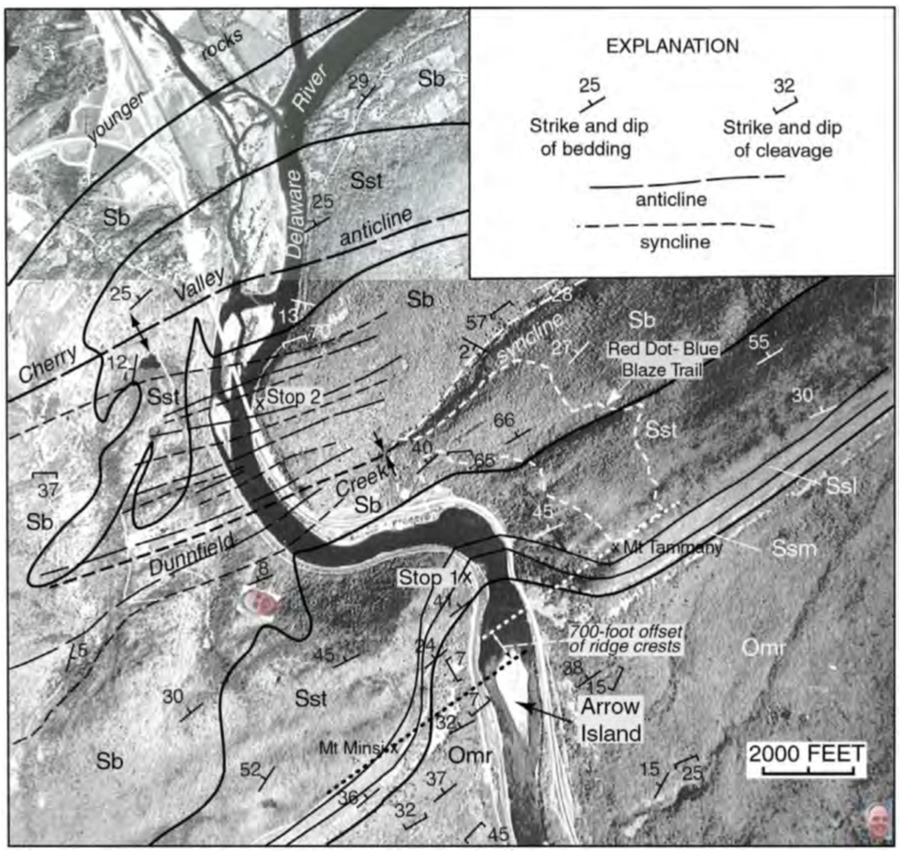

Figure 10. Aerial photograph and geologic map of Delaware Water Gap showing that at about 500 ft (152 m) southeast of the Shawangunk contact, southeast-dipping slaty cleavage in the Martinsburg Formation becomes northwest-dipping closer to the contact. Also note the 700-ft (213-m) offset of the ridge crests (dotted line) on either side of Kittatinny Mountain, to be discussed under the geomorphology section to follow. Omr—Ramseyburg Member of the Martinsburg Formation; Shawangunk Formation: Ssm—Minsi Member; Ssl—Lizard Creek Member; Sst—Tammany Member; Sb—Bloomsburg Red Beds. A series of small anticlines and synclines lie between the Dunnfield Creek syncline and Cherry Valley anticline. Arrow Island is a streamlined bar that formed where the Delaware River emerges from the constricted portion of Delaware Water Gap. The unusual pattern of the Ss-Sb contact in the western area is due to the variable nature of the color boundary (Epstein, 1973).

In many small folds involving interbedded shale and siltstone which are cleaved and more competent rocks which are less cleaved, the slaty cleavage diverges

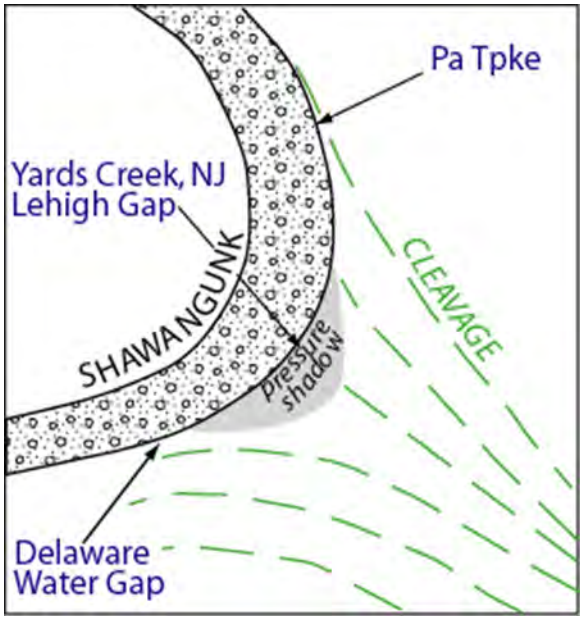

Figure 11. Strain shadows and arching of slaty cleavage in interbedded rocks of different competencies. This is a generalized cross section showing the structural relations of cleavage in the Martinsburg Formation (Om) near the contact with the more competent Shawangunk Formation (Ss). The northwest dipping cleavage is seen here in at Delaware Water Gap. The dying out of cleavage, shaded area in the diagram) can be seen at Yards Creek (Stop 5) and at Lehigh Gap (Stop 3). Steeply dipping cleavage in the Martinsburg next to the overturned synclinal limb can be seen at the south portal of the Pennsylvania Turnpike tunnel 33 miles southwest of Delaware Water Gap (Epstein and Buis, 1991; Stop 3).

around synclinal troughs and is either poorly developed or absent in the pressure-shadow area next to the trough (see Stop 3, Figure 13). This relationship is to be seen on a larger scale (Figure 11), explaining the arching of cleavage at Delaware Water Gap (Figure 12) as well as at Yards Creek (Stop 5), 5 mi (8 km) to the northwest in New Jersey. It also explains the dying out of cleavage near the Martinsburg-Shawangunk contact elsewhere, such as at Lehigh Gap, 30 mi (48 km) southwest of Delaware Water Gap (Stop 3). Similarly, in thin section, cleavage is seen to curve around clastic grains, small lenses of sandstone, or sand-filled burrows. The cleavage is most intensely developed (flattening is greatest) on top and bottom of these more competent clastic bodies and is poorly developed or absent in the areas of maximum extension to the sides of the grains in the areas of "pressure shadows."

Based on the comments above and mapped field relations, some of which are described below, Epstein and Epstein, 1967, and Epstein, 1974b, concluded that the dominant northwest-verging folds and related regional slaty cleavage were produced during the Alleghanian orogeny and are superimposed upon Taconic structures in pre-Silurian rocks. The regional slaty cleavage formed after the rocks were indurated at, or just below, conditions of low-grade metamorphism. Estrangement of the effects of the two orogenies is still the subject of some debate, and we will discuss that subject next.

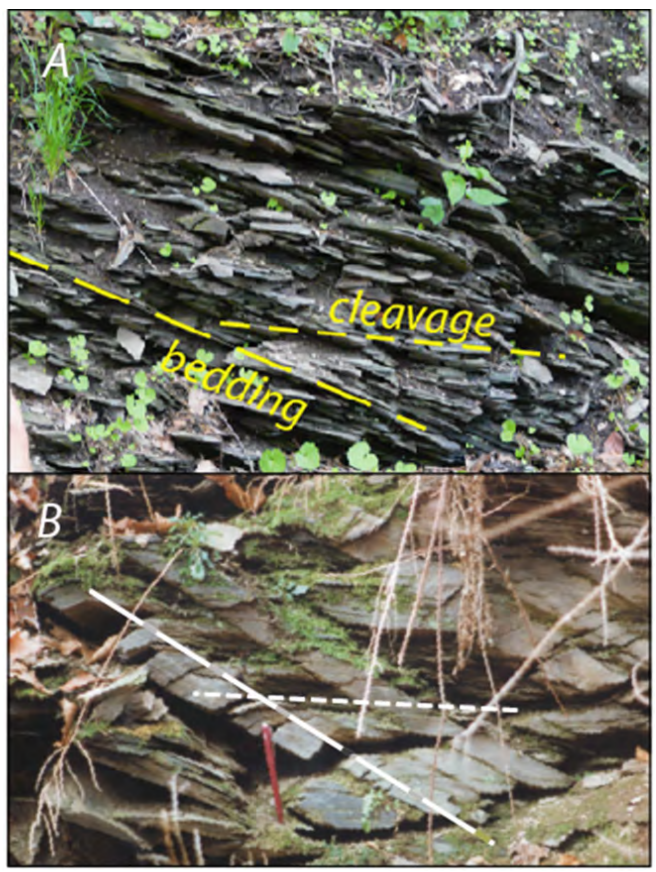

Figure 12. The bedding (solid line) and cleavage (short dashes) are well displayed in the quarry; both dip to the northwest. Note well-developed sleavage in the slate beds compared to the fractures in the graywackes.

Age of Deformation: Taconic vs. Alleghenian - Which is the Winner?

The Ordovician Martinsburg Formation was folded and faulted during complex plate movements that resulted in the Taconic Orogeny. During and following Taconic deformation, mountains rose to the east as a result of orogenic uplift, coarse sediments were transported westward, and sandstone and conglomerates of the Shawangunk Formation were deposited across beveled folds of the Martinsburg. As the mountains were worn down, finer clastic sediments and carbonates were deposited more or less continuously into the Middle Devonian. Clastic influx beginning during the Middle Devonian records a later orogeny, the Acadian. The structural effects of the Acadian orogeny did not extend as far southwest as northern New Jersey; the limit of Acadian folds, faults, and igneous intrusions lies to the east in New York State. Finally, near the end of the Paleozoic, continental collision deformed all rocks, down to and below the Martinsburg.

Based on high-angular discordances between beds above and below the Ordovician-Silurian contact in the Hudson Valley of New York, many early geologists concluded that the Taconic unconformity at Delaware Water Gap and throughout New Jersey separated highly folded Martinsburg rocks from much less folded younger rocks (Figure 13). However, field mapping of several exposures of the unconformity in eastern Pennsylvania (east of Stop 1), northern New Jersey, and as far northeast as Ellenville, NY (Stop 10) show the divergence in dip at this contact does not exceed 15°. At most places it is just a few degrees (see Some Taconic Unconformities in Southeastern New York, this Guidebook). The timing and degree of deformation of both Ordovician and younger rocks in in this area has been subject of considerable long-standing debate. The four most important questions are: (1) what is the geographic distribution of Taconic structures in pre-Silurian rocks; (2) what are the intensities of Taconic and post-Taconic deformations in pre-Silurian rocks; (3) what is the age of the folds, faults, and cleavage in these pre-Silurian rocks; and (4) is the age of the post-Taconic deformation Acadian or Alleghanian, or both? We have already answered the question of the age of the major folding and slaty cleavage in Eastern Pennsylvania and northern New Jersey. Number 4 is beyond the range of this field trip, but may be discussed at Stop 10.

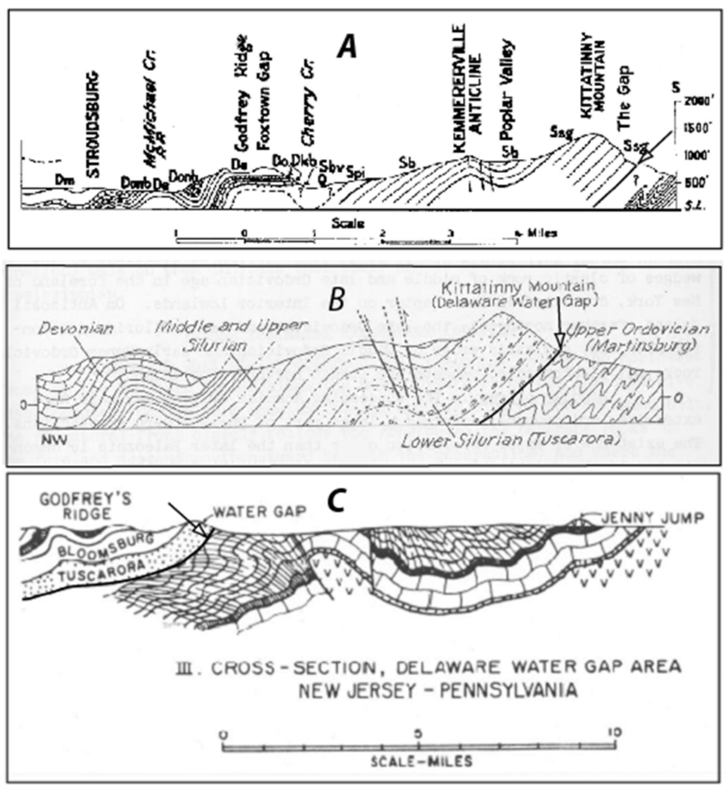

Figure 13. Cross sections showing previous interpretations of the angular relations of bedding above and below the Taconic unconformity (at arrow). A, Willard, 1938; B, King, 1951; C, Maxwell, 1962. Note in C that below the Tuscarora (= Shawangunk) slaty cleavage is shown as axial planar to folds in the Martinsburg and is warped by arching during a post-folding tectonic event.

Geomorphology: Superposition, Peneplains, and Stuff Like That

Most folks who visit Delaware Water Gap are compelled to contemplate its origin and why it is where it is. The following thoughts are summarized from Epstein (1966 and 1997).

Following the late Paleozoic orogenic uplift of the diverse sediments that were previously deposited, the original divide of the Appalachian Mountains lay somewhere to the south within the area of the present Piedmont or Valley and Ridge Province. During rifting and opening of the Atlantic Ocean, that divide shifted westward to its present position in the Appalachian Plateau. This was because the steeper stream gradients towards the Atlantic Ocean had an erosional advantage over the lower-gradient streams that flowed westward towards the continental interior. The manner of migration of that divide and how the streams cut through the resistant ridges are critical elements in any discussion of Appalachian geomorphic development. These subjects have been a source of considerable controversy for more than a century. There are many wind and water gaps in Blue and Kittatinny Mountains in Pennsylvania and New Jersey. Viewed from a distance, these gaps or low sags interrupt the fairly flat ridge top that was termed the "Schooley peneplain" by Davis (1889) and popularized by Johnson (1931) (Figure 14). Ideas on the origin of these gaps are critical factors in several hypotheses that discuss the geomorphic development of the Appalachians. Those hypotheses that favor down cutting (superposition) from an initial coastal plain cover (Johnson, 1931; Strahler, 1945) require that the location of the gaps be a matter of chance. Those hypotheses that suggest the present drainage divide was inherited from the pattern already established following the Alleghanian orogeny and controlled by the topography and structure prevalent at the time (Meyerhoff and Olmstead, 1936) or by headward erosion into zones of structural weakness (*headward piracy*; see Thompson, 1949) require that there be evidence for structural weakness at the gap sites. Thus, an understanding of the structural configuration of these gaps is necessary for adequately discussing the drainage evolution of the Appalachians.

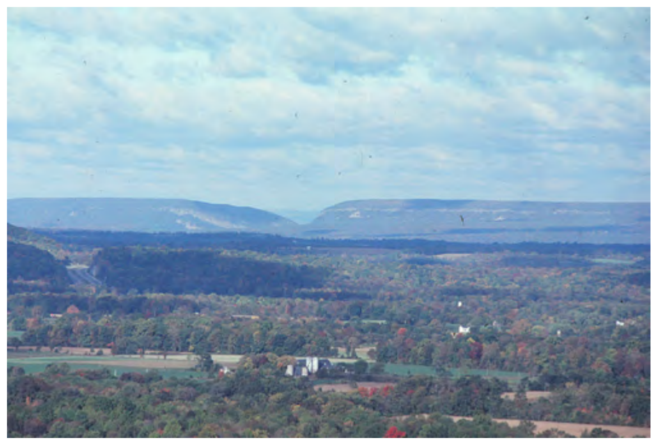

Figure 14. View of flat-topped Kittatinny Mountain looking north from the New Jersey Highlands.

Examination of sixteen gaps and cols in Blue, Kittatinny, and Shawangunk Mountains in New Jersey and adjacent Pennsylvania and New York were examined (Epstein 1997). Most of the gaps are located at sites where there are structures that are not present between these sites. The general conclusion can be made that the gaps are located at sites of structural weakness. If this opinion is accepted, then those hypotheses which suggest that streams sought out weaknesses in the rock during headward erosion are favored. The following are features that are found at gap sites: (1) dying out of folds along plunge within short distances; (2) narrow outcrop widths of resistant beds because of steep dips; (3) more intense folding locally than nearby; (4) abrupt change in strike owing to kinking along strike; (5) intense overturning of beds and resultant increase in shearing; and (6) cross faulting.

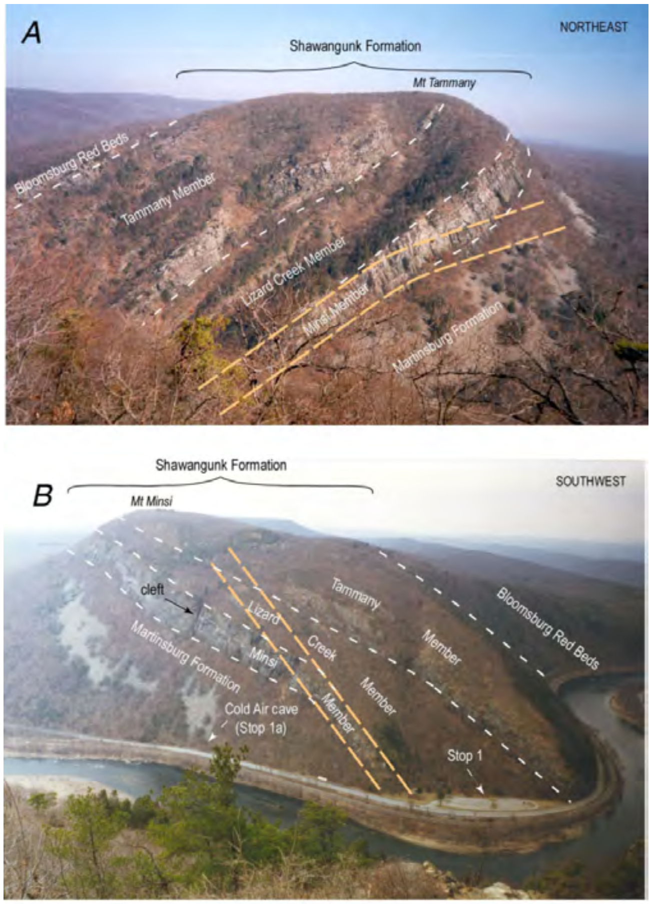

Figure 15. Middle Silurian rocks in Kittatinny Mountain in New Jersey (A) and Pennsylvania (B) at Delaware Water Gap. Long-dashed lines are the projected structural configuration of the Minsi Member of the Shawangunk Formation projected across the Delaware River from the opposite side of the gap. Figure 16 demonstrates the interpreted flexure at the gap site.

Delaware Water gap is often cited as the classic water gap in the Appalachian Mountains. Figure 10 portrays its geology. The Delaware River flows through the gap at an altitude of 300 ft (91 m). Kittatinny Mountain rises about 1,240 ft (378 m) above the Delaware River on the New Jersey side, and it is nearly 100 ft (31 m) lower on the Pennsylvania side. Also, the trend of the ridge crest lies about 700 ft (213 m) farther southeast on the Pennsylvania side than in New Jersey (see Figure 10). The three members of the Shawangunk Formation match and are aligned at river level. In New Jersey, bedding rises uniformly to the top of the mountain with a dip of about 45^{o} (Figure 15A), but in Pennsylvania the dip decreases about halfway up the mountain to about 25^{o} (Figure 15B). Therefore, there must have been a kink in the rocks that formerly occupied the gap site and as a consequence, the brittle rocks must have been weakened by fracturing in the flexure zone. The location of the gap is therefore interpreted to have been controlled by the local structure.

The overlying Bloomsburg Red Beds exhibit a series of folds just north of the gap that plunge out to the southwest within a short distance (see Figure 10). Because similar tight folding is not seen in the Bloomsburg immediately beyond the gap site, the rocks are presumably more highly sheared here, and resistance to erosion is less than elsewhere along the ridge. Also, the outcrop width of the Shawangunk Formation is narrower at the gap site than to the northeast, where the Cherry Valley anticline and Dunnfield Creek syncline widens the exposure.

Figure 16. Reconstructed flexure at Delaware Water Gap. Dotted line shows strike of beds before the gap was cut. The flexure accounts for the offset of the ridge between the two sides and presumably resulted in considerable fracturing of the Shawangunk at the gap site. View looking eastward. The flexure also explains the offset of the Kittatinny Mountain ridge between the two sides of the gap. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Epstein (2006, fig. 9).

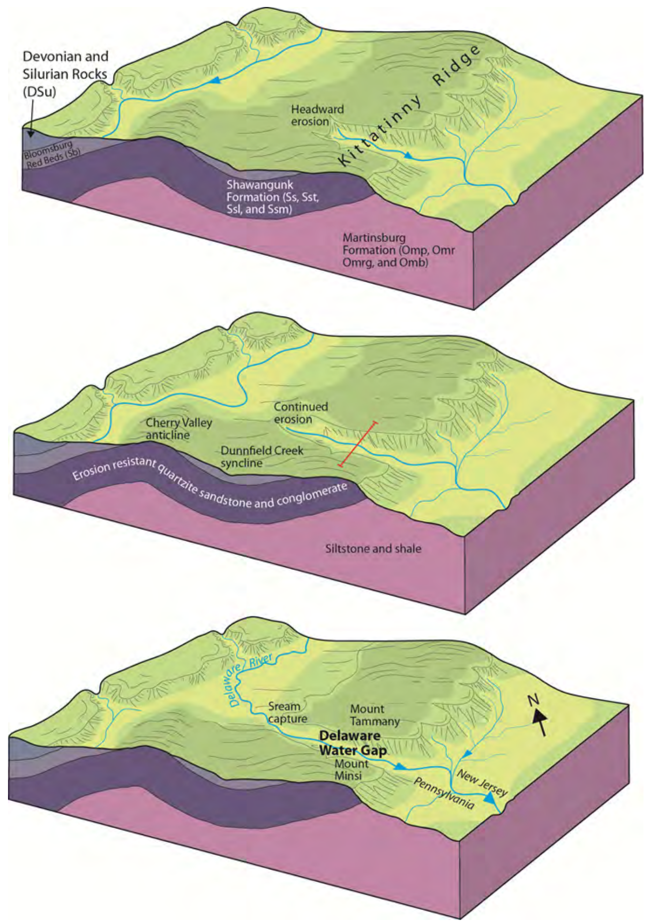

Figure 17. Formation of Delaware Water Gap through a process of headward erosion, concentrated erosion at a zone of bedrock weakness (Figure 16), and stream capture in folded rocks. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Epstein (2006, fig. 9).

The strong relationship between the position of the gaps and local structure suggests that the concept of regional superposition as applied by Johnson (1931) is invalid. Rather, hypotheses are favored that maintain that the gaps are located in zones of structural weakness, where headward erosion was most effective during the course of stream competition along the ancestral drainage divide (Figure 17). While the conclusions presented in this discussion relate to structural control of gaps, the nature and timing of stream development cannot be deduced. Of concern is whether streams are in their original (post-Permian) position, whether they have been captured and replaced by streams in front of the ridge or by tributaries behind the ridge, and what effect the structure on both sides of the ridge may have had in the geomorphic evolution.

Glacial Geology

The latest (Wisconsinan) glacial advance into northern New Jersey and eastern Pennsylvania resulted in the deposition of a conspicuous terminal moraine which crosses the Delaware River about 11 mi (18 km) south of the gap near Belvidere, NJ (Figure 18). The moraine then trends northwestward to cross Blue Mountain about 5 mi (8 km) west of Delaware Gap, locally reaching heights of more than 100 ft (31 m) in places. As the glacier retreated from its terminal position north of Blue Mountain, the melt water was dammed between the terminal moraine, the surrounding hills, and the retreating ice front. A series of stratified sand and gravel deposits, including magnificent Gilbert-style deltas, were laid down in the pro-glacial lake that formed, Lake Sciota, recording the sequential retreat of the glacier. The lake reached a depth of about 200 ft (61 m) in places. Initially, the outlet for the lake was over the terminal moraine and the water flowed west toward the Lehigh River. As the glacier retreated northeastward past the Delaware River, the waters drained through the gap and the lake ceased to exist.

A variety of glacial deposits formed in the Delaware Water Gap area, composed of varying proportions of gravel, sand, silt, and clay. On the basis of texture, internal structure, bedding and sorting characteristics, and generally well preserved landforms, the deposits have been subdivided into till (ground, end, and terminal moraine) and stratified drift (delta, glacial-lake-

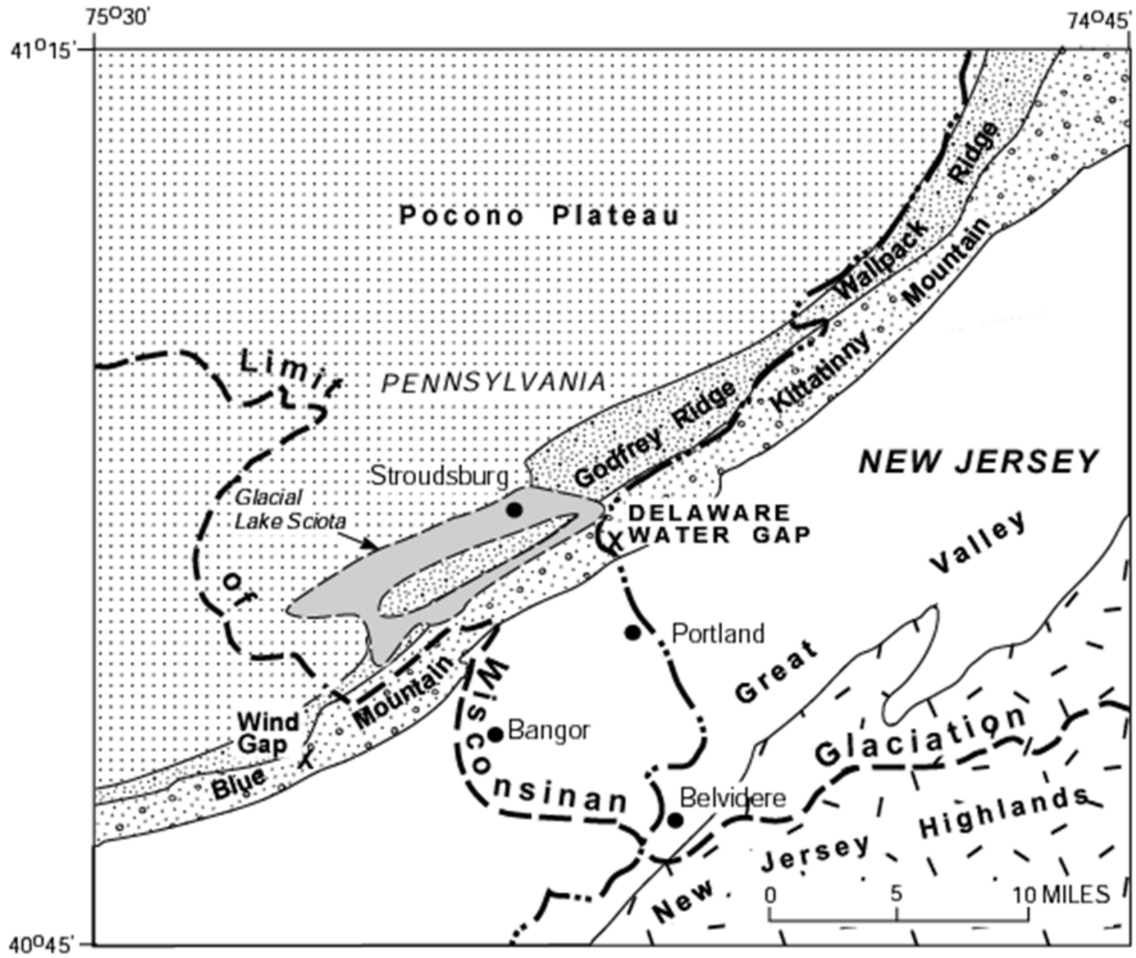

Figure 18. Physiographic map of part of easternmost Pennsylvania and northwestern New Jersey showing the position of the maximum advance of the Wisconsinan glacier. Modified from Epstein (1969).

bottom, kame, kame-terrace, and outwash deposits). Below the gap is an outwash terrace, more than 150 ft (46 m) high on both sides of the river, comprising very coarse gravel with boulders exceeding 8 ft (2 m) long. This deposit may be seen at mileage 6.6 of the Day 2 Road Log. Numerous striae, grooves, and *roches moutonnee* (seen at Stop 8) formed by Wisconsinan glacial erosion are found on bedrock surfaces in most parts of the area. Striae trends show that the ice was strongly deflected by underlying bedrock topography. Whereas the average direction of flow of the ice sheet in the immediate Delaware Water Gap area was about S20^{o}W, the base of the ice traveled mostly more southwestward parallel to the valley bottoms and about due south over the ridge top. Bedrock topography has been subdued in many places by the drift cover. Examples of drainage modifications are numerous. Talus deposits, congelifractates, rock streams, and rock cities are believed to be partly of periglacial origin. Numerous lakes, mostly in kettle holes, have made the Pocono area the tourist attraction that it is. Heart-shaped ponds, fens, and bogs have made it the "honeymoon capital of the world." There has been a long line of researchers of the glacial geology of the area around Delaware Water Gap, with the most comprehensive being Witte (2001).

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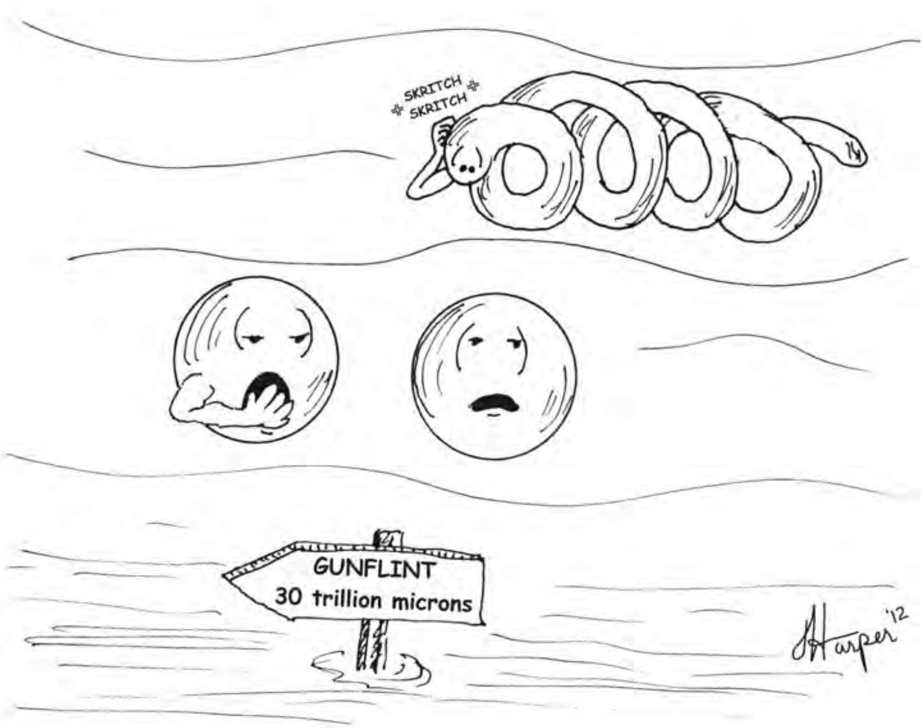
GREAT MOMENTS IN GEOLOGIC HISTORY
Part 6: The Precambrian



Just bored - being bacteria without having anything to infect is a very dull business!

STOP 4A: RESORT POINT OVERLOOK

Leader: Jack Epstein

This National Park Service pull-off was built atop the foundations of Kiattinny House, built in 1829, which started the hey-day of tourism in the Gap (see Wilson, this guidebook).

On a winter day you may see the outlines of many small folds in the Bloomsburg Red Beds (Figure 1) across the Delaware River to the east (see Day 1 Road Log, Figure 1). The Bloomsburg contains fining-upwards cycles of sandstone/siltstone, shale. Many of the bedding surfaces at the base of sandstones in fining-upward cycles in the Bloomsburg Red Beds are slickensided, showing direction of movement to the northwest, regardless of the limb of the fold. Northwest-verging ramps, such as the one across the road (Figure 2) are also common. A discussion of this type of tectonic movement was given at Stop 3.

A description of the Bloomsburg in this area is given by Epstein (1973) follows:

Figure 1. Winter view of one of the folds in the Bloomsburg Red Beds near Stop 4A. The axis of the Cherry Valley anticline is off to the right of the scene; the axis of the Dunnfield syncline parallels the creek to the right. Northwest-dipping rocks of the Tammany Member of the Shawangunk Formation hold up the ridge to the far right.

> Quartzitic, limonitic, hematitic, pale-red to grayish-red-purple and greenish-gray to pale-green, crossbedded to planar-bedded, very fine to coarse-grained, partly conglomeratic sandstone with red shale clasts in beds one foot to more than ten feet thick; pale-red to grayish-red-purple, grayish-green, pale-green, greenish-gray, and dark-gray shale and siltstone with prominent cleavage, partly mud-cracked, cut-and-fill structures, scattered ferroan dolomite concretions, local fish scales; and minor conglomerate with rounded to angular quartz and lesser red jasper pebbles as much as one-half inch in length. Upward fining cycles, with basal channel sandstones, are abundant. Formation is generally finer grained higher in the section. It consists of about 50 percent sandstone, 45 percent shale and siltstone, and 5 percent conglomerate in the lower half ex-posed at Delaware Water Gap.

Epstein, Jack, 2012, STOP 4A: Resort Point Overlook, *in* Harper, J. A., ed., Journey along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and southeastern New York. Guidebook, 77th Annual Field Conference of Pennsylvania Geologists, Shawnee on Delaware, PA, p. 292-293.

Figure 2. Small structural ramps coming off a basal bedding slip in the Bloomsburg Red Beds across the road from Resort Point. Many similar northwest-verging ramps and northwest-directed bedding-pane slickensides are abundant in the Bloomsburg in eastern Pennsylvania.

An additional interesting feature at this locality is the contact between the Bloomsburg and underlying Shawangunk. The color of many beds are laterally variable over short distances. Because the Bloomsburg in eastern Pennsylvania was defined on the basis of color (Willard, 1938), the lower contact with the Shawangunk Formation was placed at base of the first red bed going up section. Thus, the contact is extremely irregular, as shown on Figure 3, and cuts across fold axes. Thus defined, the contact cuts across fold axes and rises more than 700 ft (213 m) within a horizontal distance of less than 1 mi (1.6 km) in Delaware Water Gap. Thus, the unit is 800-1,500 ft (244-457 m) thick, depending on the location of the measurement. These color variations take place in impure sandstone and siltstone and shale. Perhaps a better approach to the mapping would have been to put the contact at the top of light gray orthoquzrtites, typical of the underlyoing Shawangunk.

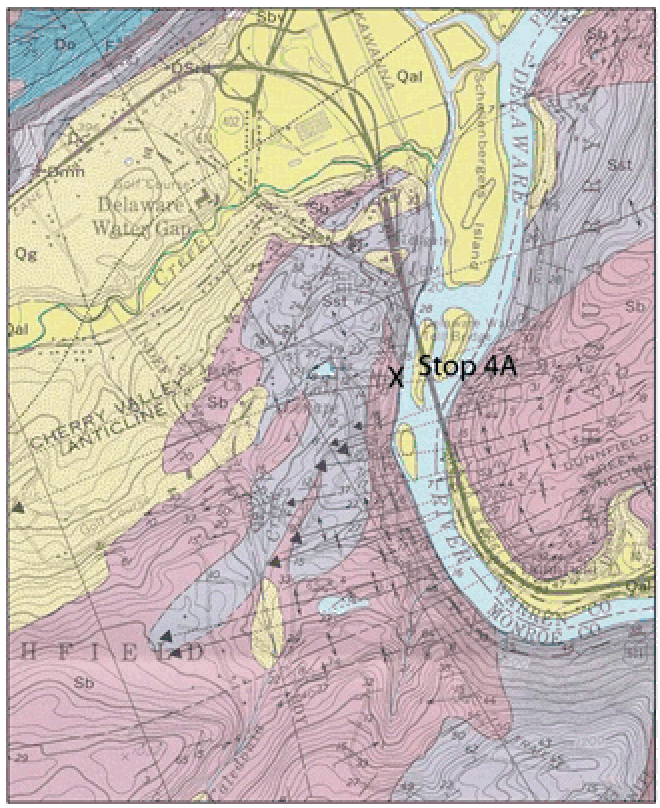


Figure 3. Geologic map of the Delaware Water Gap area (Epstein, 1973) showing the boundary between the Tammany Member of the Shawangunk Formation (Sst) and Bloomsburg Red Beds (Sb). Qal, alluvium; Qg, Wisconsinan stratified drift; Do, Oriskany Sandstone; Dc, Coeymans Formation; DSrd, Rondout Formation; Sbv, Bossardville Limestone.

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