77th ANNUAL FIELD CONFERENCE OF PENNSYLVANIA EOLOGISTS

Journey Along The Taconic Unconformity, Northeastern Pennsylvania, New Jersey, and Southeastern New York

October 18-20, 2012
Shawnee-on-Delaware, PA

Hosts:
Pennsylvania Geological Survey
U.S. Geological Survey
New Jersey Geological Survey

Guidebook for the
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Cover: Angular unconformities in geologic history: Then—James Hutton discovered this classic unconformity, where the Devonian Old Red Sandstone lies atop a Silurian graywacke at Siccar Point in Scotland, in 1787. This was his proof "that we find no vestige of a beginning, no prospect of an end." Now—The Taconic unconformity, with the Silurian Shawangunk Formation lying atop the Ordovician Martinsburg Formation, in a railroad cut in New York State. This outcrop has "gone the way of good old outcrops" (Epstein, 2012).

Cartoons: John A. Harper

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IN MEMORIAM

Thomas A. McElroy, 1949—2012

On February 8, 2012, we lost one of our former Survey colleagues, Thomas A. McElroy, to cancer at age 62. Tom passed away at home that evening after a battle with the disease that lasted for several years. He is survived by his wife, Deirdre (Dede).

Tom was born in Olean, N.Y. He served in the U.S. Air Force, including a tour of duty in Vietnam. After returning home with an honorable discharge from the military, Tom obtained a B.S. degree in geology from Harpur College of the State University of New York at Binghamton and an M.S. degree in geology from the University of Massachusetts at Amherst.

Tom came to the Survey in 1980 and worked for most of the time until his retirement in October 2010 as a hydrogeologist. He completed a number of major groundwater investigations and reports in the Allegheny Mountain section of the Appalachian Plateaus physiographic province. His countywide summaries for Fayette, Cambria, and Somerset Counties were published by the bureau. Tom also coauthored the county summaries of Indiana County, which were published by the U.S. Geological Survey. In all of these reports, Tom not only characterized the hydrogeology of the counties, but he also compiled and updated the mapping, with others, of the bedrock geology. The Somerset County report included a completely new geologic map. For this project, Tom was responsible for mapping the Mississippian Period rocks.

Tom's last hydrogeologic project was to help produce a statistical compilation of the hydrogeologic and well-construction characteristics of the geologic units of the state geologic map, and he was a coauthor of the resulting report, Water Resource Report 69. For that project, Tom reviewed each of the approximately 50,000 well records used to determine the appropriate geologic formation and physiographic section in preparation for the statistical analysis, probably his earliest foray into the use of GIS as an analytical tool.

After having done bedrock geologic mapping as part of his hydrogeological studies, it was not a major change when in his last few years with the Survey, he transferred to the Mapping Division. He first mapped the Great Bend 7.5-minute quadrangle in northeastern Pennsylvania. Then he began mapping the complexly folded and faulted bedrock in the Ridge and Valley province, in collabo-ration with retired State Geologist Don Hoskins. Together, with Tom as principal geologist, they prepared new detailed bedrock geologic maps for a number of topographic quadrangles in the Ridge and Valley province of central Pennsylvania—Lewistown , Belleville, Allensville, Newton Hamilton, McVeytown, and McCoysville. Each was published as a digital report and full-scale map.

As a result of their mapping work, Tom and Don organized and led the 72nd Annual Field Conference of Pennsylvania Geologists in 2007, *Geologic Mapping—"Walkabouts" in central Pennsylvania—1st-to-5th-Order Appalachian Mountain Folds; Folded Thrusts; Ordovician and Silurian Carbonates; Silurian Quartzites and Sandstones*.

Tom's mapping in both the Plateaus and the Ridge and Valley provinces resulted in articles in *Pennsylvania Geology* highlighting interesting and/or rare features that he discovered. Notable of these was Tom's article on recently exposed rocks on the west side of Lewistown, whose complicated geology led him to denote the area as "Oz".

Tom was also a long-time participant in the annual Field Conference of Pennsylvania Geologists. In addition to being a co-leader at the 2007 conference, he also co-led trips in 1993 (Somerset County) and 2002 (Tunkhannock). As a volunteer as well as a participant, he helped with the logistics of the trips.

Tom retired in October 2010, partly to concentrate on his health issues. He continued to participate in geologic activities until his health no longer permitted it. All of us who knew and worked with Tom miss his presence in our ranks.

Gary M. Fleeger and Donald M. Hoskins

IN MEMORIAM

John H. Way, 1943—2012

John H. Way, a former staff geologist at the Pennsylvania Geological Survey and later a professor of geology at Lock Haven University, died on February 21, 2012, in Williamsport following a brief illness. He joined our staff in 1971 and stayed for 15 years, making lasting contributions both as a field geologist and as a geological editor, before accepting a position on the faculty at Lock Haven University (LHU) in 1986.

John was born in Philadelphia in 1943 and grew up in the nearby community of Yeadon. His love of nature and geology was aroused early during visits to the Delaware County Institute of Science in Media, PA. There, under the mentorship of curator Harold W. Arndt, John developed an interest in mineralogy and geology. In addition to unique specimens that John was able to view there, John was inspired by Harold's stories of his field experiences with Sam W. Gordon's mineral collecting excursions in Pennsylvania, on which Harold had been the unofficial photographer. John started his own collection, and some of his favorite mineral-collecting areas are believed to have been Bancroft, Ontario; Herkimer, NY; and the Keystone Trappe rock quarry at Cornog, Chester County, PA.

John majored in geology at Franklin and Marshall College and earned an A.B. degree in 1965, followed by an M.S. degree in 1967 from the University of Pennsylvania and a Ph.D. in 1972 from Rensselaer Polytechnic Institute in Troy, NY. His master's degree research was a study of the sedimentary rocks that preserve a Carboniferous fossil forest that is exposed in cliffs along the Bay of Fundy near Jog-gins, Nova Scotia. His doctoral research was a study of the depositional environment and the potassium, uranium, and thorium content of Middle and Upper Devonian rocks in the Catskill Mountains of New York. While studying in Troy he met Roberta (Bobbie) Seibert, who became his wife of over 40 years. John and Bobbie raised a daughter, Mary.

During his years at the Survey, John was responsible for completing several major publications, most notably a major study of the geology of the Altoona area, *Geology and Mineral Resources of the Blandburg, Tipton, Altoona, and Bellwood Quadrangles, Blair, Cambria, Clearfield, and Centre Counties, Pennsylvania,* published with Rodger T. Faill and Albert D. Glover as Atlas Report 86 in 1989, and another Atlas Report, 154cd, *Geology and Mineral Resources of the Washingtonville and Millville Quadrangles, Montour, Columbia, and*

Northumberland Counties, Pennsylvania, published in 1993. But these reports barely tell the story of John's contributions here. He published many articles in *Pennsylvania Geology* and articles and abstracts in such outside publications as the Geological Society of America Abstracts with Programs and the guidebooks of the Field Conference of Pennsylvania Geologists, many coauthored with Survey colleagues. Research topics included the Devonian Tioga Ash Beds and Bald Hill Bentonites (with Robert C. Smith, II, Samuel W. Berkheiser, and Mary K. Roden), 19th century iron-making at Pine Grove Furnace, and the geology of South Mountain, Cumberland County. He also was a coauthor with Thomas M. Berg, Michael K. McInerney, and David B. MacLachlan of the Survey's *Stratigraphic Correlation Chart of Pennsylvania* (the "strat chart").

John's contributions to understanding the geology of the Ridge and Valley physiographic province and the economic geology of Pennsylvania were, and continue to be, significant. For example, the "strat chart" helps to define the framework of the Marcellus and Utica shale gas horizons. The Survey's Tioga Ash Bed study provided information on the base of the Marcellus play zone, but also delineated the correct direction of time transgression relative to lithologic facies. His careful work on volcanic ash beds in the Middle and Upper Ordovician Union Furnace section helped establish that exposure as Pennsylvania's de facto type section for those beds and the basis of the bentonite nomenclature used in Pennsylvania. His work on the lowermost Devonian Bald Hill Bentonites arose from the hypothesis that termination of extended periods of carbonate deposition would be marked by volcanic ash beds. The ashes marking the end of the Silurian Wills Creek, Tonoloway, Keyser, Coeymans, and New Scotland carbonates were found within an hour of searching in the transition to the lowermost Devonian Mandata black shale at Bald Hill, Blair County. Weekend trips with family eventually extended the known range of surface exposures of the Bald Hill Bentonites from near the Adirondack Mountains in New York to McDowell, WV. In the process, the resulting detailed stratigraphic sections disproved a then-current assumption that punctuated aggradational cycles (PACs) were time-stratigraphic surfaces.

Despite John's contributions that helped set the stage for the Marcellus gas development, he was concerned about its potential impact on the environment. John never profited from the Marcellus but, true to his principles, he volunteered countless hours to conservancies in central Pennsylvania seeking to protect watersheds.

John's ability to write in a clear and interesting way for the nongeologist was amply demonstrated in his publication, *Your Guide to the Geology of the Kings Gap Area, Cumberland County, Pennsylvania,* published by the Survey in 1986. John also used his excellent communication and writing skills to advantage during a three-year stint as a geologic editor at the Survey, from 1974 through 1977, when he helped convert a number of Survey publications from rough manuscripts to finished products. He performed a similar task as a volunteer, spending many hours of his personal time as the editor of the 300-page book, *The Mineralogy of Pennsylvania, 1966-1975,* by Robert C. Smith, II, published by the Pennsylvania Chapter of Friends of Mineralogy in 1978. To this same work, John contributed more than 50 finely executed pen-and-ink sketches. From alloclasite to the back piece geologic time scale, all of the drawings were drafted by John.

At Lock Haven, John proved to be a very effective teacher, conveying to his students not only his technical expertise, but his love of nature and excitement about the geological processes that shape the earth. John received the Teaching and Learning Center's Peers Choice

Award at LHU in 2004. Through papers published while he was there, he made significant contributions to understanding the regional and environmental geology of the Lock Haven and Williamsport areas. Among his contributions were four field guidebooks covering the geology of the Erie, Gettysburg, South Mountain, and Johnstown areas. He also made one additional contribution to the Survey while teaching at LHU, authoring the chapter on the physiography of the Appalachian Mountain section for the Survey's *Geology of Pennsylvania* compendium.

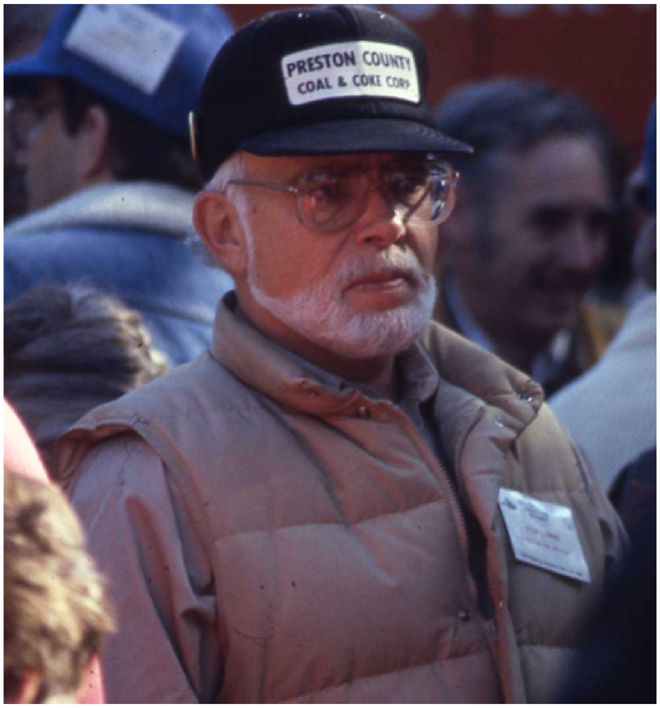
John's enthusiasm and energy were infectious. Anyone who came into contact with him was uplifted and energized by John's positive outlook and the joy that he took in everything that he did. This extended well beyond his work to include his community, his church, and his family. Those of us who were privileged to know and work with John are the better for it, and we will miss him.

John H. Barnes and Robert C. Smith, II

IN MEMORIAM

William E. Edmunds, 1932—2010

Another long-time participant of the Field Conference died on August 21, 2010. Bill Edmunds was largely a fixture at the annual conference for many years. He also was a co-leader of 6 Field Conferences during the 1980s and 1990s: 1981- Wellsboro; 1986- Huntingdon; 1988- Hazelton; 1993- Somerset; 1996- Chambersburg; 1997- Scranton



Bill worked for the Survey from 1960 to 1977, when he left for the world of consulting. He was an expert on the stratigraphy and sedimentology of the Pennsylvanian and Mississippian of the central Appalachians. In fact, there was hardly anything in geology that he couldn't explain. Likewise, there were few non-geological things that he didn't know anything about. He understood astronomy, physics, chemistry, botany and zoology, philosophy, Greek mythology, American history, photography, and, as the saying goes, "The list goes on and on."

Bill was a 'mentor' to many Survey (and other) geologists. He was a very intelligent person who was always willing to help someone understand rather complex stratigraphy, and he had a wonderful sense of humor. Bill was easy to learn from because he had the ability to take a complex concept or discussion, synthesize the main points, ignore unimportant details and rephrase the concept in plain language.

He was also a premier coal geologist who was responsible for following up what George Ashley had started. His work at the Survey during 1960s and early 1970s was first class in terms of both quantity and quality. The coal stratigraphy of Clearfield County is complex, and is further complicated by numerous strike slip faults. He, Tom Berg, Gary Glass, and Al Glover mapped most of the county, all under Bill's supervision as Chief of the Coal Section from 1967 to 1977. His contributions to the Survey far overshadowed many others.

Bill was extremely productive. For example, he single-handedly produced the last statewide accounting of coal reserves with the 1972 publication of Information Circular 72, *Coal Reserves of Pennsylvania: Total, Recoverable and Strippable (January 1, 1970).* In 2009, an analysis of the cost of re-evaluating the coal reserves for the entire Commonwealth resulted in an estimate somewhere in the neighborhood of $20 million. Bill was also responsible in 1966 for the initiation of TASIC (Temporarily Available Stratigraphic Information Collection). That program acquired large amounts of data from temporarily exposed strip-mine highwalls, and has since been expanded to include any temporary exposures.

He was the leader in defining the stratigraphy of the Mississippian in Pennsylvania. His last major work is a Magnum Opus of the Mauch Chuck Formation, and is currently being prepared for publication by the Survey.

William A. Bragonier, Gary M. Fleeger, and Tom Berg

Group Photo of the 2011 Field Conference of Pennsylvania Geologists at Phil Myers' Farm in West Virginia (photo by Yuriy Neboga).

A JOURNEY ALONG THE TACONIC UNCONFORMITY: INTERPRETATIONS, PERPLEXITIES, AND WONDERMENTS NORTHEASTERN PENNSYLVANIA, NORTHERN NEW JERSEY, AND SOUTHEASTERNMOST NEW YORK

Jack B. Epstein and Peter T. Lyttle
US Geological Survey
Reston, VA

Introduction

The “transitional” contact between Silurian and Ordovician rocks in central Pennsylvania becomes unconformable in eastern Pennsylvania to southeastern New York as the hiatus widens (Figure 1). Following the northeastward decrease in intensity of deformation in the Ridge and Valley through New Jersey, this trip will begin with the high-angle contact between the Tuscarora and Hamburg sequence at the Schuylkill River and proceed for 120 mi (193 km)

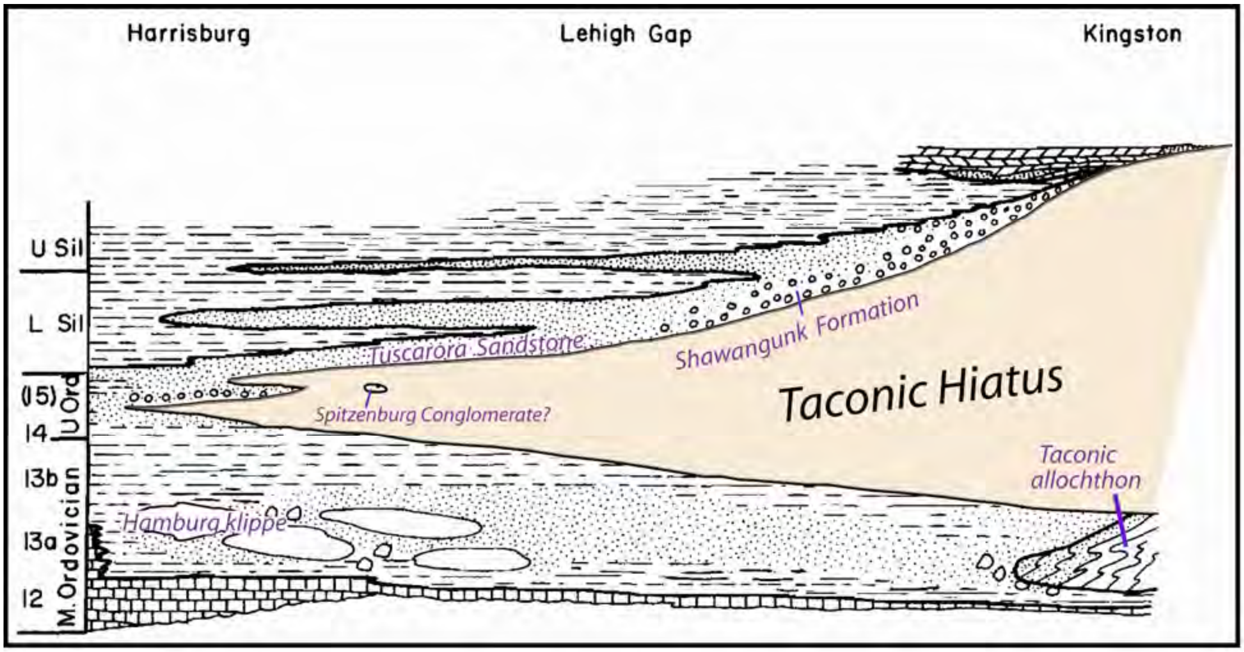


Figure 1. Schematic diagram showing the increasing west-to-east hiatus between Ordovician and Silurian rocks from south-central Pennsylvania to southeastern New York (modified from Rodgers, 1971, p. 1145). The continuous but sporadic sedimentation of Ordovician through Silurian rocks west of Harrisburg, PA, is represented by Martinsburg (or Reedsville) shales overlain by Bald Eagle (or Oswego) sandstones, then Juniata red beds, and finally sandstone of the Tuscarora. At the east end of the area in the diagram the Shawangunk pinches out and Late Silurian rocks overlie Ordovician rocks of the Taconic allochthon. This implies that the base of the Shawangunk and Tuscarora transgresses eastward from the Lower Silurian to Upper Silurian, a fact not in evidence as yet. Note that no Middle Silurian is recognized in untainted stratigraphic understanding, despite the inclusion of same elsewhere in this guidebook.

Epstein, J.B. and Lytle, P.T., 2012, A journey along the Taconic unconformity: Interpretations, perplexities, and wonderments, northeastern Pennsylvania, northern New Jersey, and southeasternmost New York, *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. 1-36.

along the very low-angle unconformable contact between Lehigh Gap, PA and Ellenville, NY. Past geologists have compared and rated Taconic and Alleghanian tectonism based on perceived geologic relations on either side of the contact, leading to continuing debate that has persisted for more than 170 years. The age and stratigraphic framework of the Ordovician rocks also has been disputed. The goal of this trip is to examine many localities along the contact, so that individual interpretations will benefit from the detailed mapping by the New Jersey, Pennsylvania, and U.S. Geological Surveys. By discussing our interpretation of the relative intensities of deformation, we will suggest predominant Alleghanian deformation along the contact and propose zones of increasing southeastward Taconic deformation away from the contact. The perplexing story of events during the Taconic hiatus, lasting perhaps 10-30 million years, will be illuminated by an unusual diamictite in southeastern New York. Several glaciations have profoundly affected the landscape of this area, especially the latest Wisconsinan. We cannot limit ourselves to bedrock geology on this trip, so the effects of glaciation also will be highlighted.

The Field Conference of Pennsylvania Geologists has visited many sites along the Ordovician-Silurian boundary in the past; several of those are unabashedly plagiarized on this trip, although new thoughts will be entered into the record. It offers an opportunity for younger geologists to see these exposures for the first time. At the time of preparation for this trip, access to a couple of the stops was in jeopardy, so alternative stops have been prepared. As a sad note, access to many instructive geologic localities has declined over the past many years due to safety, litigation, and terrorist-security concerns. We lament this loss and hope that the documentation in this field-trip will record some of these sites for posterity.

THE STOPS

Ten stops are planned for this field conference (see map on p. 166). They include:

1. Schuylkill Gap, PA—right-angle contact between Ordovician rocks of the Hamburg klippe and Tuscarora Sandstone; “Appalachian” structure in post-Ordovician rocks; greywacke.
2. Penn Big Bed Slate Quarry, PA—Stratigraphy and structure of the upper Martinsburg Formation.
3. Lehigh Gap, PA—Unconformity between the Shawangunk (Silurian) and Martinsburg (Ordovician) formations; folds and faults; northwest translation on bedding faults; rockfall mitigation.
4. Delaware Water Gap, PA—Silurian stratigraphy; slaty cleavage and age of deformation.

4A. Resort Point Overlook, Delaware River, PA—Bloomsburg wedges; defining a red bed formational boundary; history of tourism (*time permitting*).

5. Yards Creek Pump-Storage Generating Station, NJ—Martinsburg slaty cleavage affected by unconformably overlying Silurian rocks.
6. Home Depot parking lot, Newton, NJ—Retrodeforming Martinsburg deformation.
7. Lusscroft Farm and Beemerville syenite, NJ—An early Silurian intrusion into the Martinsburg Formation and unconformably overlain by the Silurian Shawangunk Formation.

8. High Point State Park, NJ—Summary of the Taconic unconformity in northern New Jersey; the Shawangunk Formation elucidated; regional glaciations.
9. Otisville railroad cut, NY—Two classic unconformities, Holocene and Taconic; enigmatic diamictite at the Taconic boundary that requires explanation.
10. Ellenville arch, NY—Retro-deformation of the Shawangunk and Martinsburg Formations; deformation zones in the Martinsburg Formation.

Stratigraphy of Rocks above and below the Taconic Unconformity, Northeastern Pennsylvania, New Jersey, and southeastern New York

A variety of rocks, in many structural configurations, are exposed for more than 110 mi (177 km) above and below the unconformity separating Ordovician and Silurian rocks in northeastern Pennsylvania, New Jersey, and southeastern New York (Figure 2). The basal Silurian clastic units, the Shawangunk Formation transitioning into the Tuscarora Sandstone in the southwest, is succeeded by a variety of sandstones, shales, and some red beds of the Clinton Formation, which is overlain by sandstone and fine clastics of the Bloomsburg Red Beds. In central New Jersey and New York the Shawangunk, also termed the Green Pond Conglomerate, bevel across Ordovician-through-Precambrian rocks in a narrow faulted syncline about 15 mi (25 km) southeast of the main ridge of Silurian rocks in New Jersey and New York. That ridge is named Blue, Kittatinny, and Shawangunk Mountain from southwest to northeast in the trip area.

The Ordovician rocks are dominated by several members in the Martinsburg Formation (Figure 2), having suffered (enjoyed?) a history of nomenclatural variation, related to discussions of its age, stratigraphic variations, and structural framework. These discussions have gone on for more than 150 years, and it is not over yet. Likewise, the Silurian rocks have had an interesting nomenclatural history, culminating in the interesting facies relations shown in Figure 3. Summaries of the stratigraphic units within the field trip area are given in Appendices 1 and 2.

Ordovician Rocks

The Martinsburg Debate

The southwest section of the field trip area is dominated by rocks of the far-travelled Hamburg klippe and by sandstones and shales comprising a deep syncline in Shochary Ridge (see Appendix 1). This is part of an area full of puzzlements, discussed at Stop 1, under the designation “Hamburg Triangle”.

The subdivision of the Martinsburg Formation in eastern Pennsylvania and New Jersey has been debated for nearly 100 years, and has been the discussed on several of our previous Field Conferences (1967, 1982, 1984, 2001). To plagiarize from Epstein (2001, p. 6-8), the arguments have been based on both faunal and structural evidence. In general, those workers who have studied the Martinsburg west of the Lehigh River have divided it into two parts, a lower slate unit and an upper sandstone unit (e.g., Stose, 1930; Willard, 1943; Wright and Stephens, 1978). In the Delaware Valley many geologists favor a tripartite subdivision, two slate belts separated by a middle sandstone-bearing unit. Behre's (1933) work was the most

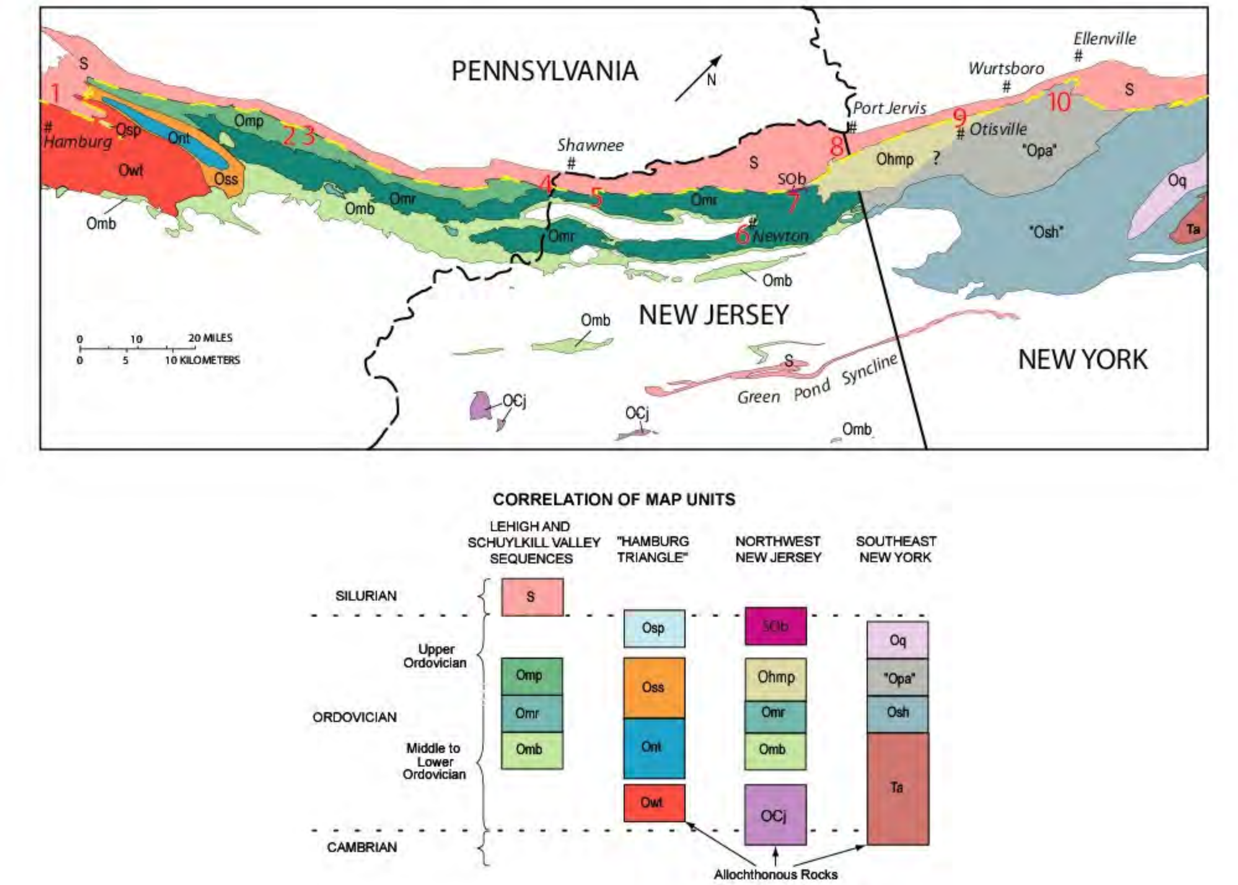


Figure 2. Geologic map showing stratigraphic units straddling the Ordovician-Silurian contact in eastern Pennsylvania, northern New Jersey, and southeastern New York. The Taconic unconformity is shown by the dashed yellow line. See Appendix 1 for description of stratigraphic units. S—Silurian rocks, Bloomsburg Red Beds, Clinton Formation, Tuscarora Sandstone, and Shawangunk Formation; Omp—Pen Argyl Member of the Martinsburg Formation; Omr—Ramseyburg Member of the Martinsburg Formation; Omb—Bushlkill Member of the Martinsburg Formation; Osp—Spitzenburg Conglomerate and sandstones at Sharps Mountain (the lovely hill, Spitzenburg [see Day 1 Road Log, Figure 13], is the easternmost of the two exposures); Oss—Shochary Sandstone of the Shochary Ridge sequence; Ont—New Tripoli Formation of the Shochary Ridge sequence; Owt—Windsor Township Formation in the Hamburg klippe; Sob—Beemervillesyenite intrusion; Ohp/Omk—High Point Member of the Martinsburg Formation/shale and greywacke at Mamakating and Sandstone at Pine Bush of Epstein and Lyttle (1987); OCj—rocks of the Jutland and Peapackklippen; "Opa"—Pen Argyl shale of Rogers et al. (1990), and Austin Glen Formation of Fisher et al. (1971); Osh—Snake Hill of Rogers et al. (1990), and Normanskill Shale of Fisher et al. (1971); Ta—rocks of the Taconic allochthon. Modified from Lyttle and Epstein (1987), Drake et al. (1996), Fisher et al. (1970), and Rogers et al. (1990).The "Hamburg Triangle" is discussed at Stop 1.

detailed in the slate belt, but his threefold subdivision was not accepted on the 1:250,000-scale, 1960-vintage Pennsylvania state geologic map (Gray et al., 1960), although the three belts of rock are clearly shown. Those who support a two-member division maintain that the northern slate belt is actually the southern slate belt repeated by folding. Detailed stratigraphic and structural evidence presented later by Drake and Epstein (1967) showed that the Martinsburg can be divided into three mappable members (see Appendix 1) in almost the same way as

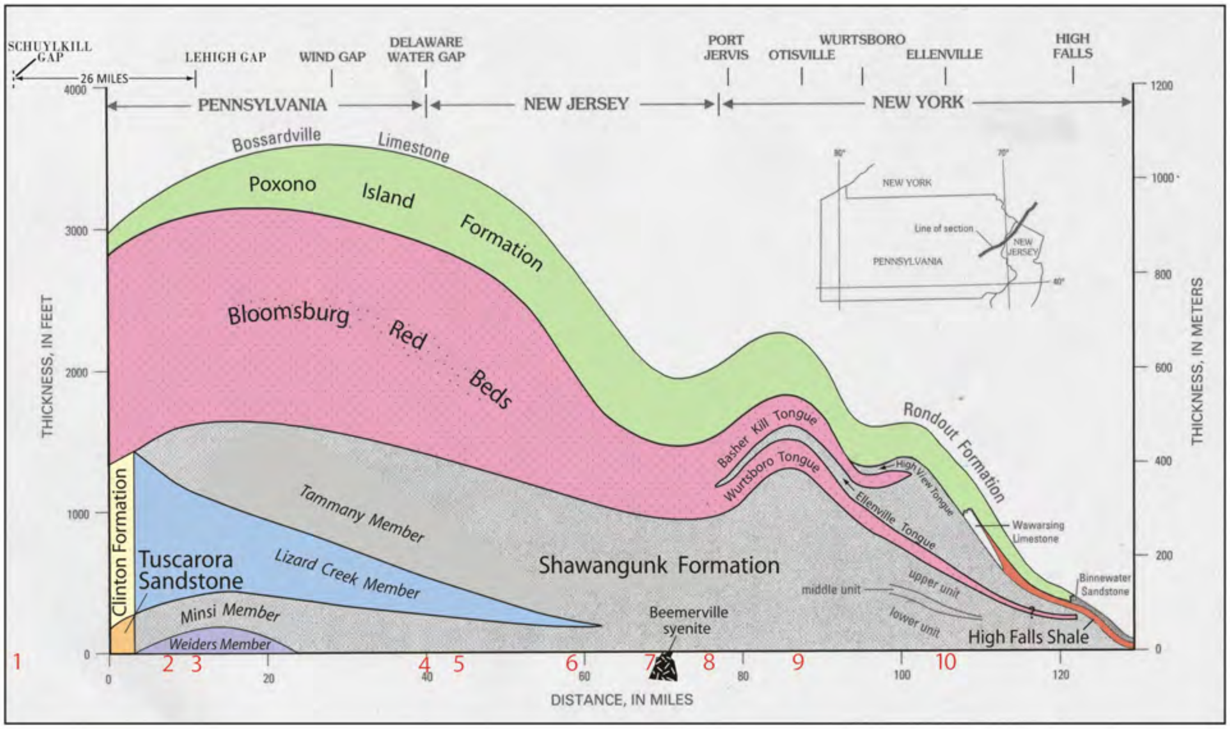


Figure 3. Generalized stratigraphic section of Silurian rocks between Schuylkill Gap in eastern PA to High Falls, NY, showing facies relations between the Bloomsburg Red Beds, High Falls Shale, Shawangunk Formation, Clinton Formation, and Tuscarora Sandstone. Red numbers are position of field stops perpendicular to the strike of the Ordovician-Silurian contact. Modified from Epstein (1993).

defined by Behre (1933). This should not be surprising because the best geologists of all, the slate quarrymen who have toiled over the Martinsburg since the first half of the 19th century, have long recognized two distinct slate belts in the Martinsburg Formation of eastern Pennsylvania and northwestern New Jersey – the "hard slate" belt in the south and the "soft slate" belt in the north. They are separated by a zone that contains a poorer quality of slate because appreciable graywacke is interbedded with the slate. Those who accepted a two-fold interpretation have estimated that the Martinsburg is as thin as 3,000 ft (915 m) (Stose, 1930), whereas those who support the idea of three members have estimated thicknesses of more than 10,000 ft (3,050 m) (Behre, 1933; Drake and Epstein, 1967). Wright et al. (1979) recognized five graptolite zones in the Martinsburg Formation in the Lehigh River area and suggested that the Pen Argyl and Bushkill Members are the same age and are simply repeated by folding. This contradicts detailed mapping in the Lehigh River area (Epstein et al., 1974; Lash, 1978), as well as in the Delaware Water Gap area (Epstein, 1973, 1990) which clearly shows that the Bushkill, Ramseyburg, and Pen Argyl Members are part of a progressively younging sequence – the Pen Argyl stratigraphically overlies the Ramseyburg as is demonstrated wherever there are adequate exposures at or near the contact. Where the Ramseyburg structurally overlies the Pen Argyl, it can be shown that the contact is overturned (e.g., Epstein, 1980, fig. 6). Furthermore, the lithic characteristics of the Bushkill and Pen Argyl are very different.

The Bushkill is a ribbon slate – beds are never more than 6 in (15 cm) thick and are generally less than 2 in (5 cm) thick. This laminated to thin-bedded characteristic is present everywhere in the member over an outcrop width of nearly 5 mi (8 km) in places and an outcrop length of more than 30 mi (48 km) in Pennsylvania. The Bushkill extends for more than 30 mi (48 km) in the Great Valley of New Jersey to and beyond the New York border. The overlying Ramseyburg Member comprises about 20 percent graywacke. The slates in the graywacke are thin bedded at the base and become thicker bedded upwards. The first 1,000 ft (300 m) or so of the Pen Argyl Member, immediately overlying the Ramseyburg, is well exposed in a belt of quarries in the Wind Gap and Bangor area, and is characterized by thick-bedded slates, some of which are more than 20 ft (6 m) thick. Most of these quarries are now inactive and flooded, but we will visit one of the few active ones on the first day of the field trip at Stop 2. The thick clear slate beds are the source for many pooltables. The thick-bedded material is not repeated south of the Ramseyburg outcrop belt, a fact long known to the slate quarrymen of the area.

The patterns of graptolite distribution of Wright et al. (1979) are used as evidence that the upper and lower Martinsburg members are the same age. An alternate explanation is that graptolites suffer from facies control just as do all paleontologic groups, and there are recurrent faunas in the two slate members (see Lash et al., 1984, p. 80-81; Finney, 1985). A study of graptolites in the Delaware Water Gap area by Parris and Cruikshank (1992) supports the three -fold interpretation. The most recent geologic map of Pennsylvania (Berg et al., 1980) avoids the issue by showing the three belts on the map, with the northern and southern belts apparently repeated by folding, but also by showing slate units both above and below the greywacke-bearing Ramseyburg Member in the explanation. Lyttle and Epstein (1987) have depicted the regional relations of the three members of the Martinsburg in eastern Pennsylvania.

Ordovician Rocks in the Wallkill Valley, Southeastern New York

The following discussion is unabashedly adapted from Peter Lyttle (*in* Epstein and Lyttle, 1987).

There has been, and continues to be, a great deal of confusion when dealing with the Ordovician clastic sediments of southeastern New York State. A brief (and by no means exhaustive) review highlighting some of the earlier work in these rocks is helpful to emphasize the complex history of names, and establish proper correlation of units. All the rocks in the area from south of Rosendale, New York, to the New Jersey border in the Wallkill Valley are considered to be units of the Martinsburg Formation (see Epstein and Lyttle, 1987, fig. 1.

In the Wallkill Valley, a thick section of glacial deposits covers much of the bedrock. Insofar as this makes structural analysis of the rocks in places difficult, if not impossible, this has a definite influence on resolving the stratigraphy. The tracing of faults and sometimes folds in the Ordovician rocks is extremely difficult, which explains why I and other geologists such as Vollmer (1981) and Kalaka and Waines (1986) have chosen to divide map areas into structural domains that can be defined in general descriptive terms. Added to this is the century-old problem regarding which Ordovician clastics in the Hudson Valley region are part of the far-traveled Taconic allochthon and which are part of the parautochthonous flysch that rests conformably on Middle Ordovician carbonates of the North American shelf. This is a problem that seems to be satisfactorily resolved to the southwest in New Jersey and Pennsylvania (Perissoratis et al., 1979; Lash and Drake, 1984; Lash, 1985; Lash et al., 1984) but remains a critical problem in parts of southern New York State, particularly along the Hudson River. There is an irony to this, since the existence of the far-traveled rocks was recognized much later in Pennsylvania (Stose, 1946) than in New York.

Mather (1840) first proposed the name "Hudson River slate group" for rocks that he had previously referred to as "transition argillite" (Mather, 1839). Subsequently, this name has seen at least seven variants including Hudson River Series, Hudson River Group, and Hudson River Formation. In addition to the variations in the name, the use of these names has been extended north into Canada and as far west as Wisconsin. Holzwasser (1926) gives a useful account of the tortured history of Hudson River nomenclature; unfortunately, she also decided to use the name Hudson River formation for the shales and graywackes of the Newburgh Quadrangle. Although the name has generally been abandoned since Ruedemann's work in the beginning of this century, it is still loosely used and misused in a variety of publications to this day. Ruedemann (1901, p. 561) first used the name Normanskill Shale for rocks in the gorge of the Normans Kill near Kenwood, New York. This type locality turns out to be one of the more spectacular exposures of melange in the northern Appalachians, as attested to by the extremely detailed mapping of the structures by Vollmer (l981). It should not be too surprising, therefore, that there has also been considerable confusion in the use of this geologic name. Later, when mapping the Catskill quadrangle, Ruedemann (1942) recognized two belts of rock that he included in the Normanskill Shale. The western "grit belt" was named the Austin Glen Member and the eastern "chert belt" was named the Mount Merino Member. Most geologists today would agree that both of the type localities for these members are within the Taconic allochthon (*sensu stricto*); that is, the rocks are part of the far-traveled slope-rise sequence. The name Snake Hill Shale was first used by Ulrich (1911), although he based his discussion on the work of Ruedemann who later published a number of papers using this name (Ruedemann, 1912, for example). The type locality for this unit is on the east side of Saratoga Lake. Berry (1963) suggested abandoning the name because restudy of this region showed that what was mapped as Snake Hill contains three different lithic units, all of which contain elements of the distinctive fauna that Ruedemann used as the unit's diagnostic feature. This points to yet another problem in the nomenclature of the clastics of the Hudson Valley region. Ruedemann and others often failed to discriminate between biostratigraphic and lithostratigraphic units, making it extremely difficult for later workers to fully appreciate the problems inherent in using a particular name.

More recently, Fisher (1962) and Offield (1967) have used the names Mount Merino Shale, Austin Glen Graywacke, and Snake Hill Shale for the lower, middle and upper units of the parautochthonous Middle and Upper Ordovician shales and graywackes that are found west of the Hudson River in the Wallkill Valley. Later, Fisher (1969, 1977; and Fisher et al., 1970) made a number of modifications to the mapping and naming of Ordovician clastic units in the vicinity of the Hudson River at the latitude of our field trip, but very little new work closer to the unconformable contact with the Silurian Shawangunk to the west has been published. For a summary of the most recent work near the Hudson River, particularly in the region underlying Marlboro and Illinois Mountains, see Waines (1986).

Offield (1967) produced a wealth of new stratigraphic and structural information in the Goshen 15-minute quadrangle (Middletown, Goshen, Warwick, and Pine Island 7.5-minute quadrangles) and recognized that his units might correlate with Behre's (1933) tripartite subdivision of the Martinsburg Formation in Pennsylvania. This subdivision was later refined by Drake and Epstein (1967) who recognized a lower thin-bedded slate unit called the Bushkill Member, a middle graywacke-rich unit called the Ramseyburg Member, and an upper thick-bedded slate unit called the Pen Argyl Member. Berry (1970) was one of several people to recognize significant similarities between the Delaware Valley sequence of Drake and Epstein and the sequence of rocks in the Wallkill Valley (Fisher, 1962; Offield, 1967). I feel that all of the names that Offield (1967) chose for the units of what he refers to as "the shale sequence" in the Wallkill Valley should be discontinued. One reason to do this is to avoid unnecessary confusion with the Normanskill Shale and its members that are clearly part of the far-traveled Taconic allochthon. Another reason, which is even more important, is that a better correlation can be made with units mapped in Pennsylvania and New Jersey. I have not done all of the detailed mapping that is necessary to establish these correlations in detail, but I feel confident that the correlations proposed herein are correct overall.

I believe that it is appropriate to refer to all of the parautochthonous Ordovician clastics in the Wallkill Valley as the Martinsburg Formation of Middle to Upper Ordovician age. All of the Ordovician clastics in the Great Valley from eastern Pennsylvania through northern New Jersey to the New York State border have been mapped in detail (1:24,000 scale), and summarized in Drake et al., 1996. The parautochthonous sequence west and southwest of Albany, New York, is not contiguous with the rocks of the Wallkill Valley; nor has the stratigraphy of the rocks near Albany been done in sufficient detail to warrant using the names established for that area in the Wallkill Valley.

There has been debate in eastern Pennsylvania over whether the Martinsburg is a tripartite sequence with a lower slate member, a middle graywacke member, and an upper slate member, or a bipartite sequence with an upper graywacke member and a lower slate member (see Lash et al, 1984, for a summary of this debate). I feel strongly that the published detailed mapping, which ultimately must answer all questions of this sort, supports the tripartite subdivision first discussed by Behre (1933) and later named along the Delaware Valley by Drake and Epstein (1967). The question that must now be answered is, how far away from the Delaware Valley can the three members of the Martinsburg be mapped? The upper Pen Argyl Member, which contains thick-bedded slates (up to 25 ft [8 m] thick), has been extensively quarried in Pennsylvania from the New Ringgold 7.5-minute quadrangle in the west, a few mi (km) east of the Schuylkill River, to the Stroudsburg 7.5-minute quadrangle in the east where it disappears beneath the Silurian Shawangunk Formation by structural overlap (Epstein, 1973). Based on my mapping and that of other geologists, it is not found in northern New Jersey and southern New York. However, the Pen Argyl correlates in part with rocks that I have mapped in the western Wallkill Valley unconformably beneath the Shawangunk, and that I am herein informally naming the shale and graywacke at Mamakating, subsequently called the Mamakating (Epstein and Lyttle, 1987, fig. 2). The Mamakating represents the upper part of the Martinsburg in the western Wallkill Valley and is named for the excellent exposure seen at Stop 7 along Route 17 (just east of Wurtsboro exit) in the eastern part of the Mamakating Township. The Mamakating first appears from beneath the Shawangunk in the Otisville 7.5-minute quadrangle, New York and extends northeastward. All of the Martinsburg we shall be seeing on this field trip is within the Mamakating. The Ramseyburg Member extends from the New Tripoli, 7.5-minute quadrangle, Pennsylvania, about 12 mi (7.5 km) east of the Schuylkill River, to the Middletown 7.5-minute quadrangle, New York. To the northeast it correlates for the most part with a unit that we are herein informally calling the sandstone at Pine Bush. The sandstone at Pine Bush extends from the High Point area of New Jersey through the Middletown and Pine Bush 7.5-minute quadrangles, New York, where it is thickest, and appears to die out somewhere in the vicinity of the southwest corner of the Gardiner 7.5-minute quadrangle. There are excellent exposures of the Pine Bush along Route 17K that underlie the unnamed hills 1.6 mi (1 km) west of Montgomery, New York, in the Pine

Bush 7.5-minute quadrangle. Since the details of the facies changes in the middle and upper Martinsburg have not been sufficiently mapped in southern New York State, it is safest to say that the combined Ramseyburg and Pen Argyl correlates with the combined Pine Bush and Mamakating. It may eventually be determined that the Pen Argyl correlates with all of the Mamakating and the uppermost Pine Bush. The Mamakating is everywhere unconformably overlain by the Shawangunk Formation. It grades conformably downward and laterally into the Pine Bush, and the contact is arbitrarily put where beds of medium-grained, clean protoquartzite make up more than 5 percent and are thicker than 2 in (5 cm). In most places in the Wallkill Valley the Pine Bush grades upward into the Mamakating, but to the southwest near High Point, New Jersey, it is unconformably overlain by the Shawangunk Formation. We have not done enough detailed mapping in the Pine Bush, Walden, and Gardiner 7.5-minute quadrangles, New York, to resolve what happens to the Pine Bush to the northeast. From reconnaissance, it would appear to pinch out and grade laterally into the Mamakating somewhere near the northeast corner of the Pine Bush quadrangle. The lower Bushkill Member of the Martinsburg has, by far, the greatest areal extent of the three members of Drake and Epstein (1967). It extends as far southwest as Reading, Pennsylvania (and probably considerably farther) and northeast at least as far as the Newburgh, New York area.

Several very general points can be made about the Martinsburg Formation. From eastern Pennsylvania to the field trip area in southern New York, the composite thickness of the Martinsburg appears to remain fairly constant with ranges estimating from about 8,000 to 12,800 ft (2,440 to 3,900 m). It is possible that the thickness decreases going towards the northeast, perhaps by as much as 3,000 ft (915 m). All thickness estimates may be on the generous side, because of the large number of thrust faults that duplicate portions of the unit, particularly the lower Bushkill Member.

The sedimentology of the lower part, or Bushkill Member, of the Martinsburg remains remarkably constant along strike from eastern Pennsylvania through southern New York. However, the middle part of the Martinsburg shows considerable facies variation along strike. To the southwest in Pennsylvania, the Ramseyburg Member rarely contains more than 20 percent medium- to very thick-bedded graywacke beds. Also, going up-section in the Ramseyburg, the thickness of slate beds increases dramatically near the contact with the Pen Argyl. From High Point, New Jersey northward, the Pine Bush (~ lower part of the High Point Member of Drake (1990) commonly contains up to 50 percent clean, medium- to very thick-bedded sandstone, and as best as we can tell from reconnaissance, the thickness of shale beds does not increase going up in section. Both of these factors would appear to suggest that the middle part of the Martinsburg is becoming more proximal to the northeast. The upper part of the Martinsburg also shows dramatic facies changes along strike. Although this part of the section is dominated by shales or slate everywhere, in eastern Pennsylvania, slate beds in the Pen Argyl Member are commonly 12 ft (3.7 m) thick, and can be as thick as 25 ft (7.6 m). In New York, the shale beds in the Mamakating (~ High Point Member) rarely exceed 3 in (7.6 cm) in thickness.

What IS the Martinsburg Formation?

The Martinsburg Formation extends for more than 100 mi (160 km) from southeastern New York to where it dives under the Tuscarora Sandstone at the west end of the field trip area. These rocks do not reappear in outcrop to the west. Here, it is about 115 mi (185 km) northeast of the type area near Martinsburg, West Virginia, where the Martinsburg was named by Geiger and Keith (1891). It apparently was first adequately described by Keith (1894) who characterized the formation as partly calcareous shale. In the Shenandoah Valley of Virginia, the Martinsburg is possibly about 3,000 ft (915 m) thick, predominantly calcareous shale, but containing greywacke sandstone higher in the section (Butts, 1973). The continuity of the Martinsburg belt is blocked by the rocks of the structurally overlying Hamburg klippe, which extends from near the Susquehanna River to just east of Stop 1 of this field trip. The Martinsburg in the Great Valley of Virginia, West Virginia, and Maryland contains fossiliferous clastic rocks, termed "Reedsville" in places, as well as the characteristic shale and greywacke (Diecchio, 1985, McBride, 1962). In Pennsylvania north of Blue Mountain, the name Reedsville Shale is applied to the finer-grained Ordovician clastic rocks. These fossiliferous rocks are more proximal (= nearshore) than the turbidite-bearing Martinsburg of eastern Pennsylvania. They may be analogous to isolated rocks in the Shochary Ridge sequence (Figures 2 and 4). Similar fossiliferous shales can be found in southeastern New York (Feldman et al., 2009). Clearly, there are significant differences in the 200+ mi (320+ km) length of the Ordovician clastic belt to warrant reexamination of the nomenclature of these rocks. The Martinsburg of eastern Pennsylvania is significantly different than the type Martinsburg to ask, "should it even be called Martinsburg"? The rocks identified as Martinsburg in the Harrisburg area (Wise et al., 2010, Stop 12) is a very fine-grained shale that is very different from any of the Martinsburg east of the klippe. It most closely resembles the New Tripoli Formation of the Shochary Ridge sequence. Perhaps a better understanding of the regional distribution of the various Ordovician clastic lithofacies is warranted at this time.

Silurian Rocks

The Tuscarora/Clinton-Shawangunk Relationship

Basal Silurian sandstones, quartzites, and conglomerates hold up a ridge system that extends throughout the length of the Appalachians of the Eastern United States. In the area of this field trip the ridge is made up of Blue, Kittatinny, and Shawangunk Mountains. In Pennsylvania, the Tuscarora Sandstone and overlying Clinton Formation (Clinton Group is some places) merges eastward into the Shawangunk Formation while the superjacent Bloomsburg Red Beds is happy to remain on top of all of these units (Figure 3). The change takes place about one mi (1.6 km) east of the Schuylkill River. As explained at Stop 4, Delaware Water Gap, the Shawangunk is subdivided into four members; two quartzite-conglomerate members (Weiders and Minsi) at the base and top (Tammany), separating sandstone-shale sequence in the middle (Lizard Creek). The Tammany and Weiders Members pinch out westward, leaving the Lizard Creek and Minsi, which according to stratigrpahic rules, become the Clinton and Tuscarora.

Silurian Clastic Facies in New Jersey

In the east section of the field trip area, the Silurian sequence seen in Delaware Water Gap thins dramatically across New Jersey towards southeastern New York (Figure 3). In New Jersey, the shales of the Lizard Creek Member become less abundant and more scattered

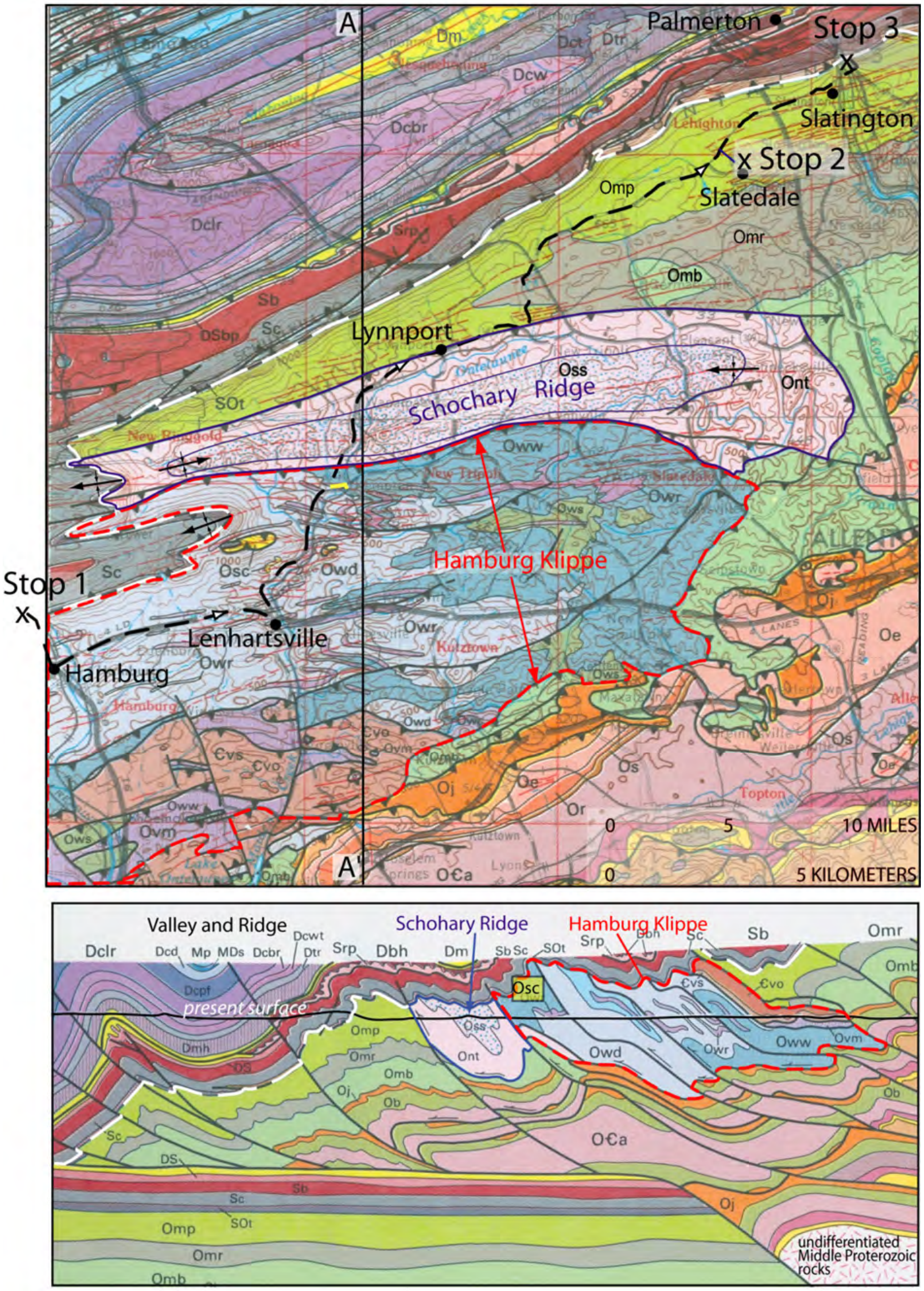


Figure 4. Geologic Map and cross section showing travel route (black dashed line) between Stops 1 and 3 and tectonic relations of the Hamburg klippe (red dashed line), Schochary sequence (purple dashed line) , and position of Osc. The white dashed line is the angular unconformity between Silurian and Ordovician rocks. Standard structure symbol shows direction of selected synclinal plunge. Significant formation symbols are: Dm—Marcellus Shale; Dsbp—Middle Devonian through Upper Silurian rocks, undivided; Sb—Bloomsburg Red Beds; Sc—Clinton Formation; Sot—Tuscarora Sandstone; Osc—Spitzenberg and Sharps Mountain; Oss—Schohary Sandstone; Ont—New Tripoli Formation; Owr—Windsor Township Formation; Omp—Pen Argyl member of the Martisnburg Formation; Omr—Ramsyeburg Member of the Martinsburg Formation; Omb—Bushkill Member of the Martinsburg Formation. Modified after Lyttle and Epstein, 1987.

throughout the section and the unit can no longer be mapped in the middle of the state. Thus, a unified member-less Shawangunk underlies red beds (Bloomsburg) northeastward. Earlier New Jersey State geologic maps (e.g., Lewis and Kummel, 1910-1912) identified the red beds above the Shawangunk as High Falls Shale, a name derived from the type section of that formation at High Falls, NY, about 40 miles northeast of the state border. However, as shown by Epstein (1993) the Shawangunk thins northeastward, two of its sandstone/conglomerate bodies intertongue with two red bed tongues of the Bloomsburg, all of which can be traced across New Jersey without complication to southeastern New York. These tongues terminate and do not intersect the rocks at High Falls, NY. These relations required the use of the name Bloomsburg on the most recent State geologic map (Drake and others, 1996). Some of the rocks of the Shawangunk tongues contain polymictic conglomerates, some of which are similar to those in the Green Pond Conglomerate of the Green Pond outlier, about 15 miles to the southeast in New Jersey. One can easily envision a stratigraphic section between the main outcrop belt and the outlier that shows the Shawangunk tongue becoming thicker and encompassing more of the lower part of the section going eastward. In the outlier most of the Green Pond Conglomerate would be included in the tongue.

Structural Geology

The Provinces

The area of the 77th Annual Field Conference of Pennsylvania Geologists will pass through several stratigraphic packages of differing structural style, summarized in Appendix 3. Figure 4 is a geologic map and section of the western section of the trip, seen during day 1.

The unconformable Ordovician-Silurian contact represents a hiatus of at least 10 m.y. and could be much greater depending on the age of the Beemerville syenite body (see Stop 7) and whether it is agreed that the Shawangunk lies nonconformably on the syenite. The divergence in dip at the unconformity is less than 15° with the Martinsburg Formation east of the Schuylkill River through eastern Pennsylvania, northern New Jersey, and into southeastern New York (Epstein and Lyttle, 1986, 1987). To the west, a more pronounced angular unconformity exists between the same Silurian rocks and the complexly deformed Middle and Lower Ordovician rocks of the far-travelled Hamburg klippe.

In general, going from Pennsylvania to New York, structures become simpler (Figure 4), from highly faulted and folded along the Schuylkill River (Stop 1, Figure 1), where the Tuscarora Formation rests on both the Martinsburg Formation and rocks of the Hamburg klippe, to overturned and faulted rocks at Lehigh Gap (Stop 3, Figure 6), to oversteepened folds at Delaware Water Gap (Stop 4, Figure 4), and upright to slightly overturned folds at High Point, New Jersey (Stop 8, Figure 7), and finally into a fairly simple arch at Ellenville, New York (Stop 10, Figure 4). Slaty cleavage in both Ordovician and younger rocks is common, particularly in the southwestern part of the study area. A second-generation crenulation cleavage is also found in all rocks, more so in the southwest and generally absent in the northeast. Timing and degree of deformation of these rocks has been the subject of considerable long-standing debate. The three most important issues 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 (and what is the age of the folds,

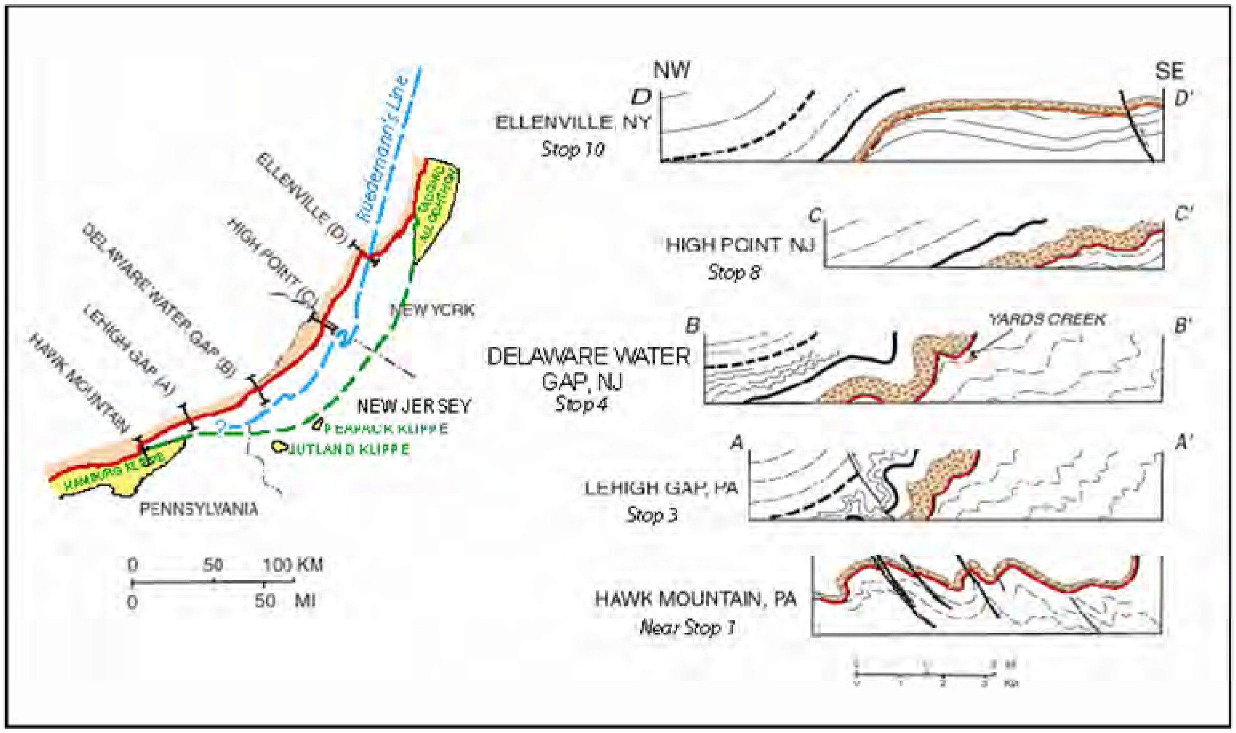


Figure 5. Generalized tectonic map and cross sections along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and New York. Red line is the Taconic unconformity separating Silurian clastic rocks from the underlying Ordovician rocks. Solid heavy line separates the lithotectonic unit containing relatively thin Upper Silurian limestones, shales, and sandstones from the thicker Bloomsburg, Clinton, Tuscarora, and Shawangunk rocks below. The heavy dashed line separates those rocks from the Devonian sandstones and shales of the moderately dipping to flat lying rocks of the Pocono and Catskill Plateaus. Ruedemann's line, in blue, separates broad open Taconic folds to the north and west from more intense structures to the south and east. Orange-shaded, dotted unit in the cross sections is the Tuscarora Sandstone – Shawangunk Formation. Modified from Epstein and Lyttle, 1987.

faults, and cleavage in these rocks); and 3) is the post-Taconic deformation Acadian or Alleghanian, or both?

On this field trip we will suggest that: 1) with only a few exceptions, the Shawangunk and equivalent Tuscarora Formation overlie the Martinsburg Formation with an angular unconformity that ranges between an angle that is barely discernible, to about 15°; 2) the dominant regional folding in all rocks along the contact is Alleghanian in age, 3) the regional slaty cleavage in the Martinsburg formation, and possibly in the Hamburg klippe in the trip area is Alleghanian in age, 4) Taconic folds in the Martinsburg Formation below the unconformity are mostly broad and open along the entire 120 mi (193 km) length of the contact that we have studied; 5) southeast of Ellenville, New Yor, the structures in the Martinsburg become more intense and the angular disparity between beds above and below the unconformity is greater; and 6) the strike of Taconic structures trend a bit more northerly (by about 3-20°) than later structures in the Ellenville area, and possibly elsewhere in the trip area.

The Taconic Unconformity: A Short Geologic History

Precambrian rocks more than one billion years old underlie parts of Pennsylvania. Following the breakup of the early Precambrian continent, Rondinia, about 725 million years ago, a shallow-water carbonate bank existed along the east coast of the North American continent during the Cambrian to mid-Ordovician. A volcanic arc in the middle of the ocean (*Iapetus* and its friends) subsequently collided with North America (Taconic Orogeny) breaking up the bank, forming highlands to the east which shed thick muds and sands into forearc basins. Uplift of the shales and turbidite sandstones (Martinsburg), beveling by erosion, and deposition of coarse clastics Shawangunk/Tuscarora) from the ancient Taconic Mountains during the Silurian Period, resulted in the Silurian-Ordovician unconformity. More intense hinterland Taconic deformation resulted in significant thrusting and formation of the Hamburg klippe, nappes, and all the fine stuff visited on the 2010 Field Conference of Pennsylvania Geologists (Wise and Fleeger, 2010; and in the References). The age of the rocks missing along the Taconic unconformity increases from central Pennsylvania (where Ordovician rocks appear to be transitional into Silurian rocks) through eastern Pennsylvania and New Jersey, into New York (Rodgers, 1971, for example; see Figure 2). Continued tectonic movement, not of concern here, resulted in deposition of all manner of sedimentary rocks during the remainder of the 200 million years of the Paleozoic, culminating in the Alleghany orogeny near the end of the era (of concern here), with the docking of the African plate with North American, and the birth of the super-continent *Pangea*. Pangea stayed intact for more than 50 million years, and near the end of the Permian, did some nasty things that killed off the largest number of species ever. But its days were numbered beginning in the late Triassic, when the docked African and North American blocks started their rifting separation during seafloor spreading, which is still going on today. Glaciers invaded eastern United States several times during the Pleistocene, upon which Ron Witte will elucidate at several stops. The geomorphic evolution of the Appalachians following the termination of mountain building and Mesozoic rifting has encouraged many differing thoughts on such subjects as peneplains, superposition, antecedent streams, and headward erosion. The mountains have also produced some of the finest breweries in the world. ENJOY!

Historical Perspective

The contact between the Martinsburg Formation of Ordovician age and the Silurian Shawangunk Formation in eastern Pennsylvania, New Jersey, and southeastern New York has attracted the attention of geologists every since Rogers (1838) recognized that it was an unconformity and later proclaimed that the orogeny was the "...most omentous...revolution" in North America (Rogers, 1858, p. 785). White (1882) described the contact as unconformable at Lehigh Gap, Pa., and Otisville, N.Y., but Chance (in White, 1882) and Lesley (1883) maintained that the angular relations were due to faulting. Later, Clark (1921) and Keith (1923), among others, maintained that the angular unconformity seen between Ordovician and Silurian rocks to the northeast is not to be seen in Pennsylvania.

Miller (1926) disagreed. He believed that an angular unconformity is present in Pennsylvania and based his conclusions on the following reasons: 1) the disconformable relations seen in exposures; 2) sericitized slate pebbles, apparently derived from the underlying Martinsburg, in the basal beds of the Shawangunk Formation; 3) omission of beds along strike; 4) the Martinsburg Formation is more highly metamorphosed than Devonian shales a few miles (kilometers) away; 5) structures in Ordovician and Cambrian rocks are more complex than those in Devonian and Silurian rocks; and 6) the cleavage in the Martinsburg, which was formed during the Taconic orogeny, is itself deformed into folds and was faulted during the Appalachian orogeny.

Behre (1924, 1933) argued that the Taconic orogeny produced slaty cleavage, close overturned folds, and thrust faults and was more intense than later Appalachian deformation which merely distorted the slaty cleavage. He (Behre, 1927, 1933) divided the Martinsburg into three members, a lower and upper slate separated by a sandstone unit. Stose (1930), however, maintained that the upper slate member of Behre is the lower member repeated by folding; hence, the Taconic orogeny must have been intense, for the Shawangunk Formation rests on the lower member of the Martinsburg. Stose's interpretation has had a profound influence on understanding the stratigraphy of the Martinsburg, as well as interpreting the intensity of Taconic deformation in the Martinsburg. Detailed mapping of the Martinsburg in the critical areas in the Delaware Valley clearly showed that it contained three mappable units rather than two (Davis et al., 1967; Epstein, 1973, 1990), which Drake and Epstein (1967) reestablished the threefold subdivision of the Martinsburg as proposed by Behre (1933), named the three members, and concluded that Stose's interpretations were wrong.

Willard and Cleaves (1939) showed that the angular unconformity extends as far southwest as Susquehanna Gap in Pennsylvania, where the Bald Eagle Conglomerate rests conformably on top of the Martinsburg Formation. Willard (1938) previously presented a cross section of the unconformity at Delaware Water Gap, but his interpretation does not agree with the interpretation presented in at stop 4.

Hess (1955) believed that the Taconic orogeny was so intense that it was not only the cause of folding of the sediments in the Appalachian "geosyncline", but rather the cause of the geosyncline itself. Woodward (1957) maintained that the slate belt of the Martinsburg is the result of the superposition of three periods of folding (Taconic, Acadian, Alleghanian), each having a different trend. However, no field evidence is recognized in Pennsylvania and New Jersey to support Woodward's Views.

Detailed mapping in the Delaware Valley by different geologists mapping on either side of the unconformity have led to different views on the intensity of Taconic and Alleghanian deformation. Drake et al. (1960), working in rocks older than Silurian, led to the interpretation that the Taconic orogeny was more severe than the Alleghanian orogeny in that area, resulting in regional fold nappes, and that the regional slaty cleavage in the Martinsburg is Taconic in age. At the same time, Arndt and Wood (1960), working in rocks generally younger than Ordovician, concluded that the Appalachian orogeny was by far the stronger. Additionally, Wood et al. (1963, p. 78) suggested that the discordant contact between the Martinsburg and Shawangunk might be largely the result of faulting. Lowry (1957) suggested that the regional cleavage in all rocks in eastern Pennsylvania formed at the same time—post-Ordovician.

Maxwell (1962) concluded that the flow cleavage in the Martinsburg Formation in the Delaware Water Gap area was produced by relatively minor deformation during the Taconic orogeny, believing that the regional slaty cleavage was the product of diagenesis, rather than metamorphism, and that the slaty cleavage does not migrate up into Silurian and younger rocks. He maintained that a later fracture cleavage cuts all rocks across the Taconic unconformity. His comments about cleavage is discussed at Stop 4.

The tacit acceptance of two orogenies led Broughton (1946) to believe that the slaty cleavage in the Martinsburg of New Jersey was a product of Taconic tectonism and that a cross-cutting slip cleavage was formed during the later Appalachian orogeny, although he suggested that "These structures might well be explained as the result of two peaks in the stress cycle of one period..." (Broughton, 1946**, p. 17**). However, both slaty cleavage and slip cleavage are found in all rocks in the Delaware Water Gap area, they are believed to have formed during the same continuing period of deformation (Epstein and Epstein, 1969). This same interpretation was accepted in the Harrisburg area by Root (1970). The idea that the Martinsburg was severely cleaved during the Taconic orogeny led Stevens (1966) to conclude that it was Taconic metamorphism that produced anthraxolite in the Martins-burg, although he noted (Stevens, 1966, p. 111) that, "It is a curious coincidence that the westward diminution of Taconic metamorphism in the Martinsburg conforms to the pattern of later metamorphism for the Pennsylvanian coals."

The interpretation that a large nappe underlies the Great Valley in easternmost Pennsylvania (Drake et al., 1961; Drake, 1967a, 1967b; Drake and Epstein,, 1967; Davis et al., 1967) with no structural counterpart in rocks younger than Ordovician argued for an intense Taconic orogeny. Nappes have been mapped in other parts of the Great Valley (Stose, 1950; Gray, 1954; Field Conference of Pennsylvania Geologists., 1966). While intense Taconic deformation is well documented in central Pennsylvania, such as in the Harrisburg area, the potential overriding effects of Alleghanian deformation has been recognized (Wise and Fleeger, 2010). Bird and Dewey (1970) explained the Taconic nappes in Pennsylvania in their plate tectonic model for evolution of the Appalachian orogen, although they were not certain to what extent Alleghenian deformation affected pre-Silurian rocks.

Based on detailed field mapping between Lehigh and Delaware Water Gaps, Epstein and Epstein (1967;1969; Epstein et al., 1974) concluded that the folding in Ordovician and Silurian and younger rocks in that area are dominantly Alleghanian in age. Rodgers (1971, p. 1164), on the other hand, based on the interpretation of regional nappes of Ordovician age with their associated cleavage, and which are cut by later (Alleghanian) cleavage, believed that the dominant structure in the Delaware Valley is pre-Silurian in age. Interpretation of regional nappes has changed over time. The present geologic map of New Jersey (Drake et al., 1996) interprets the structure of the Great Valley in that state as one of imbricate foreland thrusting; no regional nappes are shown. Finally, an Alleghanian age for the regional slaty cleavage is supported by 40Ar/39Ar whole-rock analysis from the Martinsburg Formation at Lehigh Gap (Wintsch et al.., 1996).

Structural Conclusions

In this report, I and my co-leaders conclude the following about the Ordovician-Silurian boundary issue in the field-trip area:

1. There is an angular unconformity between the Martinsburg and Shawangunk and Windsor Township formation and Tuscarora.
2. The Taconic orogeny was a period of mountain building, indicated by the thick coarse Silurian clastic wedge overlying the Martinsburg.
3. 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.
4. Folds of proven Taconic age in the Martinsburg Formation below the unconformity are mostly broad and open along the entire 120 mi (193 km) length of the contact between the area east of the Hamburg klippe in Pennsylvania to Ellenville, NY. Southeast of this zone of gentle folding the structures become tighter and faulting increases.
5. The regional slaty cleavage formed after the rocks were indurated at, or just below, conditions of low-grade metamorphism.

6. Arching of cleavage in the Martinsburg Formation as the contact with Silurian rocks is approached, which has been ascribed to folding of Taconic-age cleavage by later Alleghanian folding (Drake et al., 1960; Maxwell, 1962), is attributed to a pressure-shadow mechanism, to be discussed at Stop 3, 4, and 5, possibly 7.
7. 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 (see Day 1 Road Log, Figure 19). No unoriented slate fragments have been found in basal Shawangunk/Tuscarora beds. Argillite intraclasts in the basal Shawangunk, especially at Lehigh Gap, have cleavage that is parallel to one of two cleavages present in the beds above.
8. In the area east of the Schuylkill River Taconic deformation immediately adjacent to the unconformity is limited to gentle folding; Alleghanian deformation is much more intense.
9. The contact at Schuylkill Gap presents a puzzlement – rotating the near-vertical Silurian rocks there back to horizontal makes for a weird picture. *More field mapping is needed here!* Please see the section "The Role Of Geologic Mapping: A Call For Future Mappers" below.

The Hamburg Triangle: Figure 6

After we leave Stop 1 of the field trip, we will travel up the valley of Maiden Creek with the Tuscarora Sandstone holding up Blue Mountain on our left, passing thorough the Hamburg klippe, Sharps Mountain on our left and Spitzenburg on our right, then passing through rocks of the Shochary sequence and onto the fault-separated Martinsburg Formation. All this will happen over 11 mi (18 km) of travel. Many of the geologic features are a source of wonderment and have been discussed in geologic literature, not to be summarized here. Here they are. Few conclusions will be drawn. They are offered for future investigatory enlightenment.

1. Typical "Appalachian" folds, Pennsylvania style, lie to the east. The repetition of rock units over and over again as the folds are traversed to the north, indicate a shallow level of folding, before the rocks plunge deeper into the Alleghany Plateau. These folds don't last too long towards the east as they merge into the Pocono Plateau. Then there is the peculiar banana-shaped Lackawanna Syncline. And the thermal maturity line that separates Marcellus gas production for the "dead zone" to the south. Decollements at depth? Effects of Salina salt? Just asking.
2. Why does the Hamburg klippe end wher6e it does just as the folds in the Tuscarora skoot to the north east of the city of Hamburg?
3. What the heck is the Shochary syncline? A deep tight fairly uncomplicated structure in the midst of rocks with tight folds of all scales? How do the Shochary sequence rocks relate to those in the Hamburg klippe, to the Martinsburg Formation to the east, and to correlative rocks south of Harrisburg? Note that the axis of the syncline in those Ordovician rocks appears to pass into a syncline in Blue Mountain in the Tuscarora to the west (see Faill, 2011). *But*. . . whereas the fold pattern in the Tuscarora in Blue Mountain shows the folds there plunge to the southwest, the Shochary syncline, based on the contact relations between the Schocharie sandstone and New Tripoli Formation clearly show the syncline to plunge to the east Lyttle and Epstein, 1987). Just asking.
4. Sharps Mountain is weird. It is held up by a thin sliver of Tuscarora Sandstone. Its

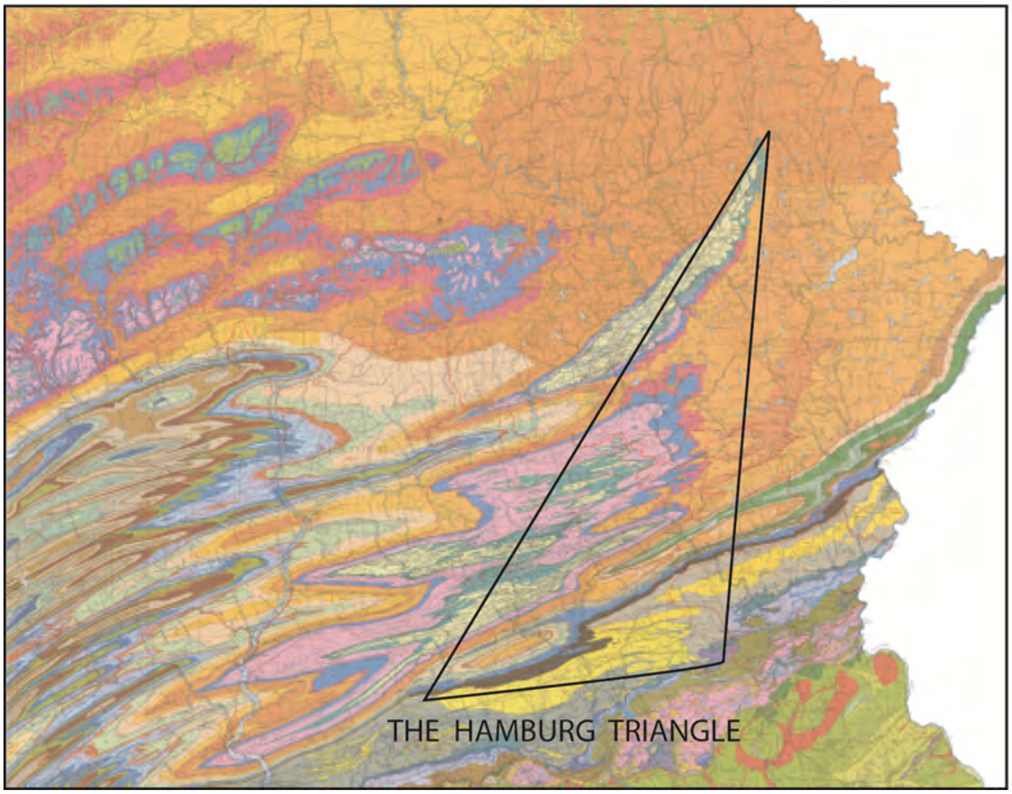


Figure 6. The Hamburg Triangle. The geology of eastern Pennsylvania changes relatively abruptly, almost along the straight red line, from the typical Pennsylvania/ Appalachian folds on the west to the Pocono plateau to the east, and where the Martinsburg slate belt disappears under the Silurian and the Hamburg klippe and Schochary Ridge terminate.

moderate northwest dip does not match the projected dips from the main outcrop belt a mi (1.6 km) to the west (see Lash, 1987). A trip a bunch of years ago suggested to me that the pile of Tuscarora there is a landslide.

5. Spitzenburg Conglomerate. Two small erosional outliers, containing unique crossbedded conglomaerates and sandstone with limestone cobbles, apparently derived from the Hamburg klippe and Great Valley rocks. They were discussed in a previous Field Conference (Lash et al., 1984), and concluded to have lay unconformably beneath the Tuscarora. *But* the same rocks are not seen at Sharps Mountain (graywackes are present there under the Tuscarora overburden, nor are similar conglomerates seen under the Tuscarora in the main outcrop belt immediately to the west. What gives? It is a bit of a stretch to correct these conglomerates with the Juniata or Bald Eagle many tens of miles (kilometers) to the west.

The Role Of Geologic Mapping: A Call For Future Mappers

Much of the information presented in this guidebook is the result of detailed field mapping by the co-leaders. Much of the discussion about the Hamburg klippe and Martinsburg Formation is the result of efforts by USGS geologists Peter Lyttle (now coordinator of the USGS National Cooperatiove Geologic Mapping Program) and Gary Lash (now at SUNY in Fredonia, NY, and involved in studies of the Marcellus Shale). Without detailed mapping by

both state and federal geologists and only by walking and visiting all outcrops, tracing rock units, and recording structural data, could the structural and stratigraphic conclusions many of the conclusions presented here could not have been possible. The sparse data available for Stop 1 cries out for the arrival of young detailed geologic mappers to fill in our geologic knowledge between the Auburn quadrangle on the Schuylkill River, to the Indiantown Gap Quadrangle several quads to the west where the Pennsylvania Survey is presently mapping.
In 1990 the US Congress realized that only 20 percent of the U.S. has detailed geologic map coverage. In 1992 Congress passed National Cooperative Geologic Mapping Act and in 1995 added the EDMAP is added as a component of the Program. The NCGMP is authorized until 2019. See **http://pubs.usgs.gov/fs/2010/3088/support/fs2010-3088.pdf** (accessed 9/11/2012)

The EDMAP program was established for university students to gain experience and knowledge in geologic mapping whilecontributing to national efforts to map the geology of the United States. It is a matching-funds grant program with universities. Geology professors whose specialty is geologic mapping request EDMAP funding to support upper-level undergraduate and graduate students at their colleges or universities in a 1-year mentor-guided geologic mapping project that focuses on a specific geographic area. Every Federal dollar that is awarded is matched with university funds. EDMAP is invaluable not only because it contributes to national geologic mapping efforts but also because it helps fund academic research, thoroughly prepares students for realworld careers in the geoscience field, and gives participants a competitive edge in the job market:

- Students participating in the EDMAP Program receive training and first-hand field experience in geologic mapping and thus acquire skills useful in many geoscience fields.
- EDMAP geology professors and their students frequently work closely with nearby State geological surveys and U.S. Geological Survey geologists.
- Student work contributes to geologic mapping of the United States.
- So far, EDMAP has benefited 144 universities and more than 850 students from geoscience departments across the Nation.
- Results from a recent EDMAP participant survey show that 95 percent of the respondents either went on to take jobs in the geoscience field or pursued further degrees in geosciences.
- Surveyed participants considered the program to have been a great opportunity and one that was enjoyable and highly valuable to their career.

How To Apply

Grants are awarded through an annual, competitive, and matched grant process. Per-project funding that was available in fiscal year 2011, for example, for graduate projects is $17,500 and for undergraduate projects is $10,000. A peer-review panel consisting of university faculty, State Geologists, and USGS representatives determines awards.

Applications for professors and students interested in participating in this program are solicited via the online EDMAP Program Announcement, where you can find detailed instructions for submitting EDMAP proposals (U.S. Geological Survey, 2011). Visit **http://www.grants.gov** and click on “Find Grant”.

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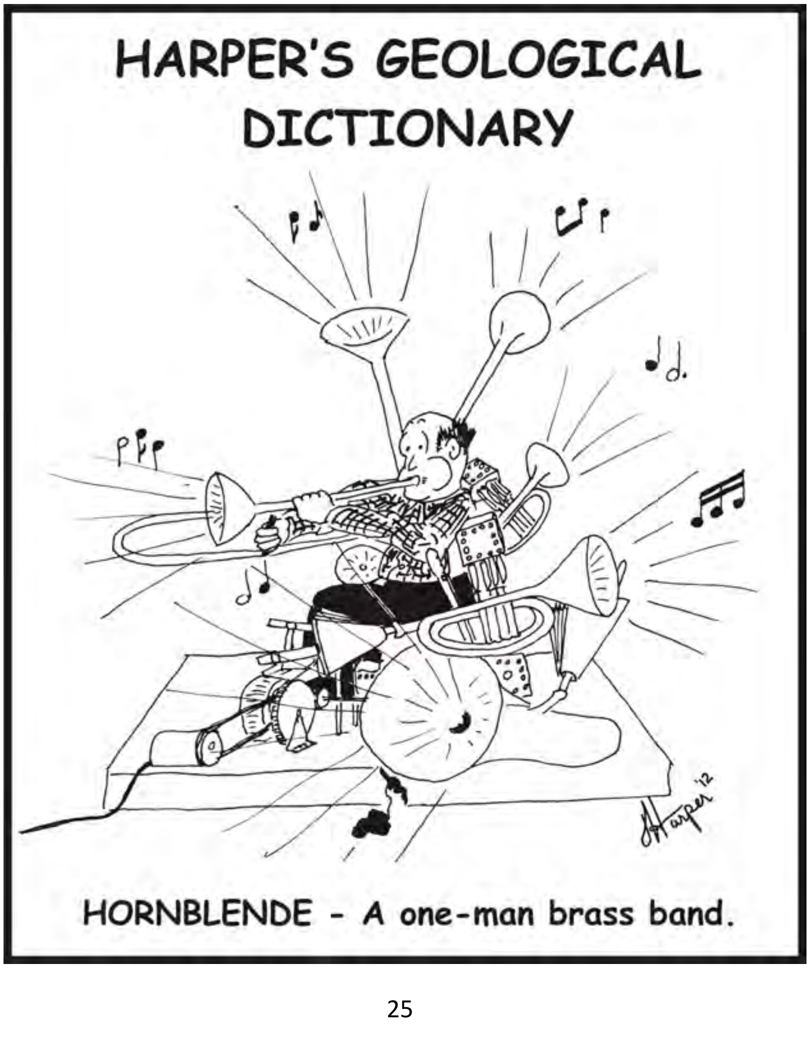

APPENDIX 1: Generalized stratigraphy of the rock units that we may encounter in the area of the first day of the field trip or are shown on figure 1 in Pennsylvania and New Jersey. Modified from Epstein and Lyttle (1987).

MAHANTANGO FORMATION (Middle Devonian, 1,200-2,500 ft [366-762 m] thick): Medium-dark-to dark-gray, poorly bedded and laminated to thin-bedded, bioturbated, shaly siltstone and silty shale. Fossils are diverse and scarce to abundant in biostromes different parts of the formation.

MARCELLUS SHALE (Middle Devonian, about 250-1,000 ft [76-305 m] thick): Medium-dark-gray to grayish-black, laminated to poorly bedded, sparingly fossiliferous shale and silty shale. Lower part, 70-200 ft (21-61 m) thick, consists of laminated to thin-bedded, calcareous, shaly siltstone and argillaceous limestone (Stony Hollow Member) above, and medium-dark-gray to grayish-black shale (Union Springs Member) below. The basal rocks of the Marcellus is deformed wherever exposed.

ROCKS OF ONESQUETHAW AGE (Middle to Lower Devonian, <50-about 700 ft [<15 - 213 m] thick): **Onondaga Limestone**—gray, fossiliferous, cherty limestone and argillaceous limestone; deeply leached in western exposures grades to the southwest into the **Palmerton Sandstone**—medium- to very coarse grained, generally massive sandstone and conglomeratic sandstone with quartz pebbles as much as 0.75 in (2 cm) long; **Schoharie Formation**—laminated to very thick bedded, slightly cherty, fossiliferous, calcareous siltstone with Taonurus and other burrows; **Esopus Formation**—Medium- to dark-gray, well-cleaved, generally laminated to poorly bedded siltstone with abundant *Taonurus.*

ORISKANY GROUP THROUGH HELDERBERG GROUP (Lower Devonian, <50-~400 ft [<15–~120 m] thick): **Ridgeley Sandstone,** Oriskany Group—fine- to very coarse grained, fossiliferous (spiriferid brachiopods), calcareous sandstone and conglomerate with quartz pebbles as much as 0.75 in (2 cm) long, with minor siltstone, arenaceous limestone, and chert; **Shriver Chert**, Oriskany Group—calcareous, fossiliferous shale and siltstone and minor calcareous sandstone; **Port Ewen Shale**, Helderberg Group—fossiliferous, calcareous shale and siltstone; **Minisink Limestone**, Helderberg Group—fossiliferous, argillaceous, limestone and calcareous shale; **New Scotland Formation**, Helderberg Group-- cherty, fossiliferous, calcareous and silty shale and argillaceous limestone, deeply leached in western exposures; **Coeymans Formation**, Helderberg Group—argillaceous and arenaceous, partly cherty, fossiliferous, burrowed, partly biohermal limestone, and medium-gray, fine- to coarse-grained and pebbly, fossiliferous, crossbedded and planar bedded, calcareous sandstone and conglomerate with quartz pebbles as much as 1 in(2.5 cm) long;

UPPER SILURIAN ROCKS (about 50-1,000 ft [15-300 m] thick): **Rondout Formation**—fossiliferous, laminated to thin-bedded limestone; mudcracked, calcareous shale; and dolomite; **Decker Formation**—calcareous, crossbedded to planar-bedded to flaser-bedded, fossiliferous, burrowed partly conglomeratic sandstone, calcareous siltstone and shale, arenaceous limestone, and mudcracked dolomite; **Andreas Red Beds**—grayish-red and light- to greenish-gray, fine- to coarse-grained and conglomeratic sandstone and burrowed shale and siltstone. May correlate with either the Coeymans Formation or upper part of the Decker Formation to the east; **Bossardville Limestone**—laminated to thin-bedded, fossiliferous, argillaceous, and partly dolomitic limestone; and calcareous shale with deep mudcrack polygons; **Poxono Island Formation**—Green to gray, partly mudcracked, laminated to thick-bedded, calcareous shale; very fine to fine-grained dolomite; and argillaceous limestone with dessication breccia locally at the top and pale-red, interbedded shale near the bottom. Grades into the High Falls Shale in New York (see Figure 3 on p. 5).

BLOOMSBURG RED BEDS (Upper Silurian, 800-1,800 ft [244-549 m] thick): Red, crossbedded and planar-bedded, laminated to thick-bedded shale, siltstone, very fine to coarse-grained sandstone, and minor conglomeratic sandstone with cut-and-fill structures, mudcracks, in fining-upward cycles in the east. Lower contact gradational, very irregular in places, and placed at base of lowest red bed above gray rocks of the Shawangunk or Clinton Formation (see mileage 142.9 of Day 1 Road Log).

SHAWANGUNK FORMATION (Middle Silurian, 1,600 ft [488 m] in the west, thins to about 400 in the east end of the field trip area): Comprises four members in western New Jersey and eastern Pennsylvania, from youngest to oldest: **Tammany Member** (0-800 ft [0-244 m] thick**—**Medium- to medium-dark-gray, planar-bedded and crossbedded, thin- to thick-bedded, fine- to coarse-grained and conglomeratic quartzite with quartz and argillite pebbles as much as 2 in(5 cm) long, and minor beds of dark-gray argillite. Lower contact gradational into the **Lizard Creek Member (**0-1,400 ft [0-427 m] thick)**—**Light- to dark-gray and light-olive- to dark-greenish-gray, very fine to coarse-grained, laminated to very thick bedded, planar-bedded, crossbedded, flaser-bedded, rippled, partly channeled, burrowed quartzite with flattened argillite cobbles as much as 4 in(10 cm) in diameter; minor dark-grayish-red-purple, fine-grained, burrowed, hematitic quartzite, interbedded with medium-light- to dark-gray and olive-to greenish-gray, laminated to thin-bedded, flaser-bedded, burrowed siltstone and shale; scattered thin beds contain collophane, siderite, and chlorite nodules, quartz pebbles as much as 0.25 in (0.6 cm) long, and *Lingula* and eurypterid fragments. Lower contact transitional and placed at base of lowest argillite in sequence containing abundant argillite above quartzites of underlying member; **Minsi Member** (100-350 ft [31-107 m] thick)**—**Very light- to dark-gray and light-olive- to greenish-gray, partly burrowed, planar-bedded and crossbedded, thin- to thick-bedded, fine- to coarse-grained, partly conglomeratic quartzite with pebbles of quartz and chert not more than 2 in(5 cm) in diameter and cobbles of shale as much as 7 in(18 cm) in diameter; minor medium-dark- to dark-gray and greenish-gray, laminated to thin-bedded, locally mudcracked siltstone and shale. Local *Arthrophycus*. Lower contact placed at top of uppermost bed of the Weiders Member containing quartz pebbles more than 2 in (5 cm) long in sharp unconformable contact with the Martinsburg Formation. 200-350 ft(61-107 m) thick; **Weiders Member** (0-220 ft [0-67 m] thick)**—**Medium-light- to medium-dark-gray and greenish-gray, planar-bedded and crossbedded, thin- to thick-bedded, medium- to very coarse grained quartzite; conglomerate with quartz and chert cobbles as much as 6.5 in(17 cm) in diameter and shale cobbles as much as 8 in(20 cm) in diameter; and rare, greenish-gray, laminated to thin-bedded argillite. Lower contact with Martinsburg Formation unconformable.0-220 ft(0-67 m) thick. The Minsi and Weiders Members merge into the Tuscarora Sandstone 4.5 mi (7.2 km) west of Lehigh Gap as the Lizard Creek Member merges into the Clinton Formation as the Tammany Member pinches out.

CLINTON FORMATION (Middle Silurian; 1,400 ft [426 m] thick): Gray, green, and red sandstone, siltstone and shale laterally continuous with and lithically similar to the Lizard Creek Member of the Shawangunk Formation, except that it contains more red beds.

TUSCARORA SANDSTONE (Lower or Middle Silurian; about 100 ft [31 m] thick at Schuylkill Gap): Gray quartzite laterally continuous with and similar to the Minsi Member of the Shawangunk Formation.

Many rocks of Paleozoic age are present in the Green Pond syncline in New Jersey and New York. It is a narrow, northeast-trending, faulted syncline containing a thin, but fairly complete section of Paleozoic sediments, that sit unconformably on the Proterozoic basement. Many of the Paleozoic rocks correlate with thicker units in the Valley and Ridge Province showing that these rocks once were present between the two areas, a distance of more than 15 mi (25 km). Units of interest include:

HIGH FALLS FORMATION (probably the Bloomsburg Red Beds; Upper Silurian; 300 ft [91 m] thick): Grayish-red, nonfossiliferous, silty shale with thin sandstone common in lower half.

GREEN POND CONGLOMERATE (Upper Silurian; 1,000-1,400 ft [304-427 m] thick): Gray and reddish-gray sandstone and conglomerate with predominantly white quartz and minor gray, green, red, and yellow chert, red shale, and red sandstone cobbles as much as 3 in(7.6 cm) long. Lower contact unconformable (see article by Herman in this guidebook).Also termed Shawangunk Conglomerate.

MARTINSBURG FORMATION (Upper and Middle Ordovician; probably more than 15,000 ft [4,572 m] thick): In New York the identifications of correlative rocks have been given various names (see Figure 2 on p. 4 and discussion by Lyttle below). In Pennsylvania and most of New Jersey, consist of three distinctive members: **Pen Argyl Member** (Upper Ordovician, *Climacograptus spiniferus* Zone, 3,000-7,000 ft [914-2,134 m] thick)**—**Dark-gray to grayish-black, thin- to thick-bedded, evenly bedded slate, commonly more than 12 ft(3 m) and in places 20 ft(6 m) thick; rhythmically interlayered with carbonaceous slate, sandy slate, and very fine to medium-grained graywacke with parallel lamination, lenticular bedding, convolute bedding, and sole marks. Units in fining upward sequences (turbidite-flysch sequence).Quarried extensively for slate ("soft slate" of Pennsylvania quarrymen). Upper contact is unconformable and site of a regional decollement. Lower contact is gradational and is placed where graywacke is in excess of about 5 percent of local sequences and supplies abundant float. In Pennsylvania the Pen Argyl is overlapped by the Shawangunk Formation just west of the Delaware River and is absent in northern New Jersey; **Ramseyburg Member** (Upper and Middle Ordovician, *Orthograptus ruedemanni* to lower *Climacograptus spiniferus* Zone, 2,000-3,500 ft [610-1,067 m] thick)**—**Medium- to dark-gray slate that alternates, in part cyclically, with light- to medium-gray, thin- to very thick bedded graywacke and graywacke siltstone (turbidites). Graywacke comprises about 20 percent of member, but may make up more than 50 percent of some thick parts of the section, and less than 5 percent in others. Slates are generally thick bedded at the top and thin- to medium-bedded at the bottom of the member. Lower contact is placed at the base of lowest conspicuous graywacke bed, generally recognized by abundant float, but contact may be transitional through several hundred ft (scores of m), where discontinuous and lenticular graywacke beds are present in the underlying Bushkill Member); **Bushkill Member** (Middle Ordovician, C*limacograptus bicornis* to *Diplograptus multidens* Zone, 1,500-5,000 ft [457-1,524 m] thick)**—**Medium- to dark-gray, laminated to thin-bedded slate containing thin beds of quartzose slate, graywacke siltstone, and carbonaceous slate in fining upward sequences. Bed thickness does not exceed 6 in(15 cm) throughout member, and is generally less than 2 in(5 cm), except for graywacke beds that probably are less than 12 in(30 cm) thick in discontinuous units near the top of the member. Lower contact transitional through 3 ft(1 m). Formerly quarried for slate ("hard slate" belt of Pennsylvania quarrymen). In northernmost New Jersey and adjoining New York, rocks of slightly different composition than the upper part of the Ramseyburg are included in the **High Point Member** by Drake (1990), Upper and Middle Ordovician, 4,500 ft [1,372 m] thick)**—**thick-bedded greywacke and shale. These include rocks that were informally named Mamakating, above, and Pine Bush, below by Lyttle (*in* Epstein and Lyttle, 1987); **Shale And Graywacke At Mamakating—** Thick sequences of thin- to medium- bedded, medium dark gray shale interbedded with very thin to thick-bedded graywacke (as much as 6 ft [1.8 m] thick) alternating with thinner sequences of medium-bedded graywacke interbedded with less thin- to medium- bedded shale. Grades downward and laterally into the sandstone at Pine Bush; **Sandstone at Pine Bush—** Medium-grained, medium- to thick-bedded, medium-gray, speckled light-olive-gray- and light-olive-brown-weathering quartzitic sandstone interbedded with, and containing rip-ups of, thin- to medium-bedded, medium-dark-gray, greenish gray-weathering shale and fine-grained siltstone. Lower contact with Bushkill Member is interpreted to be conformable, but in many places it is marked by a thrust fault.

JACKSONBURG LIMESTONE (Middle Ordovician, 65-800 ft [20-244 m] thick):Dark-gray argillaceous limestone at top (“cement rock facies) grading down into gray, medium- to coarse-grained, calcarenite and high-calcium limestone. In New Jersey, the lower contact which is conformable in

Pennsylvania, is marked by beds of dolomite pebble- to boulder-conglomerate.

BEEKMANTOWN GROUP (Middle and Lower Ordovician): **Ontelaunee Formation—**Fine- to coarse-grained dolomite, cherty at the base, grading into dolomite that contains beds of medium-grained calcilutite at the top in some places. Generally absent in New Jersey Thickness ranges from a feather edge to 650 ft(200 m); **Epler Formation** (Lower Ordovician, 900 ft [274 m] thick)**—**Very fine grained to cryptogranular, limestone and dolomite. Upper part is absent in much of New Jersey; **Rickenbach Dolomite** (Lower Ordovician, 700 ft [213 m] thick)**—**Fine- to coarse-grained dololutite, dolarenite, and dolorudite. Upper part generally thin-bedded and laminated; lower part characteristically thick-bedded; **Stonehenge Limestone** (Lower Ordovician,)**—**Fine-grained, thin-bedded limestone marked by silty or sandy laminae with subordinate beds of orange to buff-weathering, irregularly laminated and mottled dolomite.

ALLENTOWN DOLOMITE (Lower Ordovician and Upper Cambrian, 575 ft [175 m] thick): Alternating light- and dark-gray weathering, rhythmically bedded dolomite; with abundant flat-pebble conglomerate, calcilutite, calcarenite, ooliticcalcarenite, calcirudite, algal stromatolite, dolomicrite, and scattered beds and lenses of orthoquartzite.

LEITHSVILLE FORMATION (Middle and Lower Cambrian, 1,000 ft [305 m] thick): Interbedded dolomite and calcitic dolomite, light-gray to tan phyllite, and very thin beds and stringers of quartz and dolomitic sandstone.

HARDYSTON QUARTZITE (Lower Cambrian, 0-900 ft [0-974 m] thick): Fine- to medium-grained, fine-to medium-grained, massive, but in some places thinly laminated and crossbedded, *Scolithus-*bearing, feldspathic quartzite interbedded with arkose, quartz-pebble conglomerate, and silty shale or phyllite.

SPITZENBERG AND SHARPS MOUNTAIN OUTLIERS: These two small erosional remnants in the Great Valley north of Hamburg, PA contain reworked sediments of both the Hamburg klippe and the Great Valley sequence. These rocks rest unconformably, and perhaps with structural discontinuity, on rocks of the Hamburg klippe and unconformably beneath the Tuscarora Sandstone. Although difficult to prove, these rocks may have been deposited after the rocks of the Hamburg klippe were folded during the Taconic orogeny and may represent the youngest Ordovician clastics in the area.

SPITZENBURG CONGLOMERATE (Late Ordovician, 0-200 ft [0-61 m] thick): At Spitzenberg (see Figure 2 on p. 4), the unit consists of medium- to coarse-grained, medium- to thick-bedded, poorly to well-sorted, crossbedded, red and green weathering, conglomeratic sandstone, interbedded with a thick-bedded, polymict conglomerate. The clasts include green chert, milky-white calcilutite and laminated to cross-laminated calcisiltite, red and maroon shale, brown sandstone and siltstone, and clasts of the same red sandstone that is interbedded with the conglomerate. Conodont biostratigraphy shows that the clasts are youngest at the bottom of the unit and oldest at the top. At Sharps Mountain, the sandstone weathers differently to a greenish-white and the conglomerate is absent. These rocks are unconformable, and possibly in thrust contact, with the underlying rocks of the Hamburg klippe. The underlying klippe rocks are the source for this unit. At Sharps Mountain, the unit is unconformably overlain by the Tuscarora Sandstone.

ROCKS OF THE SHOCHARY RIDGE AREA: This group of Ordovician clastic rocks crops out over a fairly small area in the Great Valley of eastern Pennsylvania (Figure 2 on p. 4). It is entirely fault bounded, and sits structurally on top of all three members of the Martinsburg Formation (Pen Argyl, Ramseyburg, and Bushkill), and structurally beneath the Greenwich slice of the Hamburg klippe. The eastern end of the Shochary Ridge outcrop belt coincides almost exactly with the eastern end of the

Hamburg klippe. It is very likely that the rocks of Shochary Ridge are derived from the Hamburg klippe and were transported in Taconic time as a thrust slice beneath the two major slices of the klippe. The two faults that mark the present limits of the Shochary Ridge area, are probably Alleghanian in age. The rocks of the Shochary Ridge area probably formed as a local, northward-prograding fan from the advancing accretionary prism of the Greenwich slice of the Hamburg klippe. These rocks are roughly the same age as the slightly deeper water clastics of the Martinsburg Formation, which were deposited by longitudinal (dominantly northwest or southeast) currents within a very long northeast-trending basin.

SHOCHARY SANDSTONE (Upper and Middle Ordovician, about 5,000 ft [1,524 m] thick): Medium dark-gray, thin- to thick-bedded calcareous, pyrite-rich, graywacke turbidites interbedded with light-olive-brown weathering slate, calcisiltite, and minor thin beds of conglomerate. Graywacke generally comprises 10 to 20 percent with rare instances of 50 percent, particularly near the top of the exposed section, and beds become thick-bedded with rare parallel laminations. Graywacke beds contain abundant faunal debris. Sedimentary structures in some turbidites obliterated in places by bioturbation. Rusty-weathering channels filled with coarse-grained sandstone, abundant shelly fauna, and pyrite are common in light-olive-brown-weathering graywackes. Graywacke beds also contain rare clasts of rounded chert. Upper beds of this unit are not present due to faulting and erosion. The Shochary is structurally and unconformably overlain by the Tuscarora Sandstone. Lower contact transitional over 50 ft(15 m) with underlying New Tripoli Formation and is placed where sandstones commonly make up less than 10 percent and beds are less than 2-4 in(5-10 cm) thick.

NEW TRIPOLI FORMATION (Middle Ordovician, more than 4,900 ft [1,494 m] thick): Medium-dark-gray, light-olive-brown weathering, thin, evenly bedded, calcareous graywacke interbedded with fairly thick slate and calcisiltite beds as much as 20 in [50 cm] thick) The calcisiltite beds are most commonly 1-2 in(2-5 cm) thick and are more resistant to weathering, giving the rock a ribbed appearance. This contrasts markedly with the ribbon slate of the Bushkill Member of the Martinsburg Formation. Shelly fossil debris is common, especially near the upper contact of the unit, but not abundant. Lower contact is faulted.

HAMBURG KLIPPE: This structurally and stratigraphically complex group of far-travelled rocks is located in the Pennsylvania Great Valley and resembles the Taconic allochthon of New York State. The klippe is divided into two tectonic slices: 1) the Greenwich slice, an accretionary prism of sediments displaying scaly cleavage that composes the Windsor Township Formation, the only unit that will be seen on this field trip, and 2) the Richmond slice, a sequence of rise and slope deposits that composes the Virginville Formation. Although emplaced by thrust faults during the Taconic orogeny, these faults have been obscured by later Alleghanian folds and faults. In general, rocks of the Lehigh and Lebanon (Great)Valley sequences have been thrust on top of the rocks of the Hamburg klippe during Alleghanian time. The Weisenberg Member of the Windsor Township Formation only will be see on this trip.

WINDSOR TOWNSHIP FORmation (Middle and Lower Ordovician, about 12,000 ft [3,658 m] thick): **Dreibelis Member—**medium- to very thick bedded, partly graded, fine- to coarse-grained, locally conglomeratic, somewhat calcareous graywacke sandstone interbedded with dark-greenish- to light-olive-gray, fissile to poorly cleaved mudstone, siltstone, and shale; **Switzer Creek Member—** medium- to thick-bedded, massive, medium- to coarse-grained to conglomeratic graywacke interbedded with lesser amounts of dark- greenish-gray mudstone and shale. Graywacke is rich in carbonate grains and pebbles, which weather to very distinctive, rotten and porous, limonite-stained rocks; **Weisenberg Member—**At least 5,700 ft (1,737 m) of light-olive-gray to grayish-olive, fissile to poorly cleaved shale and mudstone to micaceous siltstone with minor amounts of medium-dark- to dark-greenish-gray, silicified shale, mudstone, and argillite. In some places, thin-bedded siltstone and graywacke sandstone, and debris flows of chert and silicified mudstone are interbedded with the shale and mudstone. Soft-sediment slump folds are common. Local channels contain a very distinctive conglomerate with chalky-white-weathering feldspar grains and rare volcanic rock fragments. Polymicitc conglomerates contain clasts as much as 10 ft (3 m) long of graywacke, carbonate, siltstone, shale, and chert. Scattered throughout are red beds of locally silicified mudstone and argillite, interbedded with very thin to thick-bedded siltstone, sandstone, black calcilutite to calcarenite, and chert. Carbonate is found locally as clasts and megaclasts within a matrix of varicolored shale and argillite.

VIRGINVILLE FORMATION (Middle Ordovician to Upper Cambrian, about 1,800 ft [549 m] thick): **Moselem Member—**mudstone and shale interbedded with silicified argillite; minor thin-bedded, ribbon limestone, black shale, dolostone and minor carbonate-clast conglomerate; **Onyx Cave Member—**calcarenite, peloidal limestone, quartzose limestone, and calcareous quartzite, thick-bedded carbonate-clast conglomerate, and laminated black shale and dolostone; **Sacony Member—**thick-bedded, structureless, micaceous siltstone and sandstone interbedded with grayish- to pale-blue-green micaceous shale and mudstone.

JUTLAND KLIPPE (Ordovician and Cambrian, 600 ft [183 m] thick): These rocks resemble some of the rocks found within the Greenwich slice of the Hamburg klippe in Pennsylvania. Unlike the Taconic allochthon and Hamburg klippe, which occur on the foreland side of the external massifs of the Berkshires and Reading Prong, the rocks of the Jutland klippe occur on the hinterland side of the Reading Prong. Consist of interbedded red and green shale; silty sandstone; and micritic limestone. Upper contact is placed where sandstone, siltstone, and sparry and micritic carbonate rocks (found throughout the Jutland klippe, but more rarely in this lower unit) become much more common. Upper part contains manganese-bearing shale and interbedded red and green shale, dolomite, limestone conglomerate, laminated limestone and shale, fine-grained sandstone, siltstone and shale, and yellow, red, green, and gray shales interbedded with chert.

BEEMERVILLE SYENITE (Late Ordovician to Early Silurian): Medium to coarse-grained nepheline syenite intruded into the Martinsburg Formation and unconformably overlain by the Shawangunk Formation (see comments in Stop 7). Surrounded by numerous xenolith-bearing ouachitite breccias and lamprophyre, phonolite, bostonite, and malignite dikes and sills.

References

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Epstein, J.B. and Lyttle, P.T., 1987, Structure and stratigraphy above, below, and within the Taconic unconformity, southeastern New York, *in* Waines, R.H., ed., Field Trip Guidebook. 59th Annual Meeting, New York State Geological Association, Kingston, NY, p. C1-C78.

APPENDIX 2 – Generalized stratigraphy of the rock units that are present in the area of the second day of the field trip in New York, from Epstein and Lyttle (1987).

The Mount Marion Formation wll be seen along US 209 between Otisville and Ellenville. The rocks below, to and including the Rondout Formation, will not be seen but are included to complete the listing. The rocks older than the Binnewater Sandstone are shown in Figure 3 on p. 5. The terminology for stratigraphic units above the Onondaga Limestone is not well established in this area (see Rickard, 1964).

MOUNT MARION FORMATION, Hamilton Group (Middle Devonian, 1,000+ ft [305+ m] thick): Olive-gray to dark-gray, platy, very fine- to medium-grained, sandstone, siltstone, and shale.

BAKOVEN SHALE, Hamilton Group (Middle Devonian, 200-300 ft [61-91 m] thick): Dark-gray shale. Zone of faulting at base in several places.

ONONDAGA LIMESTONE (Middle Devonian, 100 ft [30 m] thick): Cherty fossiliferous limestone.

SCHOHARIE FORMATION (Lower Devonian, 180-215 ft [55-66 m] thick): Thin- to medium-bedded, calcareous mudstone and limestone; more calcareous upwards.

ESOPUS FORMATION (Lower Devonian, 200 ft [61 m] thick; thickens to southwest): Dark, laminated and massive, non-calcareous, siliceous, argillaceous siltstone and silty shale.

GLENERIE LIMESTONE (Lower Devonian, 50-80 ft [15-24 m] thick): Siliceous limestone, chert, and shale, thin- to medium-bedded.

CONNELLY CONGLOMERATE (Lower Devonian, 0-20 ft [0-6 m] thick): Dark, thin- to thick-bedded pebble conglomerate, quartz arenite, shale, and chert.

PORT EWEN FORMATION (Lower Devonian, 70-180 ft [21-55 m] thick): Dark, fine- to medium-grained, sparsely fossiliferous, calcareous, partly cherty, irregularly bedded mudstone and limestone.

ALSEN LIMESTONE (Lower Devonian, 20 ft [6 m] thick): Fine- to coarse-grained, irregularly bedded, thin- to medium-bedded, argillaceous and partly cherty limestone.

BECRAFT LIMESTONE (Lower Devonian, 3-50 ft [0.9-15 m] thick): Massive, very light- to dark-gray and pink, coarse-grained, crinoidal limestone, with thin-bedded limestone with shaly partings near the bottom in places.

NEW SCOTLAND FORMATION (Lower Devonian, 100 ft [31 m] thick): Calcareous mudstone and silty, fine- to medium-grained, thin- to medium-bedded limestone. May contain some chert.
KALKBERG LIMESTONE (Lower Devonian, 70 ft [21 m] thick): Thin- to medium-bedded, moderately irregularly bedded limestone, finer grained than Coeymans Formation below, with abundant beds and nodules of chert and interbedded calcareous and argillaceous shales.

RAVENA MEMBER OF THE COEYMANS LIMESTONE (Lower Devonian, 15-20 ft [5-6 m] thick): Wavy bedded, fine- to medium-grained and occasionally coarse-grained, limestone with abundant thin shaly partings.

THACHER MEMBER OF THE MANLIUS LIMESTONE (Lower Devonian, 40-55 ft [12-17 m] thick): Laminated to thin-bedded, fine-grained, cross-laminated, graded, microchanneled, mudcracked, locally biostromal limestone with shale partings.

RONDOUT FORMATION (Lower Devonian and Upper Silurian, 30-50 ft [9-15 m] thick): Fossiliferous, fine- to coarse-grained, thin- to thick-bedded limestone and barren, laminated, argillaceous dolomite. Limestone lentils come and go, and the more persistent ones have been named (from top to bottom): Whiteport Dolomite, Glasco Limestone, and Rosendale Members.

BINNEWATER SANDSTONE (Upper Silurian, 0-35 ft [0-11 m] thick): Fine-grained, thin- to thick-bedded, crossbedded and planar-bedded, rippled quartz arenite , with gray shale and shaly carbonate. Probably grades southwestwardly into the Poxono Island Formation.

POXONO ISLAND FORMATION (Upper Silurian, 0-500 ft [0-152 m] thick): Poorly exposed gray and greenish dolomite and shale, possibly with red shales in the lower part.

HIGH FALLS SHALE (Upper Silurian, 0-80 ft [0-24 m] thick): Red and green, laminated to massive, calcareous shale and siltstone, occasional thin argillaceous limestone and dolostone. Ripple marks, dessication cracks.

BLOOMSBURG RED BEDS (Upper Silurian, 0-700 ft [0-213 m] thick)--Grayish-red and gray shale, siltstone, and sandstone. In southeastern New York the Bloomsburg intertongues with rocks of the Shawangunk Formation, forming two mappable units: The **Bascher Kill Tongue** above (0-300 ft [0-91 m] thick)—Grayish-red siltstone and shale and slightly conglomeratic, partly crossbeddedandstone with pebbles of milky quartz, jasper, and rock fragments, and gray sandstone; and the **Wurtsboro Tongue** below (Late Silurian, 0-330 ft [0-101 m] thick)—Interbedded red, green, and gray, cross bedded, polymictic conglomerate, sandstone, siltstone, and shale. Lithologies occur in fining-upward cycles as much as 12 ft (3.7 m) thick.

SHAWANGUNK FORMATION (Middle Silurian, 0-1,400 ft [0-427 m] thick): Crossbedded and planar-bedded, channeled, quartz-pebble conglomerate (rose quartz conspicuous in upper part), quartzite, minor gray, shale and siltstone, and lesser red to green shale. In southeastern New York the Shawangunk intertongues with rocks of the Bloomsburg Red Beds, forming two mappable units: The **High View Tongue** above (Middle Silurian, 0-100? ft [0-31? m] thick)—gray, thin-bedded quartz sandstone with well-sorted and rounded quartz grains, and some green shale; and the **Ellenville Tongue** below (Middle Silurian, 0-500+ ft [0-152+ m] thick)—medium-dark-gray to light-gray, medium- to thick-bedded, planar-bedded and cross-bedded, fine- to medium-grained quartzite, conglomerate, and minor red and greenish-gray shaly siltstone. Conglomerates are polymictic, with quartz, jasper, chert, and argillite pebbles. The Ellenville Tongue is similar to some of the rocks of the Greenpond Conglomerate exposed in central New Jersey.

DIAMICTITE (Lower Silurian or Upper Ordovician, <1 ft [<0.3 m] thick): Lying between the Shawangunk and Martinsburg Formations is a dark yellowish orange, compact sand-silt mixture with abundant clasts of fragments of the underlying Martinsburg Formation, quartz pebbles (similar to those found in the overlying Shawangunk), sheared vein quartz, clay gouge, and a variety of gray and reddish siltstone and sandstone pebbles, some of which are rounded.

MARTINSBURG FORMATION (Upper and Middle Ordovician, 10,000+ ft [3,048+ m] thick): Greater than 10,000 ft (3,050 m) thick. See Appendix 1 for descriptions of the **Ramseyburg, High**

Point, and Bushkill Members. The subdivision of Ordovician clastic rocks in southeastern New York is in a state of flux due to incomplete detailed mapping, as summarized in the section above.

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APPENDIX 3. Structural-stratigraphic packages within the field trip area.
Modified from Lyttle and Epstein (1987)

VALLEY AND RIDGE PROVINCE: The Valley and Ridge province can be divided into lithotectonic units, each comprising a group of individual formations with their own deformation and erosion characteristics (Epstein and Lyttle, 1993; Epstein and Epstein, 1969). Incompetent rocks, such as the Marcellus Formation of Devonian age, the Poxono Island Formation of Silurian age, and the top of the Ordovician Martinsburg Formation, are zones of detachment or zones of rapid change in structural style, separating the lithotectonic packages. Alleghanian deformation, dominated by a thrust system of imbricate splays, has produced a series of northeast-trending, northwest verging upright to overturned folds. Many of the anticlines may be directly related to blind thrusts at depths.

GREEN POND SYNCLINE: The Green Pond syncline is a narrow, northeast-trending, faulted syncline containing a thin, but fairly complete section of Paleozoic sediments, located in the middle of the external massif of the Reading Prong, and sitting unconformably upon, or in fault contact with the Proterozoic basement. The Paleozoic section is cut by a number of thrust faults, some possibly having a strike-slip component. Many of the Paleozoic rocks correlate with thicker units in the Valley and Ridge Province showing that these rocks once were present between the two areas, a distance of more than 16 mi (25 km).

LEHIGH VALLEY SEQUENCE OF THE GREAT VALLEY: The Great Valley of Pennsylvania and New Jersey is a northeast-trending lowland bounded by Blue Mountain-Kittatinny Mountain on the northwest and the highlands of the Reading Prong on the southeast. The Great Valley comprises a thick section of Ordovician clastics, a thinner section of Ordovician and Cambrian carbonates, and a very thin Cambrian quartzite at its base. All of these rocks have been multiply deformed by a continuum of deformation between Taconic and Alleghanian time. These rocks contain numerous thrust faults, generally concentrated at several stratigraphic levels, such as the entire lower thin-bedded slate member of the Martinsburg Formation, the incompetent Jacksonburg Limestone which sits stratigraphically on top of the much more competent, dolomite-dominated, Beekmantown Group, and the base of the Cambrian Allentown Dolomite or Leithsville Formation. At the southwest end of the field trip area, the Lehigh Valley sequence rocks are structurally overlain by the Lebanon Valley sequence, which appear, at least in part, to be slightly deeper water, and perhaps farther travelled, equivalents of the Lehigh Valley sequence.

SPITZENBERG AND SHARPS MOUNTAIN OUTLIERS: These two small erosional remnants in the Great Valley north of Hamburg, PA contain reworked sediments of both the Hamburg klippe and the Lehigh Valley sequence (Lash et al., 1984, p. 74-78). These rocks rest unconformably, and perhaps with structural discontinuity, on rocks of the Hamburg klippe and unconformably beneath the Tuscarora Sandstone (Stephens, 1969). Although difficult to prove, these rocks may have been deposited after the rocks of the Hamburg klippe were folded during the Taconic orogeny and may represent the youngest Ordovician clastics in the area

ROCKS OF THE SHOCHARY RIDGE AREA:This group of Ordovician clastic rocks crops out over a fairly small area north of Lenhartsville, Pennsylvania. It is entirely fault bounded, and sits structurally on top of all three members of the Martinsburg Formation, and structurally beneath the Greenwich slice of the Hamburg klippe (Figure 4 on p. 11). It is very likely that the rocks of Shochary Ridge are derived from the Greenwich slice of the Hamburg klippe and were transported in Taconic time as a thrust slice beneath the two major slices of the klippe. The two faults that mark most of the present limits of the Shochary Ridge sequence of rocks are probably Alleghanian in age. The Shochary sequence probably formed as a local, northward-prograding fan from the advancing accretionary prism of the Greenwich slice of the Hamburg klippe. These rocks are roughly the same age as the slightly deeper water clastics of the Martinsburg Formation which were deposited by dominantly northwestward currents within a very long northeast-trending basin.

HAMBURG KLIPPE: This structurally and stratigraphically complex group of far-travelled rocks is located in the Pennsylvania Great Valley at the west end of the field trip area and resembles the Taconic allochthon of New York State. The klippe is divided into two tectonic slices: 1) the Greenwich slice, an accretionary prism of sediments displaying scaly cleavage that composes the Windsor Township Formation, and 2) the Richmond slice, a sequence of rise and slope deposits that composes the Virginville Formation (Lash et al., 1984). Although emplaced by thrust faults during the Taconic orogeny, these faults have been obscured by later Alleghanian folds and faults. In general, rocks of the Lehigh Valley sequence has been thrust on top of the rocks of the Hamburg klippe during Alleghanian time

JUTLAND KLIPPE: These rocks resemble some of the rocks found within the Greenwich slice of the Hamburg klippe in Pennsylvania. Unlike the Taconic allochthon and Hamburg klippe, which occur on the foreland side of the external massifs of the Berkshires and Reading Prong, the rocks of the Jutland klippe occur on the hinterland side of the Reading Prong.

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SOME TACONIC UNCONFORMITIES IN SOUTHEASTERN NEW YORK

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This Field Conference will have visited or discussed 12 locations where the Ordovician-Silurian contact is exposed or nearly so: six in Pennsylvania - Schuylkill Gap (Stop 1), Sharps Mountain, Spitzenburg Hill, northeast extension of the Pennsylvania Turnpike, Lehigh Gap (Stop 3), and Delaware water Gap (Stop 4); four in New Jersey - Yards Creek (Stop 5), Sunrise Mountain (mileage 54.5 of the Day 2 Road Log), the Beemerville intrusion (Stop 7), and High Point State Park (Stop 8); and two in New York - Otisville (Stop 9) and the Ellenville arch (Stop 10). Besides the contact exposed in the now-deeply flooded High View Railroad tunnel described by Inners and others in this guidebook, which is a mere 700 ft (213 m) south of the exposure along NY 17 (#3 of this list), there are an additional four excellent occurrences of the unconformity (Figure 1). They are described below. They add further insight into the faulted nature of the contact, adding to the puzzlement of how much of the contact is unconformable and how much is faulted.

1. Interstate 84

Coordinates: 41°22’24.64”N latitude; 74°37’32.26”W longitude; elevation 1,267 ft (386 m)

This exposure is located on the south side of the east-bound lane of I-84, 3 mi (5 km) east of Port Jervis, NY. The exposure is more than 1,500 ft (457 m) long, with gently folded Martinsburg (Figure 2, top) in contact with the Shawangunk, and with an angular discordance of 5° (Figure 2, bottom). Of particular interest is the occurrence of a 3-in (8-cm) layer of clay-fault gouge at the contact. The rocks were well exposed in 1966, soon after construction of the highway.

Figure 1. Generalized geologic map of parts of New Jersey and New York showing where exposures of the Taconic unconformity not seen on this Field Conference are located (X), and Stops 8, 9, and 10 (squares). *D*, Rocks of the Hamilton Group (Plattekill, Ashokan, Mount Marion, and Bakoven Formations and younger. *DS*, Rocks between the Onondaga Limestone and Binnewater Sandstone-Poxono Island Formation. *S*, High Falls Shale, Shawangunk Formation, Bloomsburg Red Beds, and tongues of the Shawangunk and Bloomsburg; Om, Martinsburg Formation. 1. I-84; 2. Guymard prospect; 3. NY 17 at Wurtsboro; 4. Napanoch Prison.

Epstein, J.B. and Lyttle, P.T., 2012, Some Taconic unconformities in southeastern New York, *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. 37-41.

Table 1. Description of units in Figure 2, bottom, I-84 (from base upwards).

Unit	Thickness (feet)	
Martinsburg Formation		
1a	1	Dark-gray argillite with interbedded argillite and greywacke below. Upper contact sharp.
1b	3.1	Medium-gray to medium-dark-gray, massive, fine- to medium-grianed, light-olive-gray to moderate-brown weathering, non-calcareouos greywacke; upper contact sharp. Much hematite in weathered rock.
1c	1.8	Interbedded, fine-grained greywacke with beds as much as 0.6 thick, interbedded with argillite in beds as much as 0.6 thick. Upper contact sharp.
1d	3	Same as in 1b.
2	3	Argillite, like unit 1a, partly concealed.
3	2.2	Graywacke, medium-dark-gray, non-calcareous, very fine- to fine-grained, feldspathic, with minor thin interbedded argillite. Upper contact gradatioal.
4	4.3	Medium-gray to medium-dark gray, very fine-grained to silty laminated graywacke interbedded with dark-gray to medium-dark-gray siltstone and dark-gray argillite. Upper contact gradational.
5	1.4	Medium-dark-gray, fine- to medium-grained, feldspathic greywacke with thin (< ¼ inch) dark-gray argillite. Upper contact sharp.
6a	0.8	Grayish black, to dark-gray, dark-yellowish-orange-weathering argillite. Upper contact gradational.
6b	0.8	Leached and sheared, medium-light-gray argillite. Shearing more intense at top with abundant moderate-reddish-brown iron staining.
7	0.5	Gouge, contains grayish black to dark-gray argillite fragments in a moderate-reddish-brown to dark-yellowish-orange clay matrix. Fragments generally up to one inch long, sheared parallel to overlying contact. Unit thins to about three inches where the Shawangunk along the contact overlies greywacke, and contain greywacke fragments along with argillite.
Shawangunk Formation		
8	9.4	Lower contact abrupt and disconformable. Medium-gray to medium-light -gray, massive quart- and chert-pebble conglomerate, quartz predominates. Pebbles rounded to well-rounded and as much as three inches long. Chert pebbles generally about one inch long. Pebbles slightly larger near base of unit. Matrix is medium- to coarse-grained sandstone. Upper contact gradational.
9	1.8	Greenish-gray, feldspathic, coarse- to very coarse-grained conglomeratic quartzite with rounded quartz pebbles at base as much as one ich long. Upper contact sharp.
10	8	Interbedded quartz-pebble conglomerate with pebbles as much as 1.5 inches long. Beds as much as two feet thick, interbedded with conglomeratic feldspathic sandstone between 0.5-2 feet thick. Quartz pebbles are iron-stained in upper part. Upper contact gradational.
11	2	Quartz-pebble conglomerate. Rounded pebbles as much as one inch log, with dark-yellowish-orange to moderate-reddish-brown iron staining on the pebbles. Unit is not exposed in valley to the north.

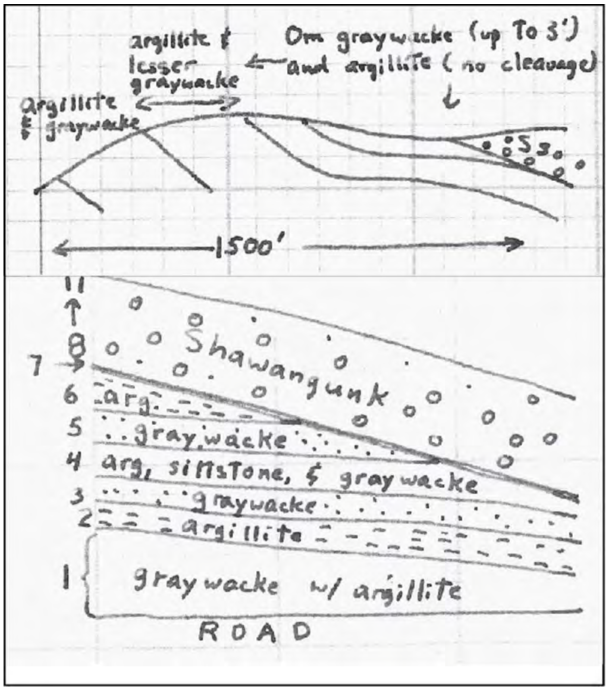

Figure 2. Field sketches of the Taconic unconformity made in 1966 along I-84, east of Port Jervis, NY. The units are described in Table 1.

Figure 3. Contact between the Shawangunk (above) and Martinsburg Formations along I-84. The angular difference between bedding in the Shawangunk (long dashes) and Martinsburg (short dashes) is 5°. Picture taken June 1966.

The outcrop has deteriorated since then. Figure 2 is a field sketch at that time, and the information gathered is given in Table 1. The pebbles here in the Shawangunk break out more readily than to the southwest at Delaware water Gap, possibly because the quartz “cement” is not as intensely diagenetically altered (= not as well “metamorphosed”). This correlates with the less intense folding noted from Pennsylvania through New Jersey, into southeastern New York. Figure 3 is a photograph of the exposure in 1966. It has deteriorated somewhat since then.

2. Guymard Prospect

Coordinates: 41°25’32.13”N latitude; 74°34’59.94”W longitude; elevation 1,180 ft (360 m)

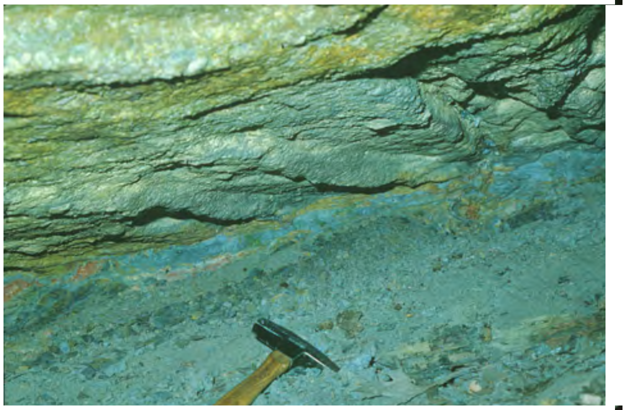

Figure 4. Assymetrical mullions that are 1 to 2 in (2.5 to 5 cm) deep in the Guymard prospect overlie about 6 in (15 cm) of clay gouge. They vary from straight (right side of the picture) to irregular (left side).

This contact is located in a small wooded prospect hole about 25 ft (8 m) wide and extends for at least 100 ft (31 m) underneath the dip of the basal bed of the Shawangunk Formation. The Shawangunk here is a typical conglomerate with rounded quartz pebbles as much as 1.5 in (4 cm) long. Bedding in the Shawangunk is N15°E, 12°NW, whereas it is N30°E, 27°NW in the Martinsburg, a dip difference of 15°. There is a poorly developed spaced cleavage in the Martinsburg (N48°E, 57°SE). Very well-developed downward-projecting mullions grace the base of the Shawangunk (Figure 4). These trend N49°E. Immediately below the mullions is a shear zone made up of milky quartz veins, fragmented and slickensided, ireon-stained fragmented Martinsburg shale fragments in a medium-light-gray clay which is extremely contorted, similar to the contortions seen at Otisville (Stop 9, Figure 5A). Alternative to the fault interpretation, Gray (1953 and 1961), who examined many of the zinc-lead mines between Ellenville and Guymard, NY, believed that the plastic clay and yellow-brown sandy clay at the Martinsburg-Shawangunk contact at Guymard was a rock flour, representing a zone of weathering on the pre-Silurian surface. He believed that the ores were deposited from hypogene solutions that reached temperatures of about 350°F (176 °C) during the "Appalachian Revolution."

3. NY 17; Wurtsboro

Coordinates: 41°33’55.73”N latitude; 74°27’48.59”W longitude; elevation 960 ft (293 m)

Figure 5. Angular unconformity between the Martinsburg and overlying Shawangunk along NY 17, near the off-ramp, 1.3 mi (2.1 km) east of Wurtsboro, NY. Inset in lower left shows the sheared shale at the contact; specimen is 2 in (5 cm) long.

This is another fine exposure of the Taconic unconformity in southeastern New York (Figure 5). The rocks of the Martinsburg and Shawangunk are similar to those we have seen elsewhere. The basal foot (0.3 m)of the Shawangunk contains much pyrite. At eye level the Martinsburg at the contact dips 16° to 31° NW, whereas the Shawangunk dips 25° NW. The angular discordance ranges up to 15° in spots. No secondary cleavage is seen in the Martinsburg at this spot. The lowest 10 ft (3 m) of the Shawangunk consist of massive, medium-gray to medium-light gray, planar-bedded, quartz- and chert-pebble conglomerate in a medium- to coarse-grained sandstone matrix. Quartz pebbles are rounded to well rounded and as much as 3 in (8 cm) long. The chert is generally not more than 1 in (2.5 cm) long. The overlying 12 ft (4 m) consist of finer, slightly feldspathic, quartz-pebble conglomerate and cross bedded conglomeratic sandstone with pebbles that are less than 15 in (38 cm) long. Graptolites of Zone 13 age (late Middle to early Late Ordovician) were identified by Berry in the Martinsburg within 135 ft (41 m) of the overlying Shawangunk (Offield, 1967, p. 53; Berry 1970). The character of the zone between the Martinsburg and Shawangunk varies from place to place. Near road level, the zone contains rotated shale fragments with some quartz veins, indicating appreciable shearing. Also included in this zone are disrupted shale fragments and a medium dark-gray sticky clay, a fault gouge.

4. Napanoch-Maximum Security Prison

Coordinates: 41°43’55.38” N latitude; 74 ° 21’25.70”W longitude; elevation 630 ft (192 m)

This is an excellent exposure in the gulley behind the Eastern New York Correction Facility, a maximum security prison, servicing many gentlemen from the New York City area. The Martinsburg-Shawangunk contact is about 20 ft (6 m) long. The angular discordance

Figure 6. Contact between the Martisnburg and Shawangunk formation (at arrow) up the steep gully behind the prison at Napanoch, NY.

between the two formations is 4° (Figure 6). The Shawangunk dips 22° NW in the northwest limb of the Ellenville arch (Stop 10). Mullions are prominent on the basal Shawangunk surface, and there is a shear fabric in both the Martinsburg and Shawangunk. The mullions trend N58°E, and bow down the slightly sheared bedding in the upper few inches (centimeters) of the Martinsburg. They are spaced about 6 to 12 in (15 to 31 cm) apart with amplitudes of about 2 in (5 cm). Within the basal 3 in (8 cm) of the Shawangunk there is a 1 to 2 mm spaced "shear cleavage" oriented N34°E, 24°NW. That is undoubtedly related to movement along the contact. The Shawangunk is medium to thick bedded (up to 2.5 ft [0.8 m] thick), planar bedded, with quartz pebbles up to 2 in (5 cm) long, with a medium- to coarse-grained sand matrix. Sedimentary structures include low-amplitude channels and cross-beds with a northwest current direction. Care should be taken if visiting this outcrop. Definitely seek permission from the prison before entering. Towers have a clean sight-line to the gulley.

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THE SILURIAN UNCONFORMITY WEST OF SCHUYLKILL GAP

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The westernmost exposure of the Silurian unconformity that we will visit on this Field Conference is the angular unconformity at Schuylkill Gap near Hamburg, Pennsylvania. However, the unconformity continues westward, north of Harrisburg and across the Susquehanna River (Figure 1). At its only two exposures through this stretch – Swatara Gap and Susquehanna Gap – the Martinsburg-Tuscarora contact is a disconformity, a significant time gap but with bedding generally parallel across the unconformity. The change from angular unconformity to disconformity through an area still profoundly affected by Taconic deformation is something of a puzzle.

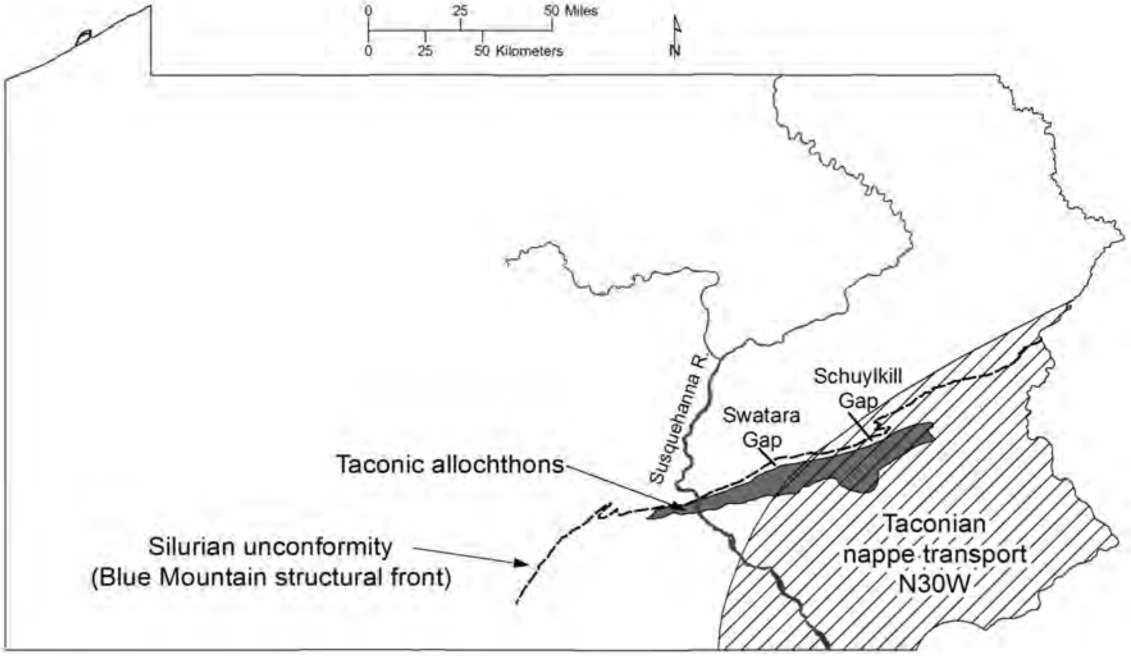

Figure 1. Model for changing character of the Silurian unconformity from the Susquehanna River to the Delaware River. White area between the Taconic allochthons and the Silurian unconformity is occupied by Martinsburg Formation. North of the Blue Mountain structural front, there was only minor deformation of the Martinsburg-Reedsville foreland in the Taconic Orogeny. Hatched area shows the general limit of major Taconian nappes. Taconian structures cut deeper and extended farther to the NNW nearer the Delaware. Alleghanian thrust sheets turned up the Silurian edge with more ENE trends, resulting in exposures having deeper pre-Silurian erosion and more intense angular unconformity toward the Delaware.

Through most of its length, the northern part of the Great Valley is occupied by the Martinsburg Formation. However, from west of the Susquehanna River in Cumberland County, through Dauphin, Lebanon, and Berks counties, the Martinsburg is interrupted by the Taconic

Ganis, G.R., Blackmer, G.C., and Wise, D.U., 2012, The Silurian unconformity west of 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. 42-45.

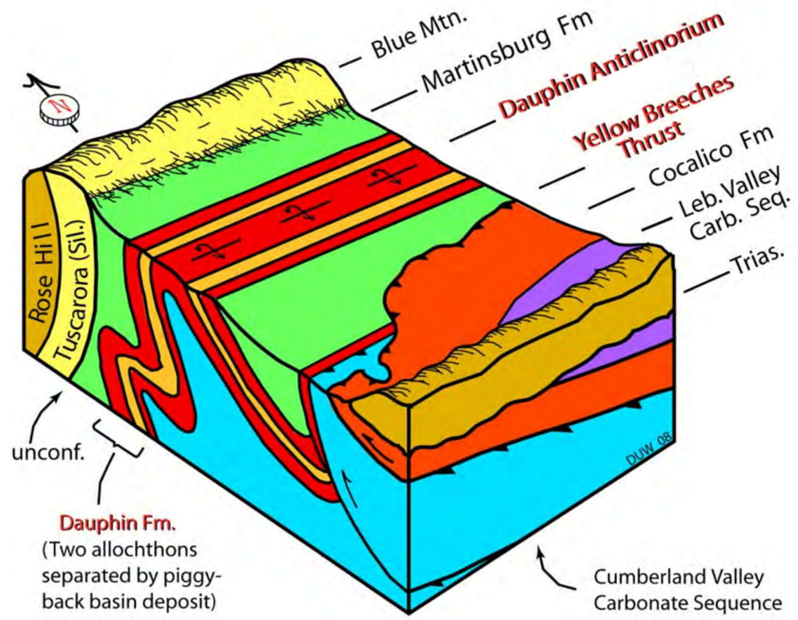

Figure 2. Cartoon block diagram showing basic structure of the Great Valley in Dauphin County. The western edge of the block is close to the east bank of the Susquehanna River.

allochthons (Figure 1). Stose (1946) called these Cambrian through Middle Ordovician rocks the Hamburg klippe, interpreting them as thrust over the Late Ordovician Martinsburg Formation. This interpretation was challenged but not overcome by Platt et al. (1972). More recent work has shown through faunal evidence (Ganis et al., 2001) and field mapping (Blackmer and Ganis, unpublished 1:24,000 maps) that the allochthons were emplaced prior to Martinsburg deposition and are therefore below the shale, rather than thrust over it (Ganis et al., 2001; Wise and Ganis, 2009; Ganis and Wise, 2008). Through Dauphin, Lebanon, and western Berks County, the allochthons and overlying Martinsburg are folded into the large overturned Dauphin anticlinorium (Figure 2; Ganis and Blackmer, 2010). The trend of the axial trace of this fold is generally parallel to the Blue Mountain structural front. The fold core exposes the "Hamburg" allochthons of the Dauphin Formation, so named by Ganis et al. (2001). The Martinsburg in the southern limb is cut off by the Yellow Breeches thrust of Alleghanian age (MacLachlan, 1967). The Martinsburg in the northern limb is overlain by the Silurian unconformity.

The overturned northern limb is marked on the ground by a belt of Martinsburg Formation. At Swatara Gap, the steeply overturned Martinsburg section has an outcrop width of about 2 mi (3 km), extending from the gap south about to the Lickdale interchange of I-81. This substantial thickness of Martinsburg thins toward Susquehanna Gap (about 18 mi [29 km] to the west) where, on the west side of the river, it is only a thin band. How much of this thickness change is due to structural causes versus original depositional conditions is difficult to decipher.

At Swatara Gap, late Martinsburg Edenian shelly fauna (Willard, 1943; Platt, 1972) and graptolites of equivalent age (Ganis ID) are directly below the Tuscarora. Moving south, through a progressively older inverted section toward Lickdale, there are additional fossiliferous exposures of late to middle Martinsburg age in the *Diplacanthograptus spiniferus* Zone and the

Diplacanthograptus caudatus Zone; and basal Martinsburg in the *Climacograptus bicornis* Zone in depositional contact above the Dauphin Formation (for details, see Ganis, 2004). Ganis (1972, unpublished data) identified a thin bed of Edenian shelly fauna, similar to the Swatara Gap fauna, at the east side of the Susquehanna Gap. Stose (1930; further discussed in Willard, 1943) found Edenian fossils, also similar to the Swatara Gap fauna, at the top of the Martinsburg on the west side of the Susquehanna. Both of these collecting locations have been destroyed by road construction. So, despite significant thickening of the Martinsburg from west to east, the contact of the Martinsburg and Tuscarora between Susquehanna Gap and Swatara Gap is consistently high in the Martinsburg. Thus it appears that the unconformity does not cut significantly downsection along this stretch.

The predominant expression of Taconic deformation in Pennsylvania is large overturned to recumbent nappe structures. It is easy to imagine creating an angular unconformity by laying down the Silurian sediments atop the Ordovician nappes, then folding the entire system during the Alleghanian orogeny to give the unconformity the steep dip it has today. It is more difficult to imagine a setting where Silurian sediments are laid down subparallel to bedding in the Martinsburg in either the upper or lower limb of a nappe fold, and still allow for exposure the core of the original nappe in the relatively straightforward map pattern observed in the Great Valley today.

The direction of tectonic transport of the Taconic nappes, as derived from a compilation of data from many small areas (Wise and Werner, 2004), was about N30°W. The Taconic front was therefore perpendicular to that direction, or about N60°E. This direction is slightly offset counter-clockwise from the later N70°E trend of Alleghanian frontal structures of the Reading Prong – Musconetcong thrust. As a result, in proceeding westward along Blue Mountain, the Taconic deformation front migrates away from the Silurian unconformity, leaving the basal Silurian against the less deformed parts of the Taconic foreland (Figure 1). To the east along Blue Mountain, the unconformity migrates deeper into the Taconic frontal deformed zone. Predictably, missing stratigraphy and increasingly angular relationships become more prominent in that direction.

Inherited local structures may also have contribute to the lack of Taconic nappe folds west of Schuylkill Gap. Ganis and Wise (2008) and Wise and Ganis (2009) describe the thin-skinned nature of Taconic deformation in this part of the Great Valley. In the earliest stages of the orogeny, the great allochthonous slices which now constitute the Dauphin Formation were thrust from offshore sedimentary basins onto the Cambro-Ordovician carbonate platform. As orogeny progressed, the allochthons moved inboard across the platform by massive gravity-driven flow and were covered by Martinsburg flysch. As loading continued, the carbonates weakened sufficiently to flow and overturn, forming the Lebanon Valley nappes. The allochthons, however, may have accommodated the continued loading by sliding along the embedded fault planes rather than by buckling into folds (think of straightening a pile of disordered papers – when you push on the outside of the pile with your hands, the odd sheet might buckle but the vast majority respond by simply sliding over each other). As a result, the Martinsburg Formation above the allochthons may have been slightly eroded but otherwise little disturbed before its unconformable burial by the Silurian sediments.

If the Dauphin Formation allochthons and their Martinsburg cover had adjusted along existing low-angle faults rather than folding during the Taconic Orogeny, the Martinsburg still could have been relatively parallel to the depositional surface during Tuscarora deposition. The whole system then would have undergone Alleghanian folding, giving the disconformity its present near-vertical attitude. In fact, Alleghanian rather than Taconic folding of the Dauphin Formation fits better with field observations in the Harrisburg to Fredericksburg area (detailed mapping has not yet progressed east of Fredericksburg). The structure in this area appears to be a relatively straightforward train of asymmetric-to-overturned anticlines verging toward the Blue Mountain structural front without the complications expected from refolding. Outcrop-scale folds are commonly observed in regions affected by nappe folding. In two quadrangles of detailed field mapping, only one outcrop-scale fold was observed, in a limestone outcrop at Harper Tavern – an asymmetric anticline verging toward the Blue Mountain structural front. The Schuylkill Gap lies near the east end of the Dauphin Formation, where a thinner stack of allochthons may have allowed Taconic fold development.

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THE NATURE OF SILURIAN MOLASSE AND THE TACONIC UNCONFORMITY IN THE GREEN POND SYNCLINE, NEW JERSEY-NEW YORK, USA

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Introduction

This paper summarizes the outcrop and subsurface expressions of the Ordovician Taconic unconformity and the overlying Silurian molasse in the Green Pond syncline (GPS), an elongate belt of down-faulted Lower and Middle Paleozoic rocks in the New Jersey (NJ) Highlands and bordering the New York (NY) Hudson Highlands on the west (Figure 1). The Taconic unconformity is the erosion surface resulting from tectonic uplift during the Taconic orogeny of the present-day New England region southwestward through the NY recess and into the Pennsylvania Salient (Figure 1). The Taconic was among the first of a series of Paleozoic mountain building episodes affecting the eastern continental margin of ancestral North America (Drake et al., 1989). It is widely thought to have

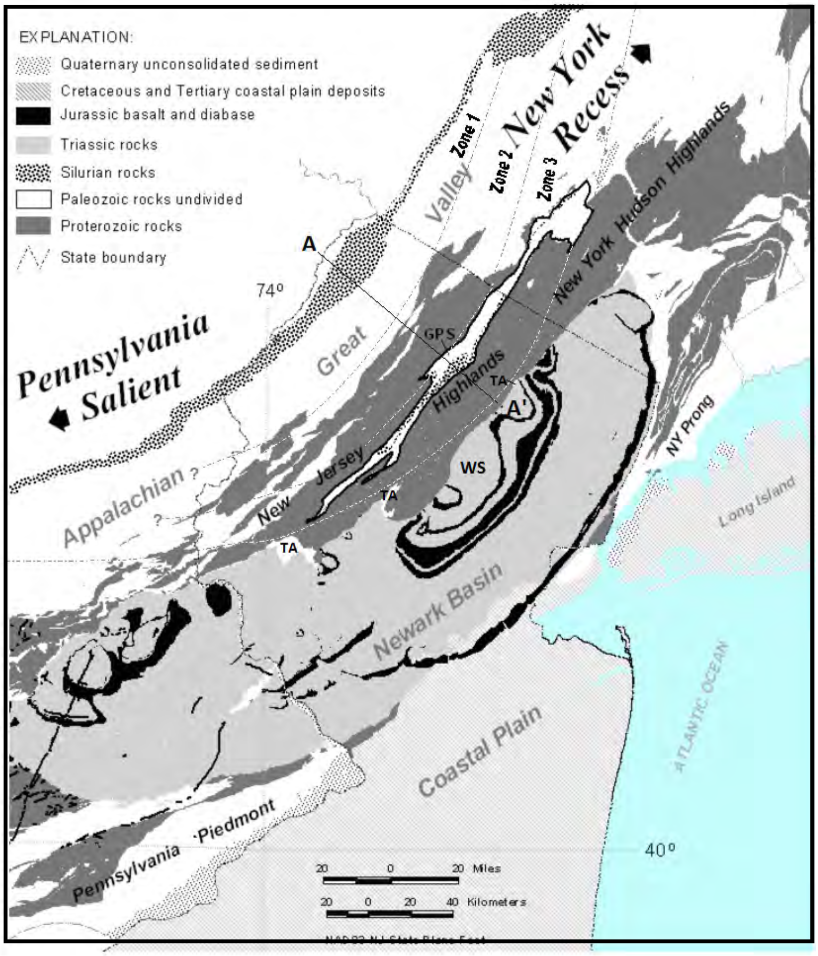


Figure 1. Generalized geology of the north mid-Atlantic region USA, showing named provinces and Appalachian terrain relative to the Green Pond Syncline (GPS). Cross section trace A-A' is coincident with parts of section A-A' of Drake et al. (1996) and Herman et al. (1997 - see Figure 2). The trace of Zones 1-3 are extrapolated southwestward into PA from New York State where Epstein and Lyttle (1987) reported increasing Taconic orogenic strains progressing southeastward toward the location of the Taconic allocthons, noted with a 'TA' along the northwest border of the Newark Basin. Fold and faults strains in each zone are detailed in the text. WS – Watchung syncline.

Herman, G.C., 2012, The nature of Silurian molasses and the Taconic unconformity in the Green Pond syncline, New Jersey-New York, *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. 46-84.

resulted from the collision and obduction of an island arc onto the continental margin beginning in the Early to Middle Ordovician period and ending in the Late Ordovician (~443 Ma), spanning a time period of about 15-20 million years (Wise and Ganis, 2009). Evidence for the unconformity now occurs where basal Silurian quartzite and conglomerate rest on Middle Proterozoic to Middle Ordovician bedrock exposed during orogenesis. The Taconic unconformity is an angular unconformity in renowned areas along the base of Hawk Mountain, Pennsylvania (PA), Kittatinny Mountain, NJ, and Shawangunk Mountain, NY at the front of the Appalachian Great Valley where dip angles across the unconformity between Early to Middle Ordovician foredeep sedimentary rocks and the Silurian molasse vary upward to as much as 15^o (Epstein and Lyttle, 1987). These relationships indicate that the current area of the Great Valley was a Taconic foreland region that was mildly to moderately strained with open-upright folds and tilting during the Taconic Orogeny (Epstein and Lyttle, 1987). Evidence of rock strain of Taconic age increasing southeastward within the Ordovician flysch of the Hudson Valley led Epstein and Lyttle (1987) to define three deformation zones before encountering Taconic allocthons (Figure 1). Zone 1 is mildly strained with open, upright folding; zone 2 contains tighter, steeper folds and localized thrust faulting, and zone 3 consists of thrust faults, overturned folds, and tectonic mélange. A recent effort of constructing palinspastic cross sections through the NJ region (Drake et al., 1996) is based on balanced foreland structures within zone 1 (Herman et al., 1997) that includes a depiction of a Taconic foreland-fold sequence of Lower Paleozoic rocks cored by Proterozoic basement (Figure 2). The restored

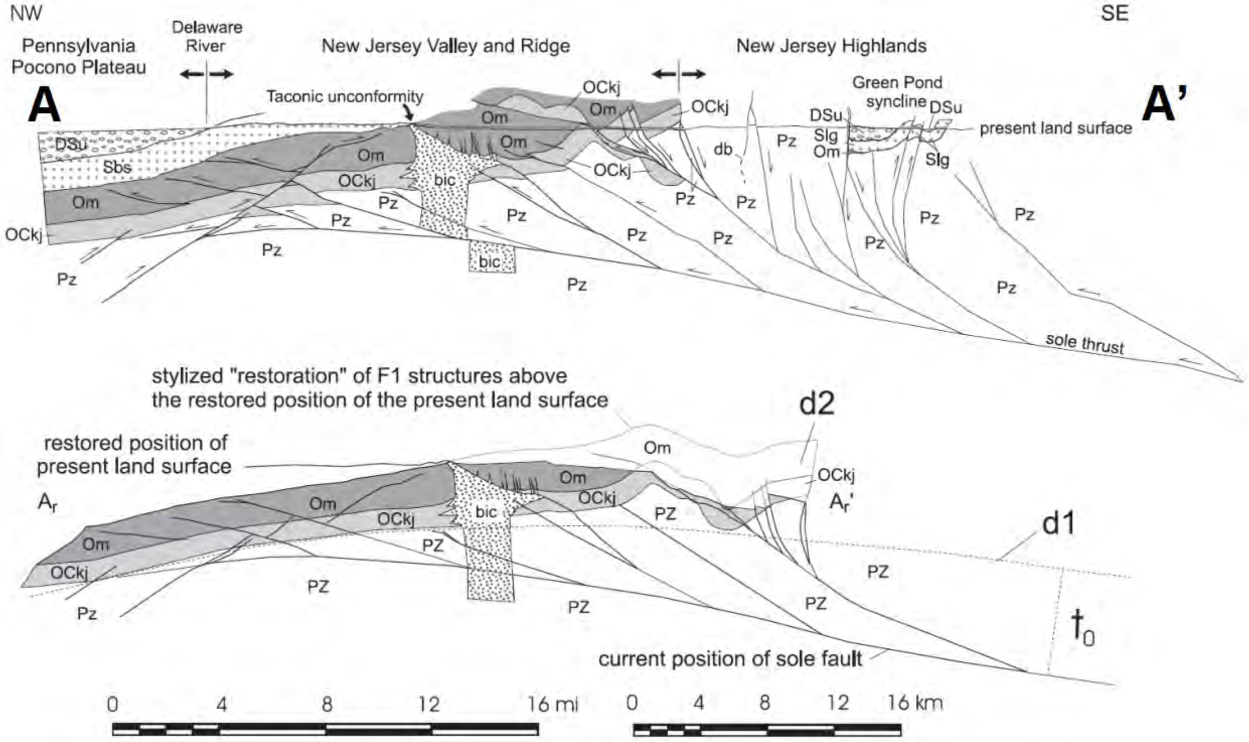


Figure 2. Details of the current (top) and palinspastic (bottom) restoration of a Taconic foreland sequence adapted from Herman et al. (1997). The section corresponds to the northwest 2/3 of A-A' of Figure 1. Abbreviations: bic—Beemerville intrusive complex; Om – Martinsburg Fm.; OCKj – Cambrian Ordvician Kittatinny Dolomite and Limestone; Pz – undivided Middle Proterzoic gneiss and granite; Sbs – Silurian Shawangunk and Bloomsburg Formations; DSu – undivided Silurian-Devonian section,; Slg Silurian Green Pond Conglomerate and Longwood Shale; d2 – restored Taconic alignment of the Cambrian-Ordvician (CO) cover sequence; d1 – restored CO base of the carbonate platform prior to sole-fault development.

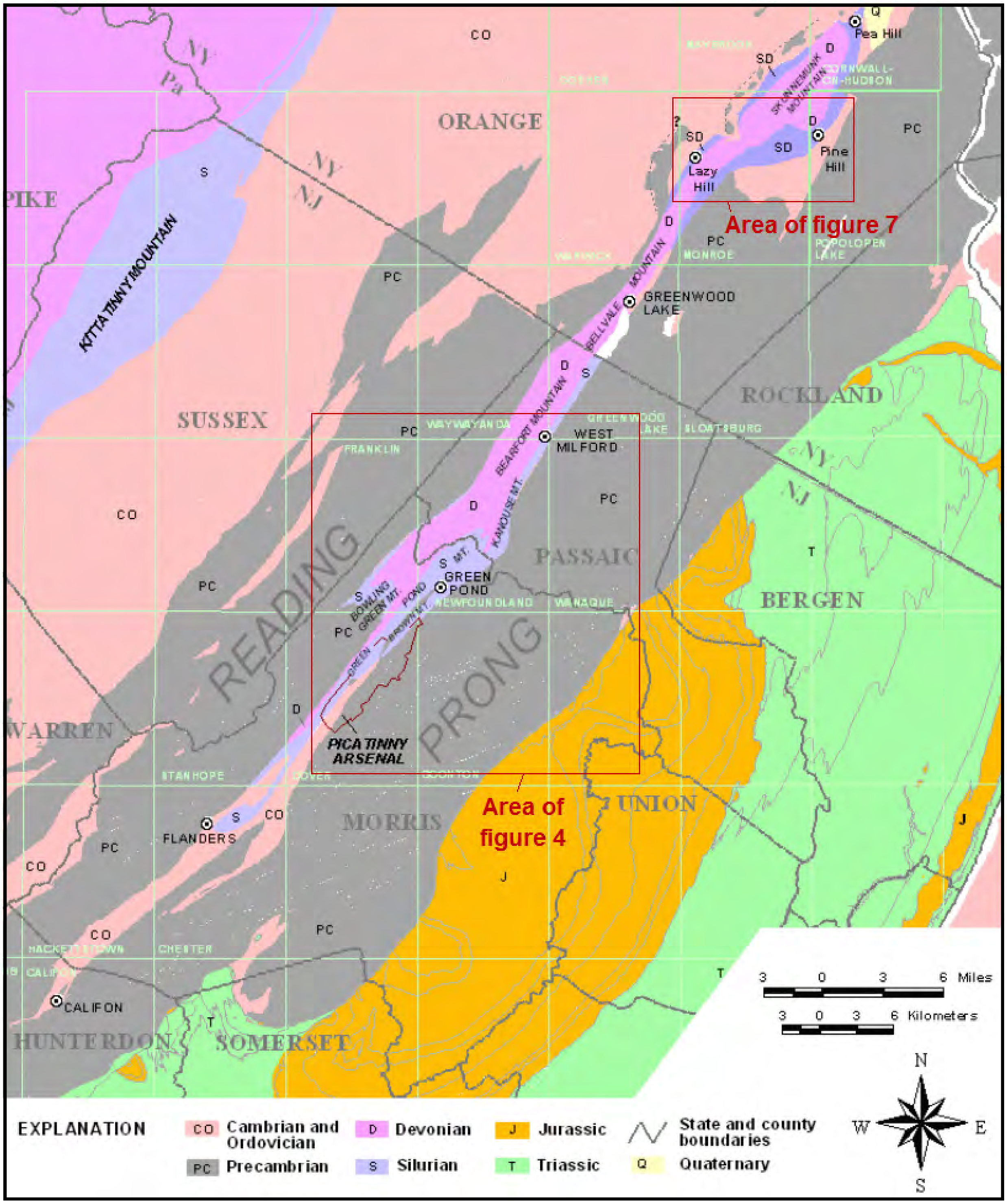


Figure 3. Generalized bedrock geology of the Green Pond Syncline. Adapted from Rickard et al. (1970) and Drake et al. (1996). Note the areas for Figures 4 and 7.

cover folds in NJ assumed a pre-Taconic, broadly arched shelf sequence for the geographic extent of the current southwest NJ Highlands, Kittatinny Valley, and Kittatinny Mountain. But the reconstructed Taconic foreland sequence doesn't reach into the northern highlands region owing to the removal of Lower Paleozoic rocks from the structural culminations of the Reading Prong (Figure 3), and thereby lacks the basis for palinspastic, balanced cross sections in those areas.

Stratigraphic and structural details of the Taconic unconformity and overlying Silurian molasse reported from previous work are reviewed as a basis to discuss their geologic nature in the GPS. Early work in NY by Darton (1894 a, b) was followed closely in NJ by Kummel and Weller (1902), who mapped and reported detailed lithological and structural relationships throughout the Green Pond Mountain region where basal Silurian sedimentary rocks rest on older rocks from Precambrian to Ordovician age. In NY however, details surrounding the nature of the unconformity are sketchier as the Green Pond Formation is restricted in its distribution and strike length at three different locations around the northeastern end of the regional syncline. Moreover, the Green Pond Formation in NY is mapped using different names in different locations, and there is a lack of detailed, uniform mapping that could otherwise shed some light on the stratigraphic variations and structural complications seen in that area. Currently, Green Pond Conglomerate is mapped on the east side of the syncline (Dodd, 1965) whereas Shawangunk Formation is mapped on the west side (Jaffe and Jaffe, 1973). These stratigraphic units are of the same age, and part of the same depositional sequence, but are mapped as separate units because of contrasting matrix color and clast composition when moving from one side of the syncline to the other. These differences are briefly noted as part of a discussion on the formation nomenclature and why the name 'Green Pond Formation' is generally used herein.

A recent trip to Orange County, NY, was made in order to visit the two locations mentioned above on different sides of the syncline where the nature of the Silurian molasse differs in outcrop. The lithological differences seen in this area are compared and contrasted with those occurring elsewhere in the GPS. A new subsurface photo of the unconformity stemming from a borehole televiewer survey of a water well from the central part of the NJ Green Pond Mountain region is also documented. This is the first subsurface record of the stratigraphic contact in NJ, and the only known record of the unconformity in the GPS besides that mentioned by Kummel and Weller (1902), which has not been corroborated. Aspects of the unconformity and overlying molasse are added from other referenced sources to help gain perspective for a palinspastic stylization of the NJ Highlands. This stylization builds on the northernmost palinspastic section from Herman et al. (1997) showing a mildly strained Cambrian-Ordovician carbonate platform and overlying Middle Ordovician flysch, both of which are arranged in open, upright folds of Taconic age. The section is extended southeast to depict the strain profile of a Taconic fold and thrust belt, an erosional unconformity, and covering molasse.

Geologic Setting

The GPS is the largest Paleozoic Valley in the Reading Prong and lies at the juncture between the central and northern Appalachian region (Figure 2). It's about 75 mi (121 km) long and up to 6 mi (10 km) wide, with about two-third's lying in NJ and one-third in NY (Figure 2). The Paleozoic sedimentary rocks in the GPS border the NY Hudson Highlands on the west (Figure 1), but are faulted and folded within the Reading Prong in NJ and PA (Figures 1 and 2). In a structural sense, the "syncline" is more formally a regional, northeast-plunging synclinorium with folded and faulted Lower Paleozoic (Cambrian-Ordovician) at the surface in the southwest and Middle Devonian rocks coring large, closed synclines at the surface in northeastern NJ and into NY (Figure 4). It's unique among Reading Prong Paleozoic valleys because it contains Middle Paleozoic (Silurian-Devonian) units of stratigraphic affinity with those cropping out northwest of the Great Valley, beginning with Kittatinny and Shawangunk Mountains over 15 mi (24 km) distance to the northwest (Figures 2 and 3).

Paleozoic rocks in the GPS range in age from Early Cambrian to Middle Devonian. As many as two to three marine cycles shape the stratigraphic column, including a Lower Paleozoic (Cambrian-Ordovician) marine transgression followed by a series of Middle Paleozoic events, including: an Early Silurian regression, a Middle- to Late Silurian transgression, and a Middle-Devonian regression (Herman and Mitchell, 1991). It is a widely held view that these Lower Paleozoic rocks sustained at least three tectonic phases of uplift and erosion including: (1) early Ordovician; (2) Late Ordovician Taconic orogeny; and (3) Late Paleozoic Alleghanian orogeny (alternatively known as the Allegheny or Appalachian orogeny).

Prior and New Work on the Nature of the Unconformity and the Silurian Molasse

The focus here is on the unconformity and nature of rocks bracketing the erosional surface resulting from the Early Silurian regression and the Middle to Late Silurian transgression in the GPS. The outcrop expression of basal Silurian strata defines the nature of Taconic unconformity, which is mapped in the NJ Green Pond Mountain region (Figures 4, 5, and 6) and three locations in Orange County, NY, near the northeast end of the GPS (Figure 3).

A Note on the Nomenclature of the Green Pond Formation

The basal, Lower Silurian unit in the GPS consists of a mixture of pebble to cobble conglomerate, quartzose and subgraywacke sandstone, quartz siltstone, and shale. Its thickness, composition, color, and texture vary by location in the syncline. Accordingly, it has been called many different names. Rogers (1836) first described the 'Green-pond-mountain conglomerate' but miscorrelated it with Triassic border-fault conglomerate (Thomson, 1957). Early miscorrelation with Devonian Skunnemunk Conglomerate by many others in the region was resolved by Darton (1894a) who found Devonian Helderberg limestone between them. Ries (1895) called it the Medina formation (Lower Silurian) in NY. Kummel and Weller (1902) and Southard (1960) preferred Green Pond Formation, but more recent workers have used Green Pond Conglomerate (Thomson, 1957; Herman and Mitchell, 1991; Drake et al., 1996) or Shawangunk Formation (Barnett, 1976; Jaffe and Jaffe, 1973). In this report, the unit is referred to as the Green Pond Formation. The decision to use "Formation" here rather than "Conglomerate" is based on the consideration that conglomerate locally constitutes less than half of the formation gross lithology, with one comprehensive measure indicating 49% sandstone, 42% conglomerate, 6% shale, and 3% siltstone (Thomson, 1959). The term "conglomerate", or "conglomerate of the Green pond Formation", or more informally "Green Pond conglomerate", is sometimes useful when describing the distribution of conglomerate with respect to specific locations in the syncline. The use of "Formation" is consistent with the

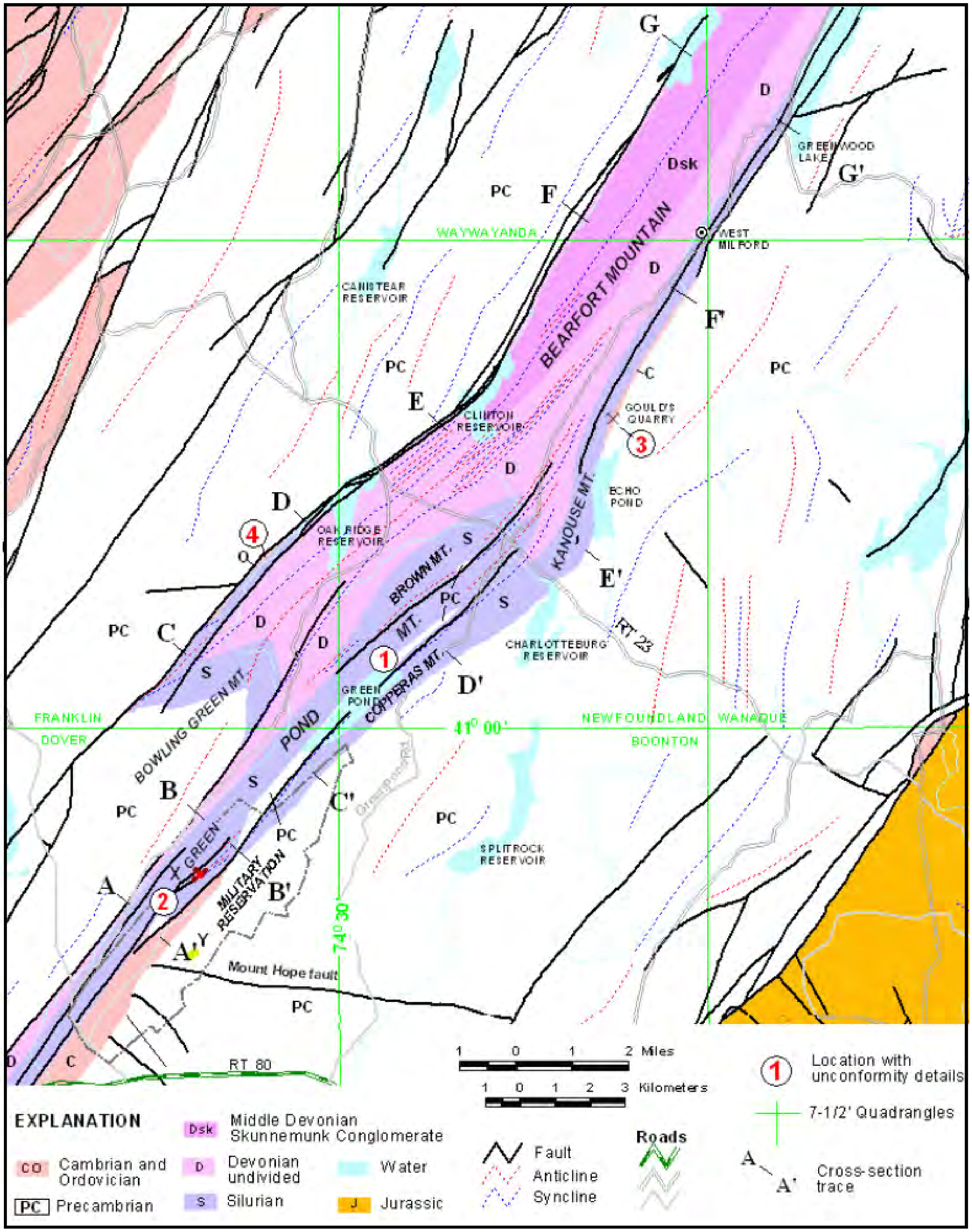


Figure 4. Generalized bedrock geology of the Green Pond Mountain region. Adapted from Herman and Mitchell (1991) and Drake et al. (1996). Note the location of section traces A through G (shown in Figure 5B). Details of the Taconic unconformity are discussed in the text for locations 1 to 4.

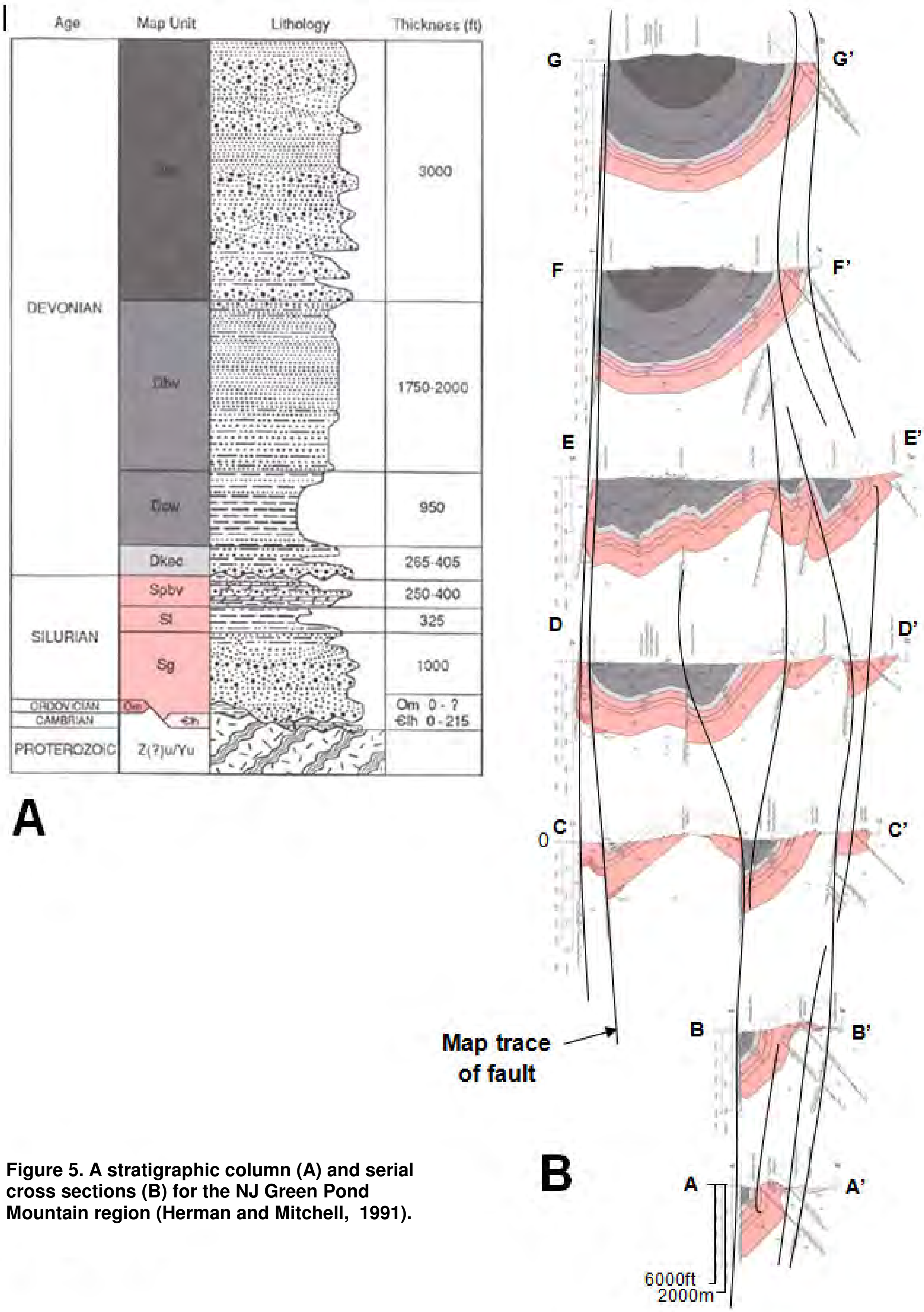


Figure 5. A stratigraphic column (A) and serial cross sections (B) for the NJ Green Pond Mountain region (Herman and Mitchell, 1991).

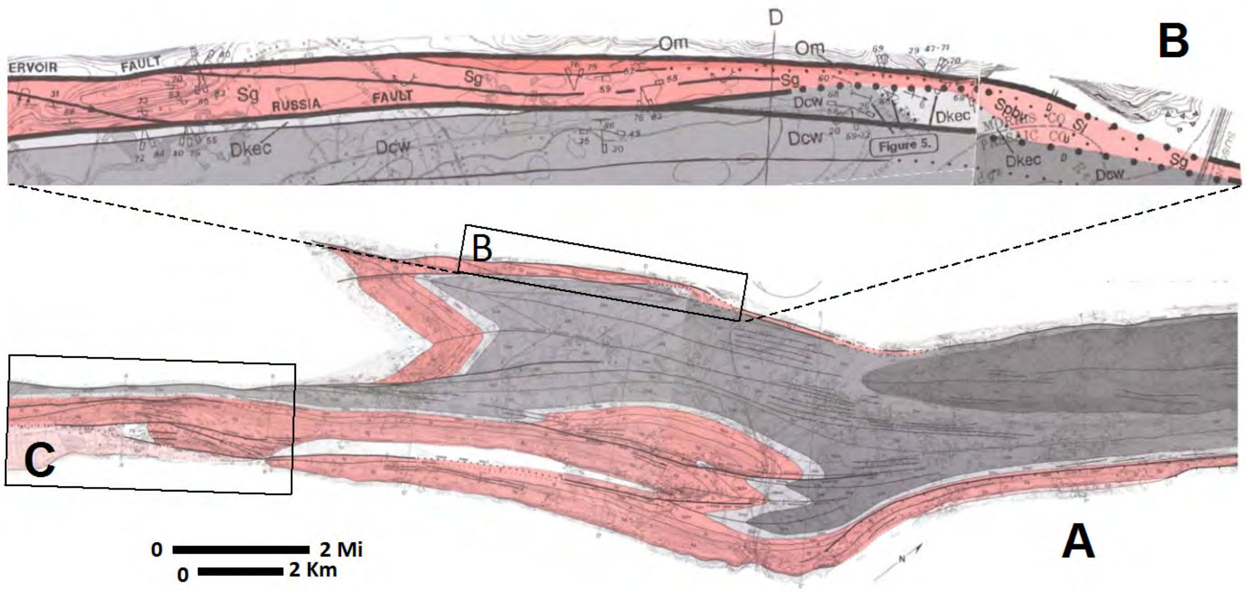


Figure 6. A. Geologic map of the central part of the Green Pond Mountain region adapted from Herman and Mitchell (1991). B. Inset map showing details along part of the northwestern boundary of the GPS where the Green Pond and Martinsburg Formations are mapped in a steeply northwest-dipping fold limb between two high-angle faults in the Reservoir fault system. The steeply-dipping limb contains is overturned steeply southeast just a short distance along strike to the west. The two shale occurrences mapped as Martinsburg are indicated by Om labels and leaders (top center of B.) C - Area C is shown in detail later in this report for the area of the US ARMY Picatinny Arsenal.

naming of the Shawangunk Formation, its stratigraphic equivalent in the Ridge and Valley Province that also contains abundant pebble conglomerate and varied alluvial-fluvial facies.

The Green Pond Mountain Region of New Jersey

The NJ part of the GPS historically has been referred to the Green Pond Mountain region and has been mapped over three time periods including the turn of the twentieth century (Kummel and Weller, 1902), around 1970 (Barnett, 1976), and again in the mid 1980s (Herman and Mitchell, 1991). The pioneering work of Kummel and Weller (1902) provides abundant stratigraphic and paleontological details, including observations of local strains such as fault attitude and slip motion.

The following excerpts are cited directly from Kummel and Weller's (1902) report on the geology of the Green Pond Mountain region:

> "The Green Pond Formation . . . consists of coarse, siliceous conglomerate, interbedded with and grading upward into quartzite and sandstones. The pebbles of the conglomerate range from one-half to three inches in diameter, and are almost entirely white quartz, but some pink quartz, black, white, yellow and red chert, red and purple quartzite and a very few red shale and pink jasper pebbles occur. The white quartz pebbles have frequently a pink tinge on their outer portion.
>
> "The quartzite . . . is interbedded in the upper portion of the conglomerate and rests upon it. It is in general a purple-red color, but presents various shades of pink,

yellow, brown and gray. Some of these beds are massive and show no laminae, but in others the thin stratification planes can be readily made out. The conglomerate beds are often very thick, with but slight trace of any bedding. In the southwestern part of the area, in the isolated hills southwest of the Rockaway River, the rock is much softer than farther north, and is friable sandstone rather than a quartzite. So completely disintegrated are some of these beds that they have been dug for sand and gravel for many years. This friable sandstone phase is well shown in the white rock cut on the D. L. & W. Railroad west of Port Oram and at the sand-pits in the vicinity of Flanders . . . The relationships of the conglomerate and quartzite to the older formations are not exposed in the isolated hills in the southwestern portion of the area."

"The relation of this formation to the overlying beds is simple. It passes upward somewhat abruptly into a soft red shale. Nowhere in NJ have the two been seen in actual contact, but they are frequently exposed in such close relationship as to render this conclusion a safe one."

"Various estimates have been made of the thickness of this formation. These range from 400 to 650 feet. All of these estimates, however, are believed to come far short of the actual thickness. In some cases they manifestly take into account only that part of the formation exposed in the steep eastward facing cliffs which characterize these ridges, and take no account of the higher beds which outcrop with steep dips on the back slopes of the mountain, and which add greatly to the thickness. In some cases, too, the small estimates may be due to an assumption that the ridges are formed by closely compressed folds. Our own estimates, measured on numerous section lines across the ridges, where at least the approximate portion of the enclosing formations were determined, and based on frequent observations of the angle of dip, indicate that the thickness of this formation is probably not less than 1,200 feet and locally it may be 1,500 feet. It is not asserted, however, that this entire thickness is exposed at any one locality, but we believe that these figures represent the thickness of the formation as developed along the greater portion of Green Pond and Copperas mountains. Toward the northern end of Kanouse mountain the thickness apparently diminishes somewhat; yet owing to the thick deposits of drift which conceal both the basal and upper portions, estimates of the thickness there may be somewhat in error. In the previous discussions of this region published in the Reports of the Survey, the conglomerate which occurs along Bearfort mountain was assumed to be the same as of Green Pond and Copperas mountains. Mr. Darton was the first to point out that this was an error, and the same conclusion was announced about the same time by Mr. Walcott. Our work corroborates completely the conclusions of these investigators in this respect. Although the conglomerates of Bearfort and Green Pond mountain resemble each other somewhat closely, yet critical examination of the two discloses at once marked lithological differences. These will be pointed out in connection with the description of the Bearfort conglomerate. Since the Green Pond formation rests unconformably in places upon the Lower Cambrian limestone, and perhaps upon Hudson River slate, and is overlain conformably by a red shale, which, as will be shown later, passes upward into a siliceous limestone containing Niagaran fossils, the correlation of the Green Pond formation with the Oneida conglomerate exposed in

> Kittatinny mountain is probably correct. The lithological differences between the two are not so great as has been assumed by some observers. The lower beds of the Green Pond conglomerate are not infrequently of the same grey color and in almost every way identical with the conglomerate of Kittatinny mountain. Moreover, reddish conglomerates so common in the Green Pond rocks are not infrequent in the Kittatinny mountain beds. Although lithological resemblances and differences are not always safe guides for correlation, particularly in a formation which is so subject to variation as a conglomerate and sandstone, yet the structural position of the two is practically the stone, and there can be no question as to the correctness of this correlation, which was first announced by Merrill. He, however, included the conglomerate of Bearfort mountain as a part of the Green Pond formation."

Specific occurrences where the Green Pond Formation crops out in close proximity to older rocks in NJ are discussed below with respect to locations identified in Figure 4. The following details mostly stem from Kummel and Weller (1902) but are supplemented by work of Herman and Mitchell (1991).

Green Pond Formation over Middle Proterozoic crystalline basement (Figure 4, locations 1 and 2 for Copperas, Green Pond, Brown, and Bowling Green Mountains). – From Kummel and Weller (1902):

> "The relation of this formation to the underlying rocks is readily determined, although only in one place has the actual contact been seen. Throughout the entire extent of Copperas mountain it rests unconformably upon the eroded surface of the crystallines, which form the lower part of the southeastern face of the mountain. At the mines opposite Green Pond the two formations are frequently exposed within twenty five or thirty feet of each other, although not in actual contact. Here the lowest conglomerate bed is rather gray in color and resembles closely the conglomerate of the Kittatinny and Shawangunk mountains. Along this face of the mountain the contact can be located definitely at an elevation of about 1,100 feet, or 225 to 250 feet below the crest"
>
> "At Middle Forge, in the quarry west of the road (near location 2, fig. 4), the conglomerate of the Green Pond mountain apparently rests upon the Kittatinny limestone, but northward a quarter of a mile the conglomerate and gneiss are apparently in contact. West of the pond a fault evidently separates the high cliff of conglomerate from the Kittatinny limestone exposed in the quarry on the shore, both formations showing strong evidence of shearing and drag at outcrops nearest the hidden contact. Elsewhere along this mountain the conglomerate apparently rests upon the gneiss, and, although this contact is nowhere exposed, yet the two are shown in close proximity to each other at many places along the wild and narrow gorge of Green Pond brook, up which the gneiss can be traced continuously to about one-quarter of a mile southwest of the end of the pond where it is lost in the swamp. However, it reappears again a mile and a half east of the upper end of Green Pond forming a narrow bench fifty yards in width and several hundred yards long, immediately below the prominent summit of Green Pond mountain. Toward the lake the ledge becomes buried beneath the drift and to the northeast it disappears beneath

> the great blocks of talus, the dip of its contact with the overlying conglomerate and quartzite being such as to carry it beneath the surface within a short distance."
>
> "The conglomerate is also seen to rest upon the gneiss in the offset of Green Pond mountain, southwest of Newfoundland, which is known locally as Brown's mountain. In Bowling Green mountain the conglomerate is wrapped around the northward end of a ridge of gneiss, and probably rests directly upon it; but the contact has not been seen, and nowhere have the rocks been found in such close proximity to each other as to eliminate beyond a doubt the possibility of a narrow strip of older sedimentary rocks between them."

Herman and Mitchell (1991) mapped Middle Proterozoic crystalline rocks with metamorphic layering dipping moderately to steeply southeast along the unconformity in the southeast-central and northeast part of the Green Pond Mountain region, whereas the Green Pond Formation dips moderately to steeply northwesterly. They also note that the contact of the conglomerate with the underlying basement rocks is not observed and is locally obscured by as little as 3 ft (0.9 m) of cover. The lack of pervasive tectonic strain fabric along the southeast syncline limb precludes a major structural contact, although limited shear strain associated with cover-layer folding is expected. These regional relations indicate that the Taconic unconformity is most pronounced in this area where the entire Lower Paleozoic section was eroded.

The basal conglomerate is coarsest to the east at Green Pond, Brown, and Kanouse Mountains where angular cobbles of shale and quartz are common, with some shale clasts measured up to 18 in (46 cm). To the west, at Bowling Green Mountain, the basal conglomerate contains mostly subangular to subrounded quartz-pebbles and is interbedded with quartzitic arkose and orthoquartzite.

Green Pond Formation over Cambrian-Ordovician Middle Proterozoic crystalline basement Gould's Quarry (Figure 4, Location 3). – From Kummel and Weller (1902):

> "At Gould's quarry, large masses of the underlying limestone are included in a conglomerate, which is believed to be the basal layers of this formation. The matrix is comprised of quartz sand, is vitreous in texture and generally of a dull red color, but white, gray and greenish strata frequently occur, particularly in the basal portion, so that the formation is not so exclusively red as implied in most of the earlier reports. The beds are almost uniformly quartzitic in texture, and, on account of their hardness, form the long, narrow, steep-sided mountain ridges characterizing this region. Locally, however, the basal portion of the conglomerate is apparently quite friable and disintegrates readily, due probably to a greater or less amount of calcareous material derived from the limestone on which it rests in places. A good instance of this was found about 2 mi (3 km) north of Macopin lake, where the basal beds are so disintegrated that they have been dug for gravel".

Herman and Mitchell (1991) show bed strike in both the Lower and Middle Paleozoic units here are the same, but bedding dips more steeply (60° to 70° northwest) in units below the unconformity in comparison to those above (42° to 56° northwest).

Green Pond Formation over Middle Ordovician Martinsburg Formation along the Reservoir Fault (Figure 4, Location 4). – From Kummel and Weller (1902):

> "The outcrops of this formation southwest of Oak Ridge reservoir apparently rest upon a black shale, which may belong to the Hudson River formation, but no positive assertions can be made. Farther to the southwest they apparently abut against the crystallines and in the fault plane."

Barnett (1976) reports Ordovician brachiopods in this shale, resulting in his mapping them as Middle to Upper Ordovician Martinsburg Formation. There are two shale outcrops that are bounded on the southeast by fault slices of Green Pond pebble conglomerate (Figure 6). Worthington (1953) reported another occurrence of the Martinsburg Formation along the Reservoir fault farther southwest where the Green Pond Formation pinches out between Holland and Bowling Green Mountains. However, the black phyllite he described differs from the tectonized shales at Oak Ridge, and occurs with other anomalous rocks of uncertain affinity. Other tectonized sedimentary rocks that crop out along the trace of the Reservoir fault directly west of the Green Pond conglomerate show abundant stretched quartz grains included within a dark greenish-gray to dark reddish-brown phyllonitic matrix. Immediately to the southwest, and southeast across the trace of a subsidiary fault, the Green Pond Formation unconformably overlies a patchy strip of very low-grade metamorphic arkose and quartzite unlike other Middle Proterozoic basement rocks in the region. These rocks are similar to the Chestnut Hill Formation of Late Proterozoic (Z) age reported in the southwest NJ Highlands (Drake, 1984).

The Green Pond Formation in Orange County, New York

The Green Pond Formation Is mapped in three areas in Orange County, NY, covered by the Monroe, Lake Popolopen, and Cornwall-on-Hudson 7-½ minute quadrangles (Figures 2, 3 and 7). These locations are specifically discussed below with respect to Lazy Hill, Pine Hill, and two bedrock ridges near Pea Hill, respectively (Figure 2). Lazy Hill lies about 2 mi (3 km) west of Monroe on the western side of Bellvale Mountain, and the western limb of the syncline (Figures 2 and 7). Pine Hill lies immediately east of Highlands Mills, NY on the east side of the syncline where one long, northeast-striking, thin bedrock ridge rises about 200 ft (61 m) above base elevations along Skyline Drive (Figure 7). The ridges near Pea Hill are more than 1 mi (1.6 km) west of Cornwall, NY within the Cornwall-on-Hudson quadrangle and at the very northeast tip of the GPS. These are a little less conspicuous, rising only about 120 ft (37 m) above base elevations.

Lazy Hill and Fault Blocks in the Monroe Quadrangle

The bedrock geology map of the Monroe quadrangle provides the only record of detailed structural readings of strata bracketing the unconformity in the NY part of the GPS (Jaffe and Jaffe, 1973 and Figure 7). Basal Silurian conglomerate and quartzite are mapped just west of Monroe in a series of fault blocks that are referred to here as south, central, and north (Figure 7). The south and central blocks flank Bellvale Mountain, whereas the north block flanks Schunemunk Mountain (Figure 3). The unit is mapped as Shawangunk Formation, and is described as green-gray to white and buff-colored orthoquartzite (25%) and conglomerate

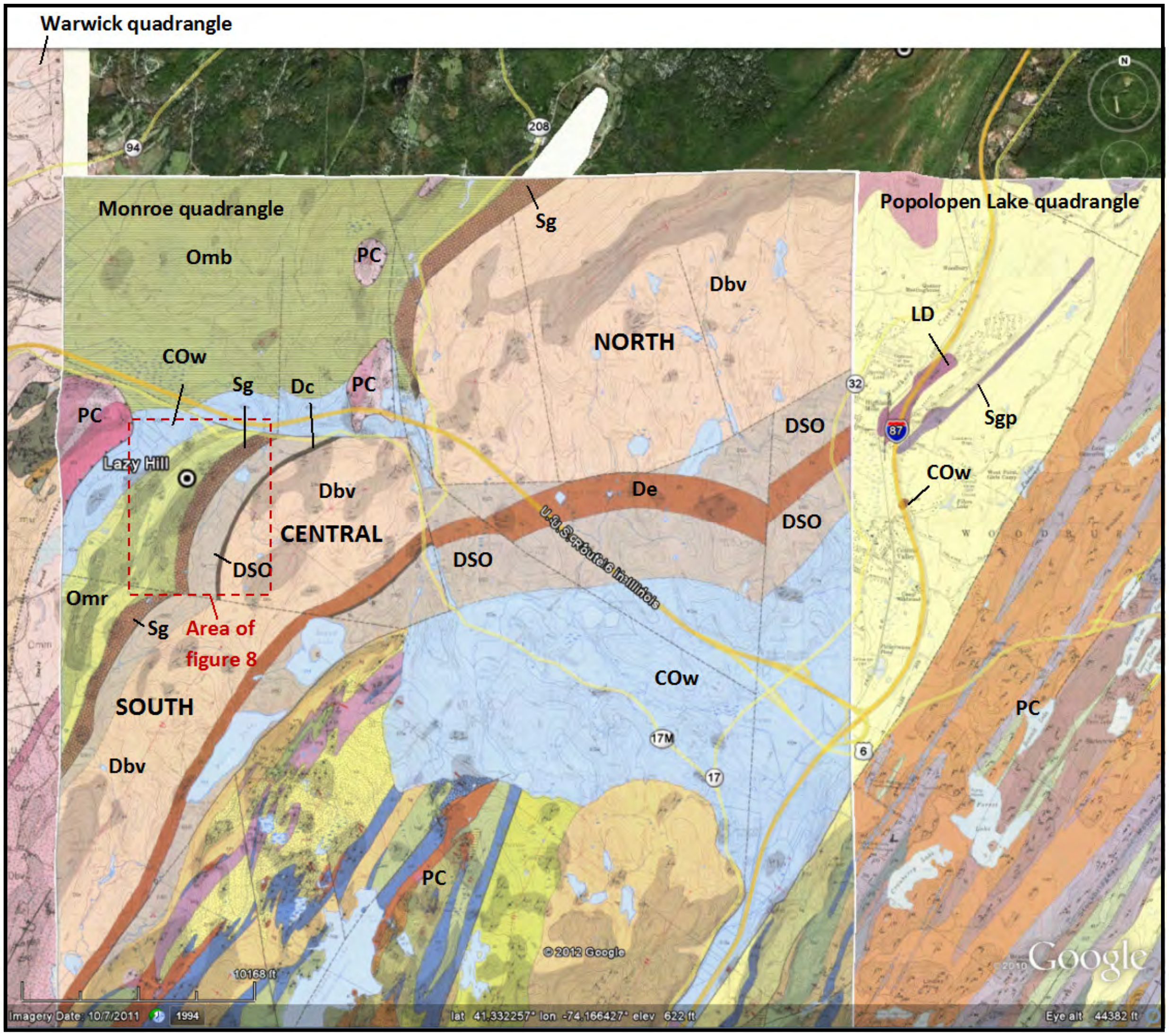


Figure 7. Composite display of three bedrock geology maps (Offield, 1967—left; Jaffe and Jaffe, 1973—center; and Dodd, 1965— right) registered in Google Earth that cover parts of the Green Pond Syncline in New York State. The Shawangunk Formation (Sg) is mapped to the west whereas the Green Pond Formation (Sgp) is mapped to the east. The Shawangunk is extended north of the Monroe quadrangle boundary based on the topographic expression of the associated hill. The relationship of the Taconic unconformity on the west side of the syncline is discussed in the text with respect to south, central, and north fault blocks in the Monroe quadrangle. Abbreviations: Dbv—Devonian Bellvale Formation; COw – Cambrian-Ordovician Wappinger Group (dolomite); Dc – Connelly Conglomerate; De – Esopus Formation; DSO - concealed Silurian, Devonian, and Ordovician strata; LD – Lower Devonian sedimentary rocks; Omr – Ordovician Martinsburg calcareous shale and quartzite; PC – Precambrian rocks.

(75%) consisting of coarse white pebbles of milky vein quartz in a matrix of fine pebbles and grains of rounded quartz.

According to Jaffe and Jaffe (1973):

> "A 10-meter section measured across the top of Lazy Hill, shows from west to east; about 1 meter of gray-buff orthoquartzite, 2.5 meters of coarse white pebble conglomerate, 4.5 meters of white orthoquartzite with ripple marks on bedding planes, and 1.25 meters of finer white quartz pebble conglomerate . . . Toward the

> eastern edge of Lazy Hill scarp, the conglomerate carries some coarse orthoclase pebbles and unit grades into a red arkosic conglomerate below the ridge top . . . Small slabs of red argillaceous sandstone were found at localities near the base of the eastern edge of lazy Hill scarp and suggest a gradation to the Longwood Shale."

Pebbles in the conglomerate are about 0.5 to 4 in (1.3 to10 cm) long, and are strongly elongated (stretched) parallel to the syncline fold axes. The rocks are reported as being shattered, sliced, and veined. They map Shawangunk Formation overlying calcareous shale and quartzite of the Martinsburg Formation, thereby having the same stratigraphic relationships as seen about the Taconic unconformity at Kittatinny and Shawangunk Mountains about 15 mi (24 km) across the Great Valley to the northwest. But the Martinsburg at Lazy Hill is comparatively more deformed than its counterpart to the northwest, with local, southeast-verging asymmetric folds and steep, northwest-dipping faults (Jaffe and Jaffe, 1973). The Shawangunk designation was used for these rocks because they closely resemble those in Shawangunk Mountain where they are white- and buff-colored rather than the grayish-purple to grayish-red color of Green Pond Formation on the eastern side of the syncline at Pine Hill, NY (Figure 7) and in the central Green Pond Mountain region of NJ. The unit thickness in the Lazy Hill area is portrayed by Jaffe and Jaffe (1973) as about 400 to 600 ft (122 to 183 m) thick based on their cross-section interpretations and calculations based on their outcrop widths and dip angles. The Shawangunk Formation of Jaffe and Jaffe (1973) will be referred to as the Green Pond Formation for the remainder of this report in accordance with the nomenclature discussion above.

In the southern and central fault blocks, the Green Pond Formation forms ridge scarp peaking at 700 to 800 ft (213 to 244 m) elevations in comparison to 900 ft (274) crest elevations of nearby Bellvale Mountain to the east. The scarps are shown as being cut by concealed cross faults striking about N95° E, having little offset of cross-cut Ordovician through Devonian strata, and are thus not included on the regional maps compiled here (Figures 1 and 2). In the southern fault block, the Green Pond Formation is mapped as overlying Martinsburg Formation calcareous shale dipping north-northeast to south-southeast at 20° to 50°, but there are no structural readings mapped close to the unconformity, and the angular relationship between the two units here is unknown. However In the central fault block, the Green Pond is mapped near outcrops of Ramseyburg calcareous quartzite (Figure 8), and the angular unconformity is characterized along two traverses across the crest of Lazy Hill (Figure 8). Both formations strike parallel (northeast-southwest), but the Martinsburg dips gently eastward 25 to 16° beneath the Shawangunk, that is mapped having moderate eastward dips of 52° to 40°. Along the northern traverse, there is about a 10° difference in northeast-southwest strike, but the formation dips are the same (60 ° southeast).

The Green Pond Formation crops out sparingly in the North block on the westward-facing hillslope at about 600 ft (183 m) elevation, with peak elevations of Schunemunk Mountain in the 1,300 to 1,400 ft (396 to 427 m) range. In all three blocks, it's mapped as being fault-bounded on the eastern side. For the south and central blocks, undivided and concealed rocks of Ordovician to Devonian age are mapped directly east of the bounding fault. The Lower Devonian Connelly Conglomerate is mapped about 1,300 ft (396 m) to the east of the Green Pond Formation, and adjacent to the concealed unit in the central block. It is also mapped as a fault sliver at the southern end of the ridge scarp in the north fault block (Figure 7) where Middle Devonian Bellvale Sandstone is otherwise mapped directly east of the bounding fault.

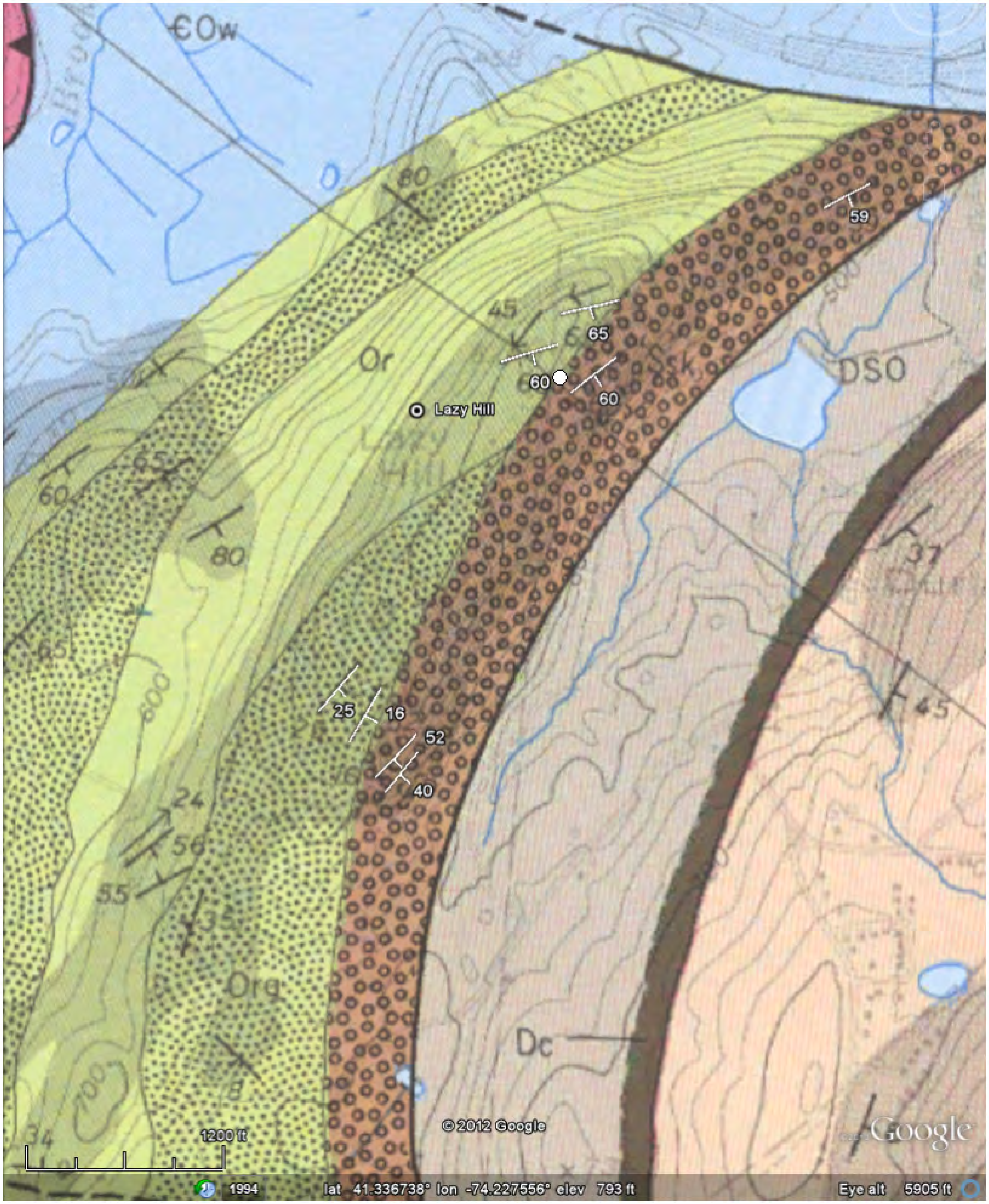


Figure 8. Structural details in the central fault block on the western limb of the GPS where the Taconic unconformity is mapped by Jaffee and Jafee (1973). Map location shown in Figure 7. Bedding strikes and dips for the two traverses across Lazy Hill are emphasized. SSk - Shawangunk Formation (referred to in the text as the Green Pond Formation), COw – Cambrian-Ordovician Wappinger Group (dolomite), Dbv – Devonian Bellvale Formation, Dc – Connelly Conglomerate, De – Esopus Formation, DSO – concealed Devonian, Silurian, and Ordovician sedimentary rocks, LD – Lower Devonian sedimentary rocks undivided, Omr – Ordovician Martinsburg calcareous shale and quartzite, PC – Precambrian rocks. Location of pictures on Figure 8 indicated by the solid white dot.

This distinction is interesting because there is enough distance between the Green Pond Formation here and the superjacent Middle Devonian Bellvale Formation to accommodate the sequence of Middle Silurian strata mapped above the Green Pond Formation elsewhere in the GPS. In NJ, the combined stratigraphic thickness of the Middle and Upper Silurian units occurring between the Green Pond Formation and the Connelly Conglomerate is about 800 ft (244 m) (Herman and Mitchell, 1991). The concealed interval in the central fault block can accommodate an 800-ft. section dipping at about 40^{o}. The closest Green Pond outcrop dips 59^{o} and the closest Connelly outcrop dips 32^{o} for an average of about 45^{o}. It is therefore possible that the Green Pond Formation is not fault-bounded on its eastern side, and for that matter, may not be fault-bounded along its entire length west of Schunnemunk Mountain where outcrops are seemingly scarce and the questionable interval is concealed by thick surficial deposits (Jaffe and Jaffe, 1973).

Don Monteverde, Jack Epstein, and I travelled to the central fault block on the west limb of Bellvale Mountain on June 28, 2012 with the hope of documenting the unconformity based on the mapping of Jaffe and Jaffe (1973). We targeted the northernmost of two traverses that they mapped across Lazy Hill in the central fault block where a power-transmission line provides access off NY Rt 17M at the base of Lazy Hill up to its crest (Figure 8). We hiked up approaching from the north, passing over pavement outcrops showing rhythmic cycles of shale, siltstone, and greywacke sandstone of the Martinsburg formation. At the location of the northernmost traverse of Jaffe and Jaffe (1973; Figure 8), there's a prominent ridge of white pebble conglomerate cropping out immediately east of the transmission line that overlies a quartzite that is about 3.3 ft (1 m) thick along the western base and southern tip of the ridge (Figure 9). Here, white pebble conglomerate sits atop siliceous, light-brown to gray, medium- to coarse-grained uartzite that is lcally thin-bedded. It was nonreactive with dilute hydrochloric acid on fresh surfaces, and it was difficult to tell if we we're looking at or Martinsburg well-cemented subarkosic sandstone or Green Pond quartzite, because both units are penetratively strained and cut by slickensided shear planes that locally offset and complicate their contact (Figure 10). But underneath a small overhang at the southern tip of the

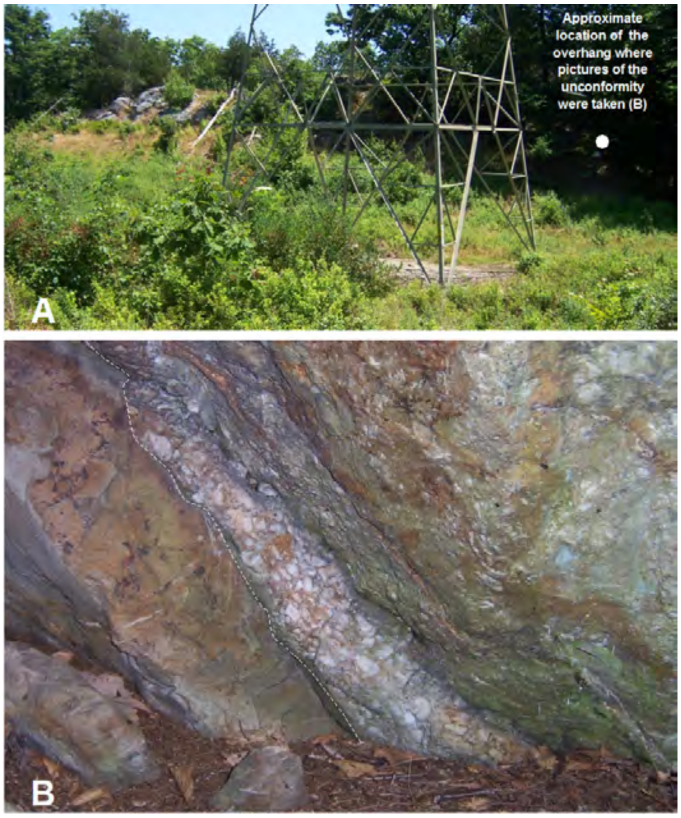


Figure 9. View of the Shawangunk Formation cropping out on a ridge atop Lazy Hill. See Figure 8 for the picture location. Photograph A is a southeast view from the trail towards the spine of the Hill. The solid white dot on the right side is the approximate location of the overhang where the unconformity crops out. Photograph B shows the overhang outcrop where white-pebble conglomerate of the Shawangunk Formation lies atop a subarkose sandstone that may be the Martinsburg Formation. Some of the strain features associated with these rocks are detailed in Figure 10, and discussed in the text. Photographs by Jack Epstein.

ridge, white pebble conglomerate sits directly on the quartzite, with very little divergence in strike and dip between the two units; the average strike/dip for the sandstone was N60°E/18°S compared to N73°E/24°S in the superjacent conglomerate. We walked the contact between the quartzite and conglomerate along strike for about 20 ft (6m) at the base of the ridge heading northeast from the overhang. The conglomerate closely resembles Green Pond conglomerate mapped along the Reservoir fault in NJ (Herman and Mitchell, 1991). In both places it contains milky-white, subangular to subrounded, vein-quartz pebbles ranging from an averaging diameter of about 1 to 2 in (2.5 to 5 cm), up to about 6 in (15 cm). The rocks along the Reservoir fault are more highly stretched and fractured in comparison to those here, but the abundance of mineral veins and stratigraphic slip and wedging at this location indicates significant Alleghanian strains here as well. The Martinsburg Formation appeared to coarsen upward towards the upper contact, but there was a significant covered interval between the Martinsburg outcrops near the trail and the base of the ridge. It is likely that the lower quartzite here is the 3-ft (0.9-m) thick quartzite at the base of the Green Pond (Shawangunk) Formation mentioned by Jaffe and Jaffe (1973). The search for the unconformity at the more southerly traverse (Figure 8) was not attempted due to time restrictions.

Pine Hill, Lake Popolopen Quadrangle

After hiking down Lazy Hill, we drove to the base of the ridge east of Highlands Mills, NY, along the base of Pine Hill in the Lake Popolopen quadrangle where the Green Pond Formation was mapped by Dodd (1965 and Figure 7). We drove into a new housing tract being built along the east side of the ridge base, and we stopped to inspect nearby boulders. The Green Pond here is the same polymictic, grayish purple and grayish red conglomerate that crops out in the eastern and central parts of the NJ Green Pond Mountain region. It has varicolored sedimentary gravel and cobbles along with abundant white, vein-quartz pebbles. The nature of the lower contact here is unknown, and it's difficult to tell whether this ridge is bounded by a fault on the east, as the ridge is separated from outcrops of Cambrian-Ordovician Wappinger Dolomite to the southeast by a large expanse of alluvium (Dodd, 1965). No description of the Green Pond is provided by Dodd (1965) as their primary focus was on the Precambrian geology. But this sequence was studied by Southard (1960) as part of a senior thesis that provides details of the lithological facies here and in the ridges near Pea Hill (Figures 3 and 11). He reports that the Green Pond Formation is nonfossiliferous and therefore of uncertain age, but probably the stratigraphic equivalent of the Shawangunk conglomerate to the west. He divided the Green Pond Formation into five subunits, four of which are quartzite that occur mostly in the eastern section. At Pine Hill he recognized an upward sequence of conglomerate, quartzite, and sandstone that is about 400 ft (122 m) thick. The conglomerate is about 300 ft (91 m) thick and is coarsest at its base where the largest pebbles (4.5 in [11 cm] in diameter) fine upward to white-quartz pebbles 1 to 2 in (2.5 to 5 cm) in diameter. The conglomerate matrix is coarse to very coarse sand that is red and yellow in color. Conglomerate bed thickness ranges from 0.5 to 15 ft (0.15 to 5 m). Conglomerate beds contain sandstone intervals that are less continuous along bed strike where they pinch and swell. The quartzite units are medium- to thick bedded, with varieties ranging in color from light-red to white, and totaling about 55 ft (17 m) thick. The upper sandstone units are more poorly exposed, range in thickness from about 5 to 15 ft (1.5 to 5 m), and show a variety of lithological textures and color variations. Red sandstone units contain minor red shale and siltstone, cross-bedded, and laminated varieties that range in

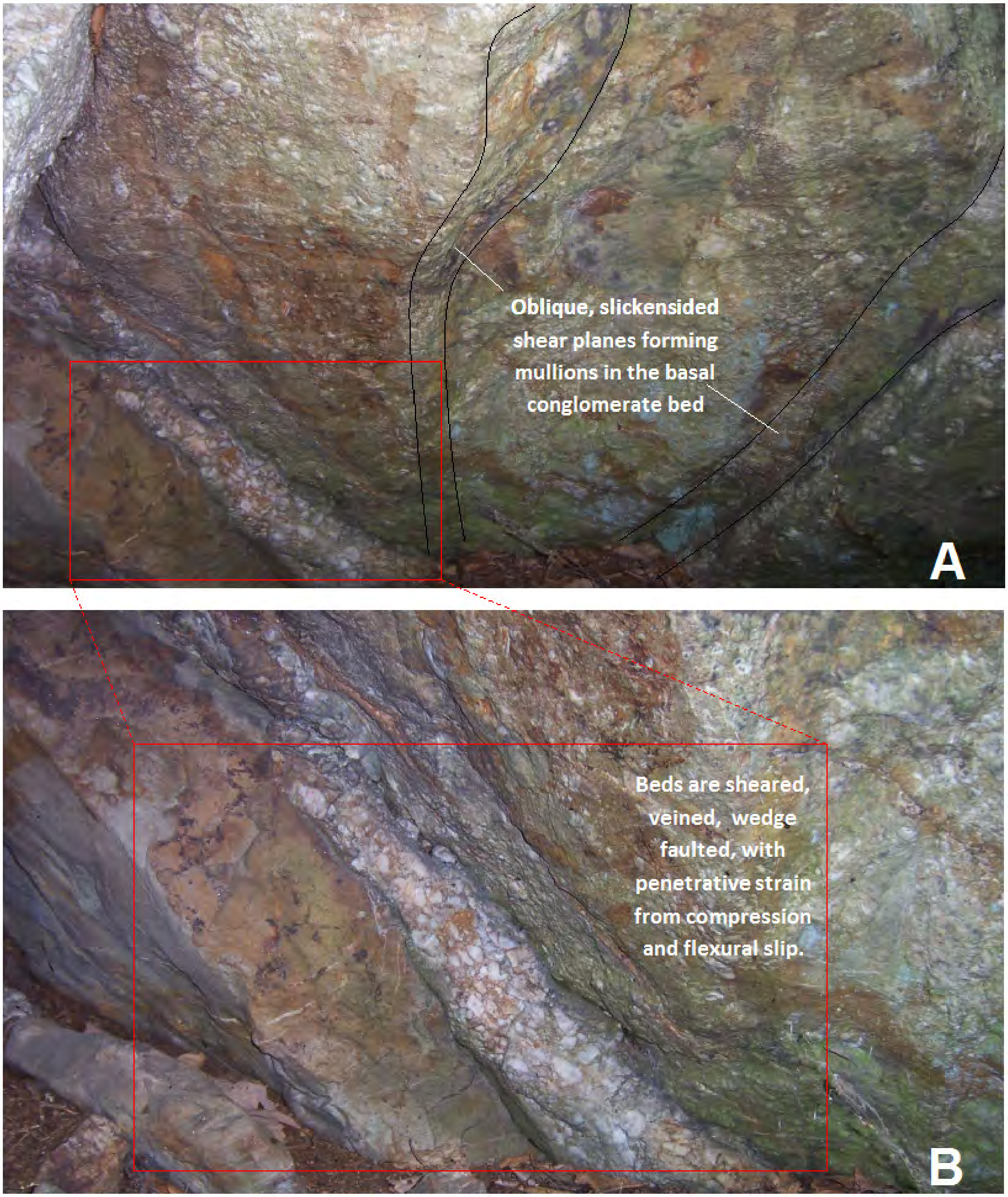


Figure 10. Detailed views of the rocks near the Taconic unconformity atop Lazy Hill. Photograph A is a northeast view of beds beneath an overhang. Beds dip left-to-right at about 20°-25° E. Slickensided shear planes form mullions (Epstein and Lyttle, 1987) at the base of a conglomerate-bed. Photograph B shows details about a contact between gray quartzite (left) and the suprajacent white-pebble conglomerate. Mineral-vein arrays and small faults locally offset the contact. The beds are penetratively strained and sheared along contacts. Photographs by Jack Epstein.

color from purplish white to purplish red and locally contain rip-up clasts, and ripple marks. This sequence at Pine Hill was also mentioned in earlier work of Darton (1894a) and Ries (1895). At that time, Ries (1895) referred to the Green Pond Formation as the Medina formation, including Oneida conglomerate at its base, with the quartzite and sandstone as upper members of the Medina formation.

The Ridges near Pea Hill, Cornwall-on-Hudson Quadrangle

At the northern end of the GPS just west of Cornwall, NY, Darton (1894a) reported conglomerate overlying Hudson Shale (Martinsburg Formation). He depicts their arrangement in a moderate- to steeply-northwest-dipping succession of Silurian to Devonian strata with Oneida conglomerate along its eastern face. Southard (1960) also studied this sequence where he reports basal conglomerate and quartzite units like those at Pine Hill, but lacking the upper sandstone unit. Ries (1895) described the east side of the eastern ridge as being formed by “coarse-grained red siliceous conglomerate (Oneida), with red sandstones and shales of Medina age”. Darton (1894a) reported about 25 ft (8 m) of conglomerate and sandstone here.

The ridge locations near Pea Hill are tentatively mapped in Figure 11 based on Darton’s (1894a) mapping as reported by Ries (1895). The Green Pond Formation was sketched in Google Earth as a pair of polygons corresponding to conglomerate noted on Darton's map (Figure 11B). Registration of the image proved challenging because the map is old, and contains sketched roads, railways, and a stream. The proposed alignment primarily uses two, linear topographic ridges and Pea Hill as reference features in Google Earth (Figure 11). Darton (1894a) depicted the structure and stratigraphy associated with the Green Pond (Medina formation) in the eastern ridge, but no details surrounding the western ridge were given. It is possible that the ridges may define a southwest plunging syncline axis of the GPS near its northeastern tip, but more detailed mapping is needed to verify it.

A New Subsurface Record of the Unconformity in the Green Pond Mountain Region from Picatinny Arsenal

A subsurface stratigraphic contact interpreted to be the Taconic unconformity was recently photographed as a digital borehole televiewer (BTV) optical image collected within the U.S. Army military reservation in Morris County, NJ, known as Picatinny Arsenal (Figures 3, 4, 12, and 13). In 2010 and 2011, the NJ Geological Survey was asked by Mr. Joseph Marchesani of the NJ Department of Environmental Protection Site Remediation Program to review optical BTV data collected by geophysical companies contracted by the US Army as part of on-going site characterization and remediation work at two groundwater-investigation (GWI) sites within the reserve (Figure 12). The 600 Area GWI site is underlain by the Green Pond Formation, whereas the Mid-Valley GWI site is underlain by Precambrian gneiss and granite lying immediately southeast of the GPS (Figures 4 and 13). The BTV surveys were provided as paper reports and used primarily used to determine the orientation of permeable stratigraphic layering and secondary brittle structures (fractures and faults) penetrated by the wells. The details of the BTV study of the Proterozoic rocks is beyond the scope of this work, but the orientation of metamorphic layering and folding geometry determined from a structural analysis of Mid-Valley area is incorporated into a cross-section interpretation below.

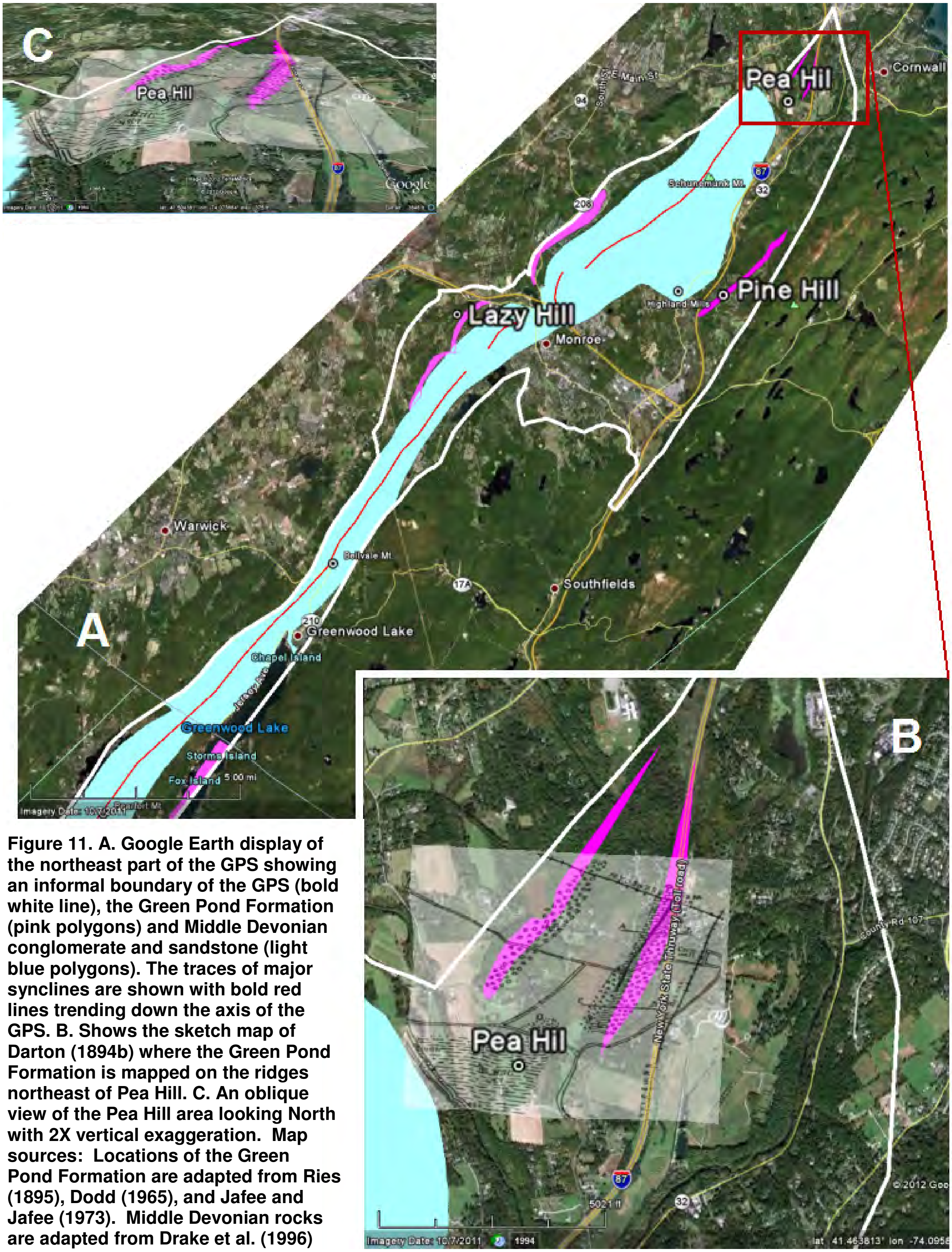


Figure 11. A. Google Earth display of the northeast part of the GPS showing an informal boundary of the GPS (bold white line), the Green Pond Formation (pink polygons) and Middle Devonian conglomerate and sandstone (light blue polygons). The traces of major synclines are shown with bold red lines trending down the axis of the GPS. B. Shows the sketch map of Darton (1894b) where the Green Pond Formation is mapped on the ridges northeast of Pea Hill. C. An oblique view of the Pea Hill area looking North with 2X vertical exaggeration. Map sources: Locations of the Green Pond Formation are adapted from Ries (1895), Dodd (1965), and Jafee and Jafee (1973). Middle Devonian rocks are adapted from Drake et al. (1996) and Rickard et al. (1970)

The unconformity was penetrated by the AWDF well within the 600 Area (Figure 14) at about a depth of about 419 ft (128 m) after passing through Green Pond conglomerate, sandstone, siltstone and shale. Below the unconformity, higher reflective, indurated, and fractured beds are interpreted to be the Cambrian Hardyston Quartzite (Figure 14). The contact between the two units is unremarkable and somewhat diffuse, but is picked at a depth of 418.65 ft (127.6 m) below ground surface (Figure 14). Figure 15 shows a statistical analysis of beds

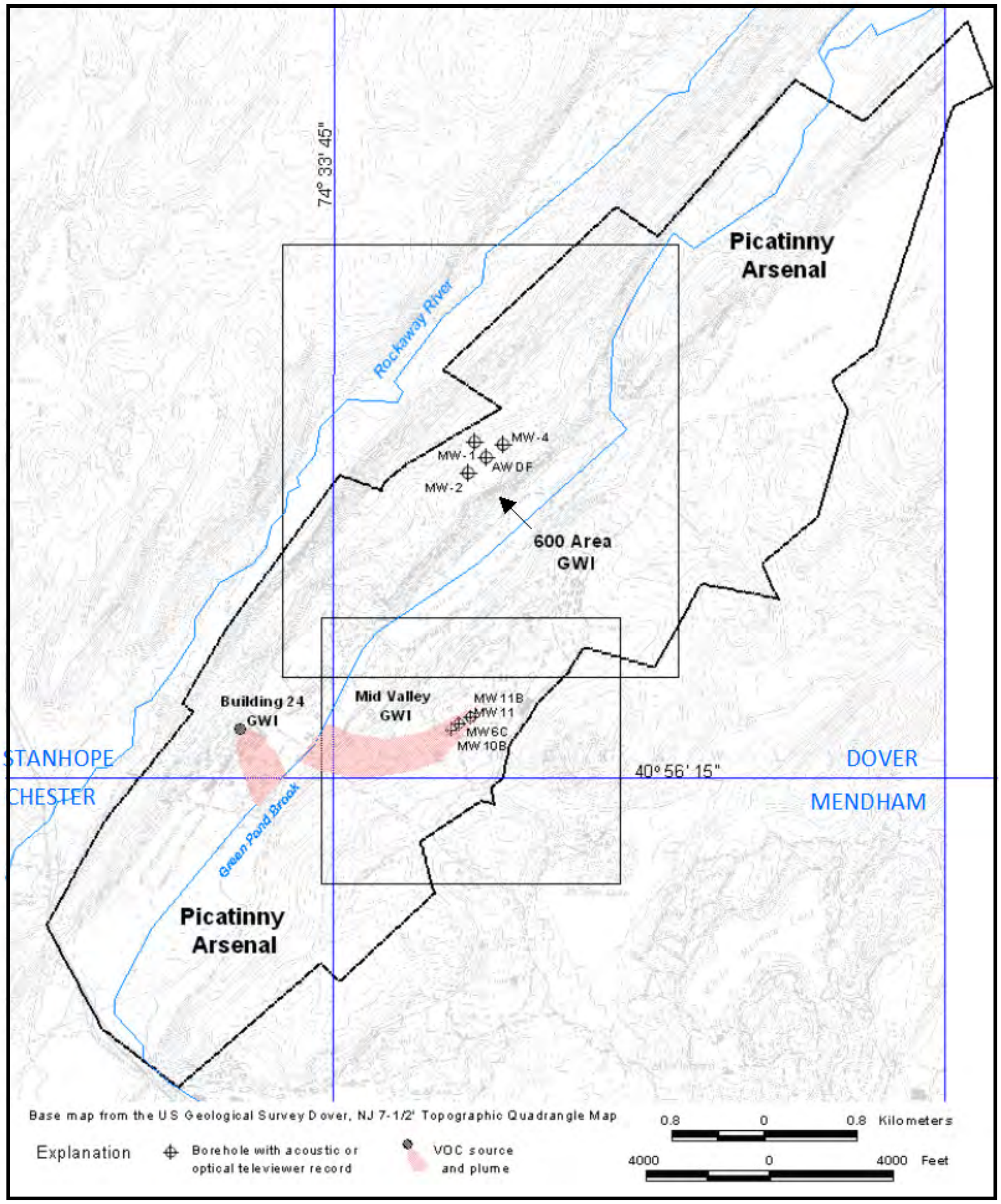


Figure 12. Location map of Picatinny Arsenal showing the locations of three groundwater investigation (GWI) sites and four USGS 7-1/2' topographic quadrangles. This paper focuses on the 600 Area GWI. The boxes correspond to the coordinate limits of digital elevation model (DEM) grids that were generated for two groundwater investigations. The unconformity was penetrated at a depth of about 419 ft (128 m) in well ADWF.

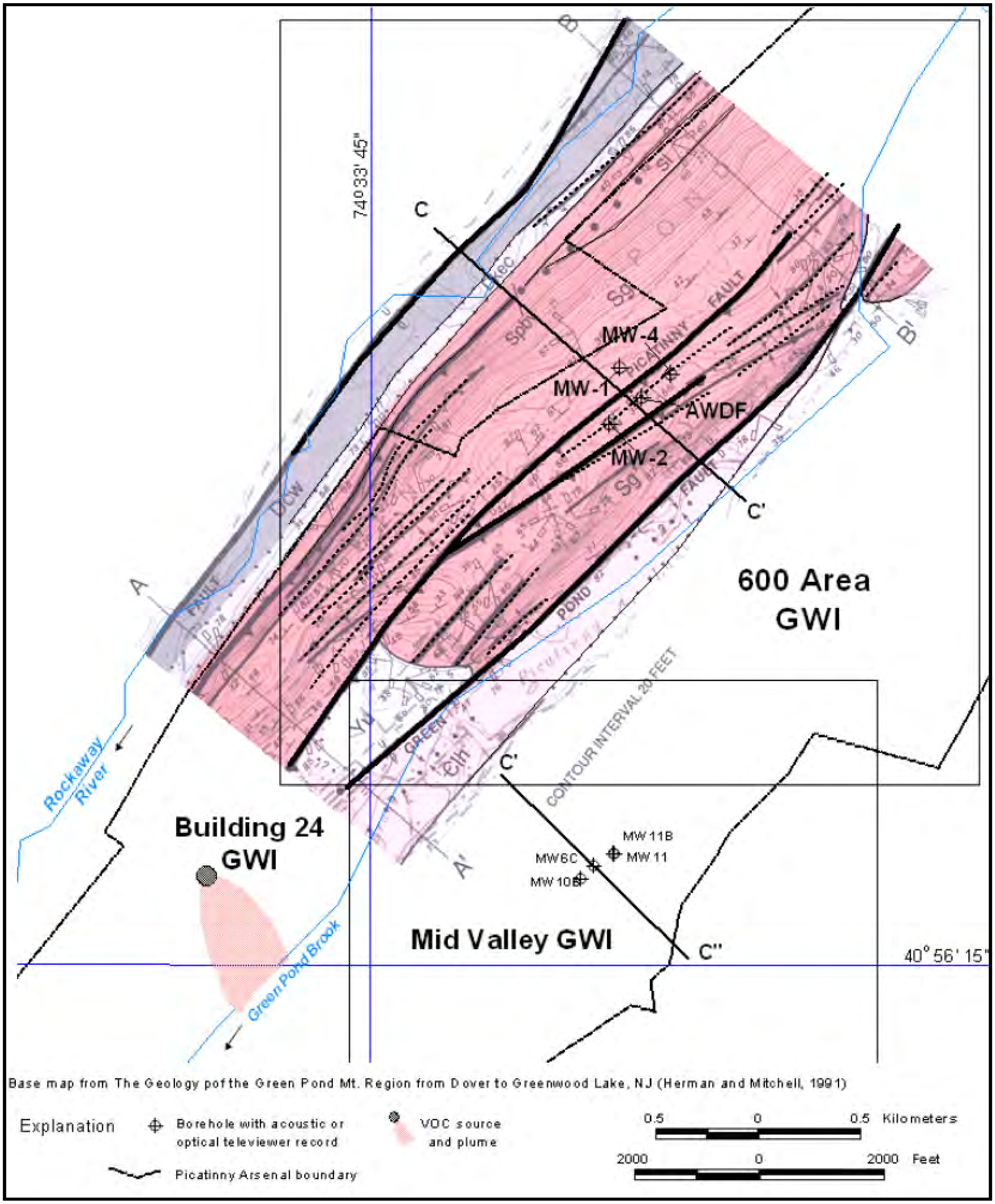
and fractures bracketing the unconformity. Figure 16 summarizes the well depths and average bed dips determined for each well from the BTV records.

The BTV images show the Green Pond Formation as a heterogeneous mix of olive green and grayish brown pebble conglomerate, sandstone, siltstone, and shale. The rock colors are described as they appear in the paper report and should be regarded with caution as they probably don't capture true colors, and the type of borehole imaging tool and data acquisition and processing parameters are unknown. But compositions and textures seen in the borehole photos facilitate distinction between conglomerate, sandstone, siltstone, and shale. The reports were only available for a brief time during the file review, which was more focused on the structural interpretation than on the stratigraphic characterization. Consequently, only a general stratigraphic review of the record was conducted and not a detailed lithological summary. As noted in the bureau review conducted then, the coarsest conglomerate beds reach 4 to 6 ft (1.6 to 1.8 m) thick, whereas the shale beds are less than 1 ft (0.3 m) thick. Sandstone beds commonly range in thickness from less than 1 ft (0.3 m) to about 2 ft (0.6 m). Beds in the basal part of the Green Pond Formation are generally finer grained than beds higher in the section (Figure 14). The Hardyston is composed of tan, brown and bluish-white, thin-to medium bedded, fine to coarse sandstone or quartzite. This unit is not folded and lacks the metamorphic and igneous textures that are seen elsewhere in Middle Proterozoic rocks. However, this lower unit may have an affinity with other anomalous metasedimentary rocks of probable Late Proterozoic age like those mentioned earlier along the Reservoir fault (Herman, and Mitchell, 1991).

Some beds in the Green Pond Formation are highly fractured whereas others are not. Bed-parallel fractures are common, as are steeply-dipping extension fractures that locally show complex banding, and therefore multiple generations of tensile opening and mineralization. Some of the steeply-dipping extension fractures show normal dip-slip movement. Most of the fractures show alteration rinds and adjacent staining of the unit matrix by groundwater infiltration and movement. The chemistry of the fracture and matrix alteration and staining is unknown. Shear fractures seem to be more common in the finer-grained beds where local wedges in the strata probably reflect bed-parallel shear strain.

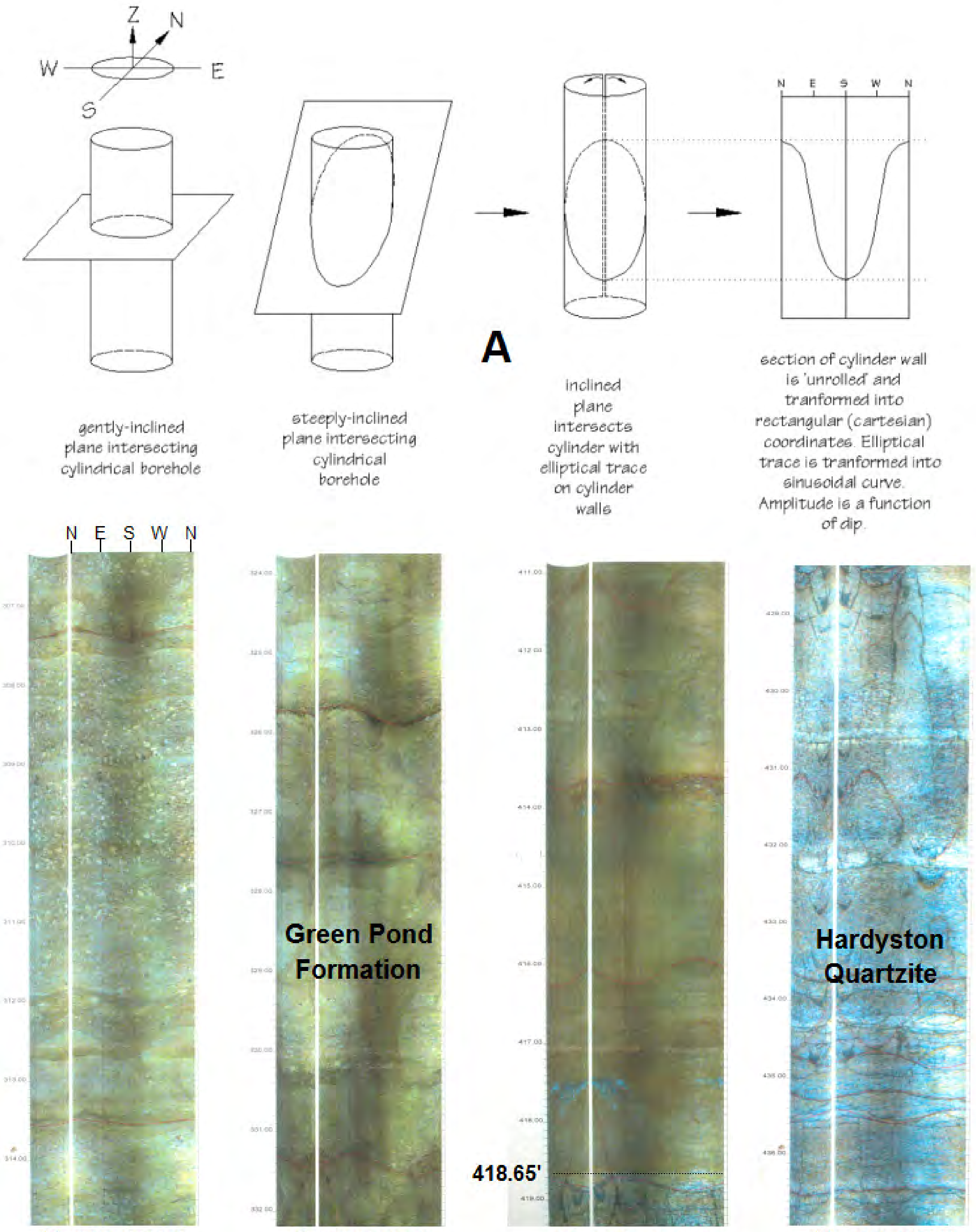
The BTV data were also used to refine the bedrock geology map (Figure 16) and to construct a new cross section through the area (Figure 17). The central part of 600 Area lies between the Green Pond and Picatinny reverse faults (Figures 13, 16 and 17). Herman and Mitchell (1991) show the Picatinny fault dipping steeply southeast and the Green Pond fault dipping steeply northwest. The BTV analyses confirm that the beds near wells MW-2 and AWDF straddle a southwest gently plunging, upright, and open anticline with limbs that dip gently northwest and southeast (Figures 15 to 17). The stratigraphic interpretation of the unconformity agrees with the existing cross section interpretations that depict a thin veneer of Hardyston Quartzite overlying Precambrian basement and underlying the Green Pond Formation (Herman and Mitchell, 1991).

3D diagrams of well-field components and bedding and fracture planes for the 600 Area wells were also produced as part of the file review. Some of these diagrams are included here to further convey the subsurface BTV results (Figures 18 and 19). The maps and 3D diagrams were generated and displayed using ESRI ArcView 3.2a software. The ArcView Spatial and 3D Analyst extensions were used for clipping digital elevation models (DEMs) and the 3D Analyst extension was used with the NJGS 3D well field visualization extension to generate and



Base map from The Geology pof the Green Pond Mt. Region from Dover to Greenwood Lake, NJ (Herman and Mitchell, 1991)

Figure 13. Part of a bedrock geological map covering the 600 Area GWI (Herman and Mitchell, 1991) was scanned and georegistered in ArcView GIS in order to refine the structural interpretation near the 600 Area based on the BTV data. The cross section interpretation C-C" is shown in Figure 17. The northwest part (C -C') lies between sections A-A' and B-B' " and edge matches to the section through the Mid Valley are (C'-C"). Note that the fault locations remain the same, but folds axes in the 600 Area have been slightly modified from those of Herman and Mitchell (1991) based on the BTV data.



B. 306-315 ft **C.** 324-332 ft **D.** 411 - 420 ft **E.** 428-437 ft

Figure 14. A. Schematic diagram illustrating how BTV images are "unrolled" and flattened for display and interpretation. B through E are optical BTV records of specific depth intervals in the well that were digitally scanned from a report by Mid-Atlantic Geoscience, LLC. Each BTV record includes a wrapped virtual core on the left showing just a sector of the well from a specific viewpoint, and a flattened, unwrapped image on the right showing the unwrapped borehole wall. Images B and C show pebble conglomerate and coarse to medium sandstone in the Green Pond Formation. Image D shows a stratigraphic contact between the Green Pond Conglomerate and the subjacent Hardyston Quartzite at about 419' depth. Image E shows a section of the Hardyston Quartzite starting about 10 ft (3 m) below the contact.

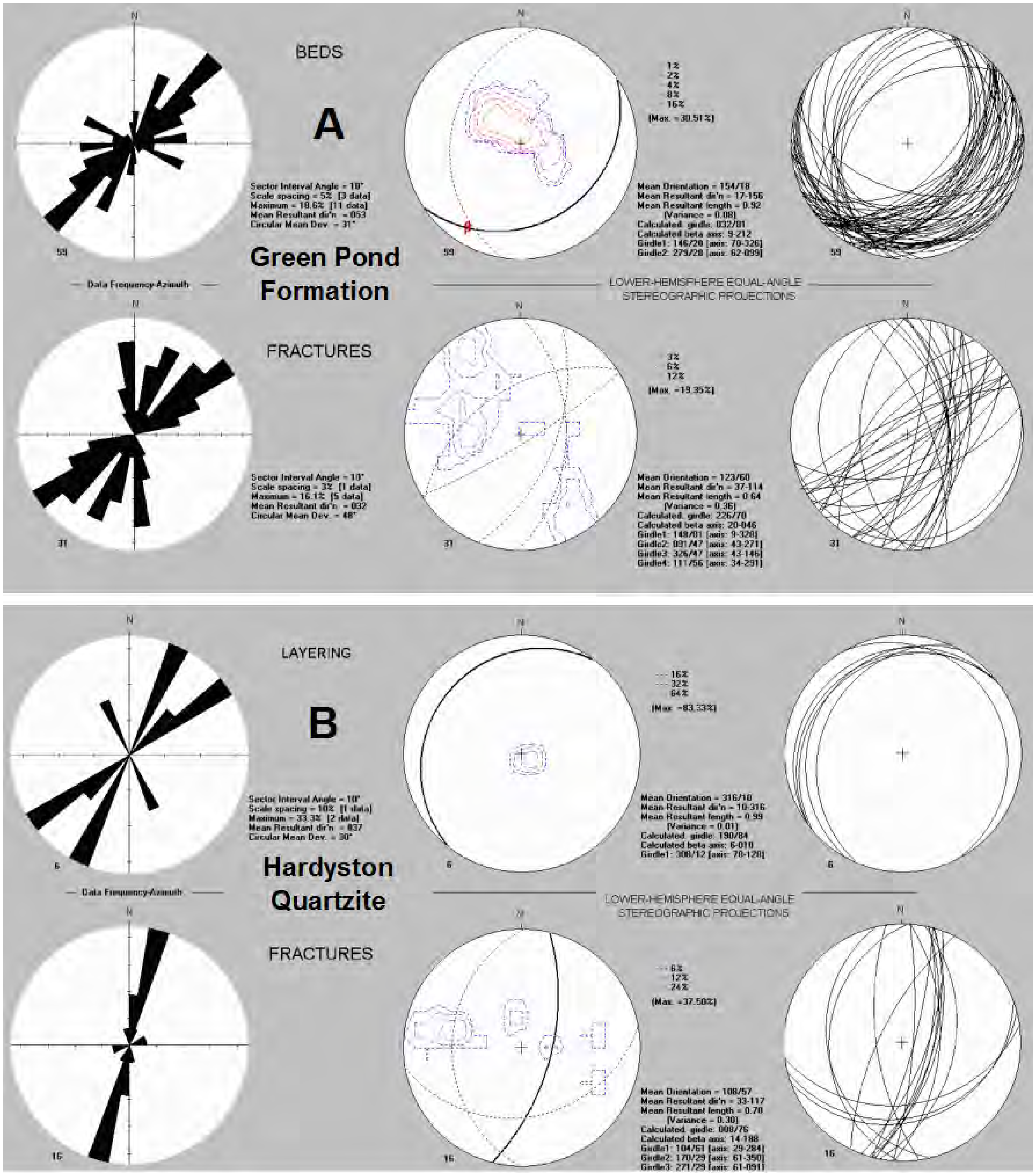


Figure 15. Structural analyses of interpreted BTV record of the AWDF well showing the orientation of beds and fractures bracketing the unconformity. A. Structures in the Green Pond Formation. B. Structures in the Hardyston Quartzite.

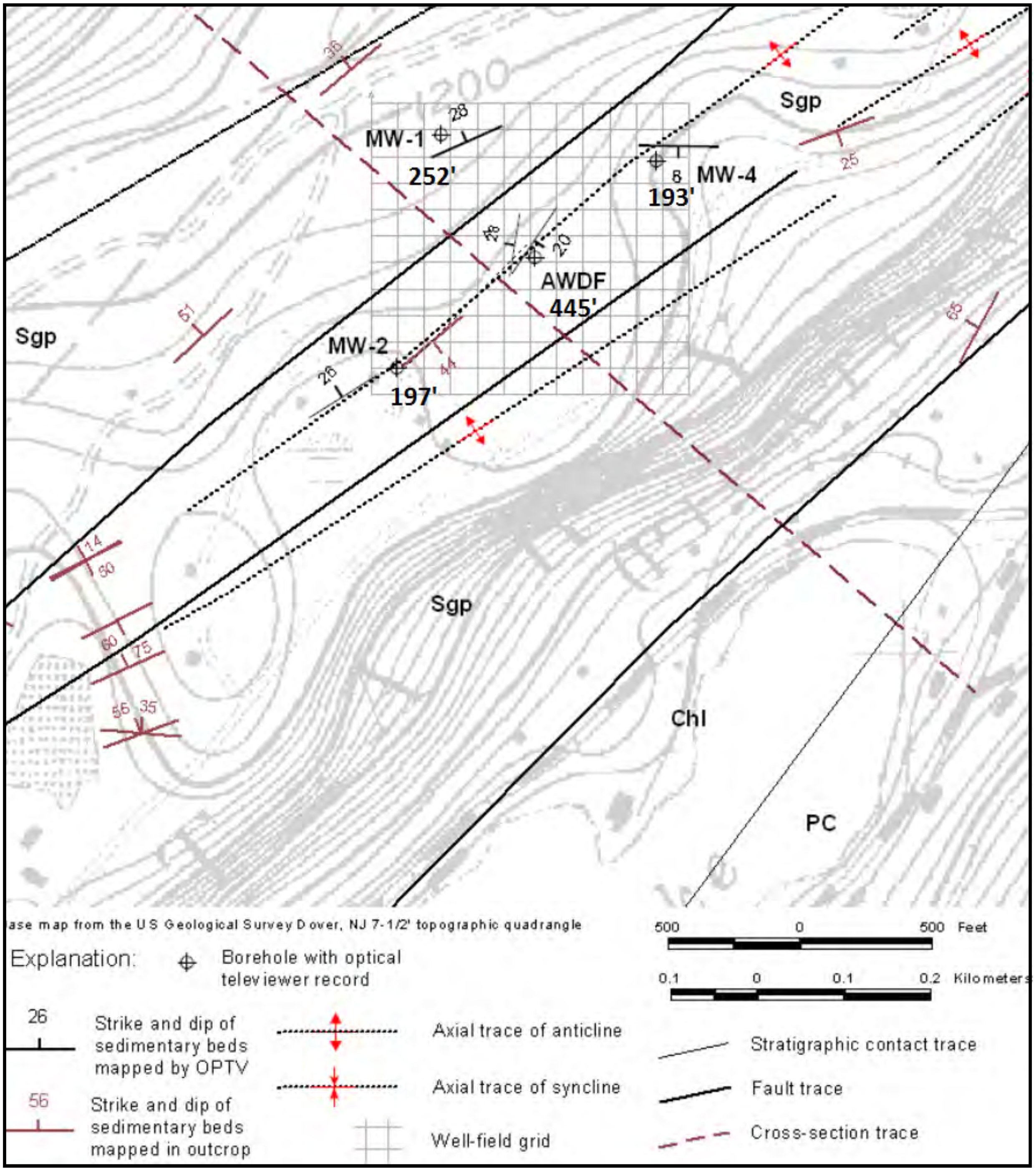


Figure 16. Geologic map near the 600 Area GWI showing a well-field grid. The AWDF well penetrates two limbs of an open, upright anticline in the Silurian Green Pond Formation before encountering the Taconic unconformity and Cambrian Hardyston Quartzite at 419 ft (128 m).

visualize 3D shapes of the boreholes, oriented structural planes, and well-field grid based on the BTV survey (N.J. Geological Survey, 2001). The borehole shapes used well-location and construction parameters taken from the consultant's report. The well and plane shapes were generated using a vertical borehole alignment because no borehole-deviation information was included in the reports.

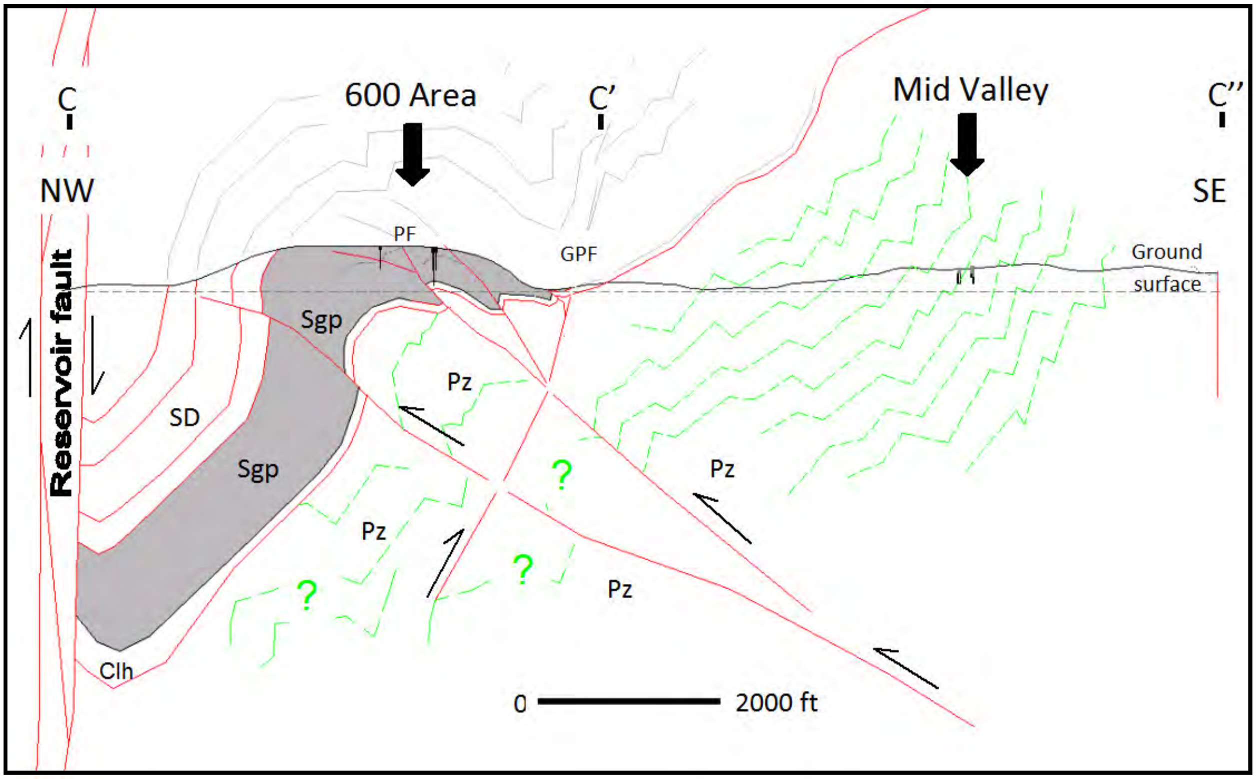


Figure 17. Cross section C-C-C" is based on earlier sections of Herman and Mitchell (1991) and the BTV analyses at the 600 Area and Mid-Valley sites (Figures 12 and 13). The section traces are shown on Figure 12. Abbreviations: Clh – Cambrian Leithsville and/or Hardyston Quartzite, Pz –Proterozoic gneiss and granite, Sgp – Silurian Green Pond Formation, SD – Undivided Silurian and Devonian rocks. GPF – Green Pond fault, PF – Picatinny fault.

Figure 18 shows that the upper beds of the Green Pond Formation in well AWDF dip gently to moderately southeast, whereas the deepest Green Pond beds dip gently (< 30°) northwest , and a little more steeply than those of the underlying Hardyston Quartzite (~10° northwest; Figure 15B). Beds close to the unconformity strike about the same. The histogram plot of dip azimuth for the lower set of Green Pond is interpreted here to reflect cross bedding (Figure 18C) that shows western and southern sedimentary dispersion.

A fault zone seen in the BTV record of MW-1 occurs at a depth of about 235 ft (72 m) (Figure 18A). The zone is a gently-dipping mineralized interval consisting of about 6 in (15 cm) of anastomosing light and dark vein-fill material. This horizon is interpreted as a reverse fault that is a subsidiary splay fault to the Picatinny reverse fault (Figure 17), and that separates beds of varying strike and dip. Upper beds in the Green Pond Formation in MW-1 dip gently northwest, and then become steep northwest deeper in the well and closer to the fault. Beneath the fault, bedding returns to dipping gently northwest.

The resulting well-field features were displayed relative to a DEM and a digital version of the cross section to examine the spatial relationships of the measured features from different viewpoints. Figure 19 shows the bedrock structures based on the BTV data relative to a DEM covering the 600 Area (Figure 10A) and a 3D display of the cross section C-C'-C".

DISCUSSION

A stylized, cross section across the Reading Prong in NJ (Figure 20) was constructed to help summarize and integrate different aspects of we know about the Taconic unconformity in the GPS region, and to facilitate discussion on some of the more speculative aspects with respect to its stratigraphic variability and probable connection with the Shawangunk Formation across the Great Valley (Figures 1 and 19). The section is pinned in the foreland by the Late Ordovician Beemerville intrusive complex (Ghatge et al., 1992) and uses the restored and balanced Lower Paleozoic cover sequence depicted in section A-A' of Herman et al. (1997). Their A-A' is extended southeast toward the Taconic hinterland roots to depict a "restored" Taconic foreland cover-fold sequence that arches over the current crystalline roots of the Reading Prong. The cover is folded above crystalline basement, with northwest verging folds

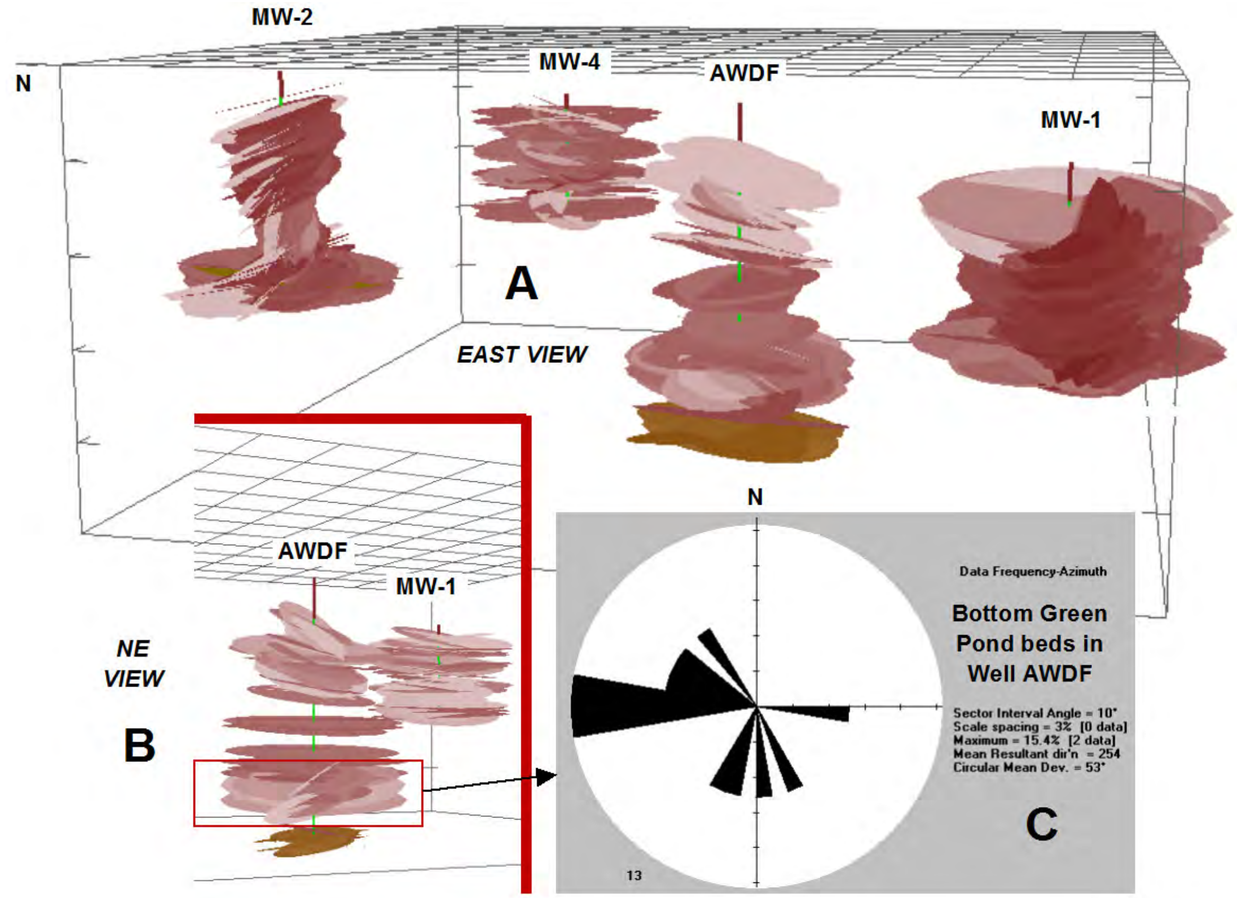


Figure 18. 3D graphic displays of the 600 Area well field and a circular histogram analysis of bed dip azimuth in the lower part of the Green Pond Formation in well AWDF. Image A is an east view showing a 3D well-field grid with 50-ft (15-m) divisions, ellipses oriented parallel to measured beds (pink polygons), and well parts including cased (upper, dark red) and open (lower, light green) well parts. Bed ellipses were generated at BTV record depths using 300 ft (91 m) major axes and 150 ft (46 m) minor axes. The pink planes are Green Pond Formation whereas the deepest beds in well AWDF (brass colored) are Hardyston Quartzite. Image B is a northeast view of wells AWDF and MW-1 showing the variability in bedding dip in well AWDF, and cross beds in the lowest part of the Green Pond Formation. Image C is a circular histogram analysis of bed dip azimuth of bottom beds in the Green pond formation from the AWDF well interval 331 to 373 ft (114 m) below land surface. The histogram and 3D display shows that the bottom beds are cross-stratified with S and W sedimentary dispersion.

that are progressively tighter with more gentle axial surfaces to the southeast, but lacking significant, emergent thrust faults that would have otherwise stack and repeat stratigraphic sections. In other words, it's one of the simplest geometric solutions that agrees with what we see at the surface, and that provides a minimal finite strain estimate based on having an eroded, folded cover sequence. As portrayed, the GPS syncline was shortened by over 50% from ensuing Alleghanian compression (Figure 20). One measurement of the penetrative, finite-shortening strain in the Devonian Bellvale Formation in the Green Pond Mountain region just from regional cleavage development is 44% (Herman, 1987).

The location of the current GPS is placed into a restored position as a Taconic synclinorium (Figure 20). The restored GPS contains broad, open, asymmetric, northwest-verging folds with localized, post-Taconic erosion of a basement-cored anticline. The anticline is a subsidiary fold in the greater synformal structure that was breeched by early erosion to expose the Proterozoic core during Taconic uplift and before Silurian deposition. Basal Silurian molasse now overlies crystalline rocks in the central area of the GPS near Green Pond, NJ, but Lower Paleozoic rocks elsewhere in all directions along strike and toward the foreland. Both Silurian and Middle Devonian molasse now occupies valleys in the GPS between crystalline blocks of the Reading Prong (Figures 3 and 4). This implies that the GPS was a structural depression then, and remains depressed today. This geometry also suggests that regional culmination during the Taconic was near the Green Pond Mountain region, where the maximum amount of erosion occurred within a great structural depression. This led Finks (1968) to conclude that there were “Taconic Islands” in this area stemming from Ordovician orogenesis.

Thomson (1957) conducted a comprehensive, petrologic and petrographic comparative study of the Shawangunk and Green Pond Formations in the NJ region. He found many sedimentary and stratigraphic relationships that bear on the depositional setting, continuity, and contemporaneity of the Silurian molasse in this region. He concluded that the two formations were probably continuous at one time from analyses of lithologies, cross-beds, and heavy-mineral fractions. Both formations contain an abundance of white quartz pebbles of probable igneous, metamorphic, and vein origin. Both formations show west to northwest cross bedding and contain white and pink zircons indicating two distinct sedimentary-source areas east of the current Great Valley and GPS. One nearby source includes the Lower Paleozoic cover and Precambrian gneiss of the Reading Prong as the source of pink zircons. The second, easternmost terrain includes argillaceous rocks of the allocthons and a “Taconia” root where other sedimentary, metasedimentary, and acidic granitic and/or metaigneous rocks provided euhedral, white zircons that reportedly are rare in the Reading Prong. He also noted that the basal Shawangunk contains considerable feldspar and the clear, euhedral zircon not found in basal sections of the Green Pond, even though is lies furthest northwest from the easternmost source. The basal Green Pond contains more jasper, chert, and flint, although Kummel and Weller (1902) noted significant plagioclase clasts in conglomerate on the east side of the GPS, and Jafee and Jafee (1973) reported coarse orthoclase pebbles at Lazy Hill, NY. The common occurrence of varicolored chert in Green Pond conglomerate led Emery (1952) to include Ordovician flysch as source rocks. Thomson (1957) also found that zircons are more rounded in the Green Pond in comparison to more elongate ones in the Shawangunk. He noted that the euhedral, white zircons first occur about 500 ft (152 m) above the base of the Green Pond Formation. He therefore proposed that the lower 500 ft (152 m) of basal Shawangunk is older than basal Green Pond because erosion began earlier, progressed more rapidly, and continued

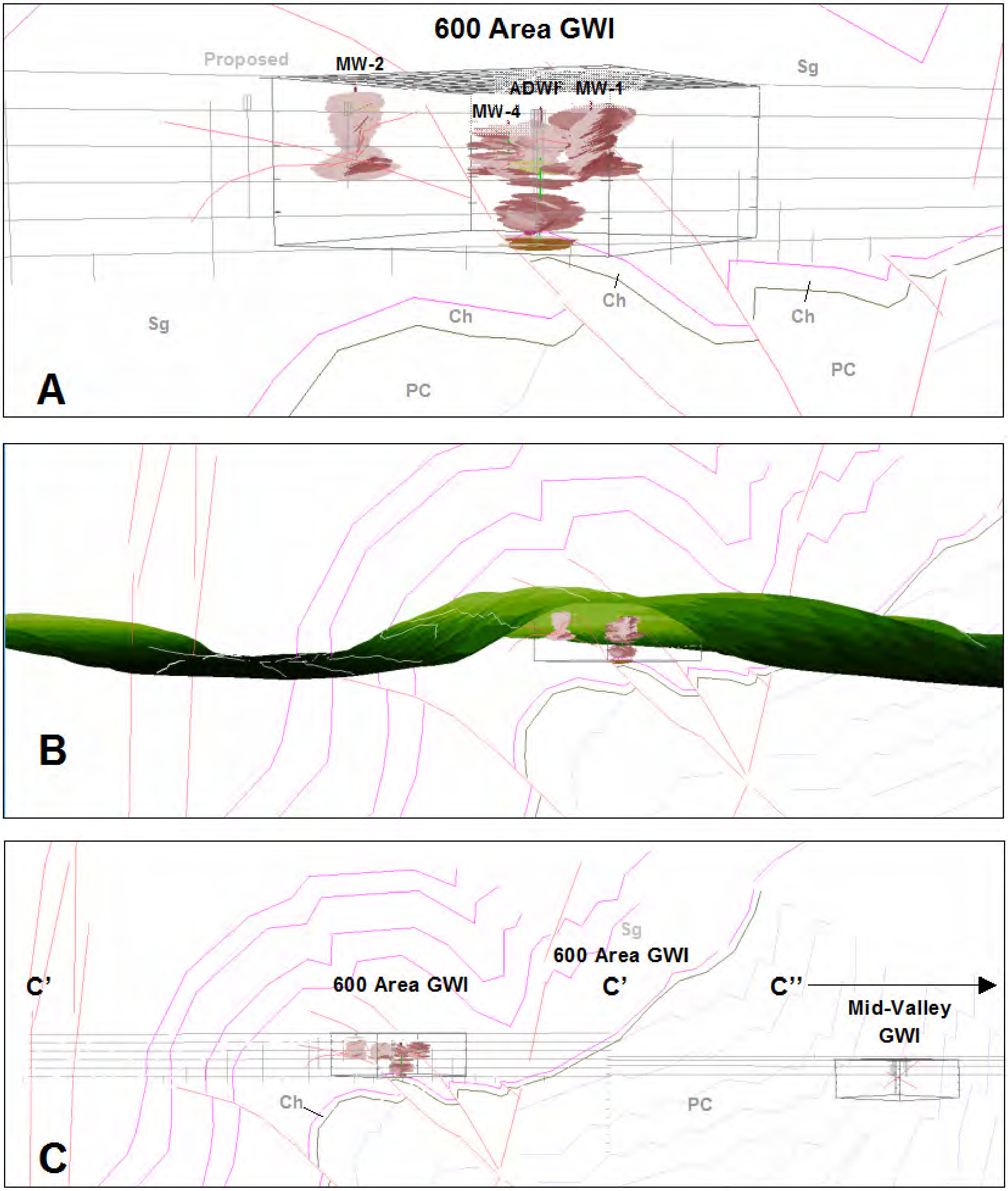
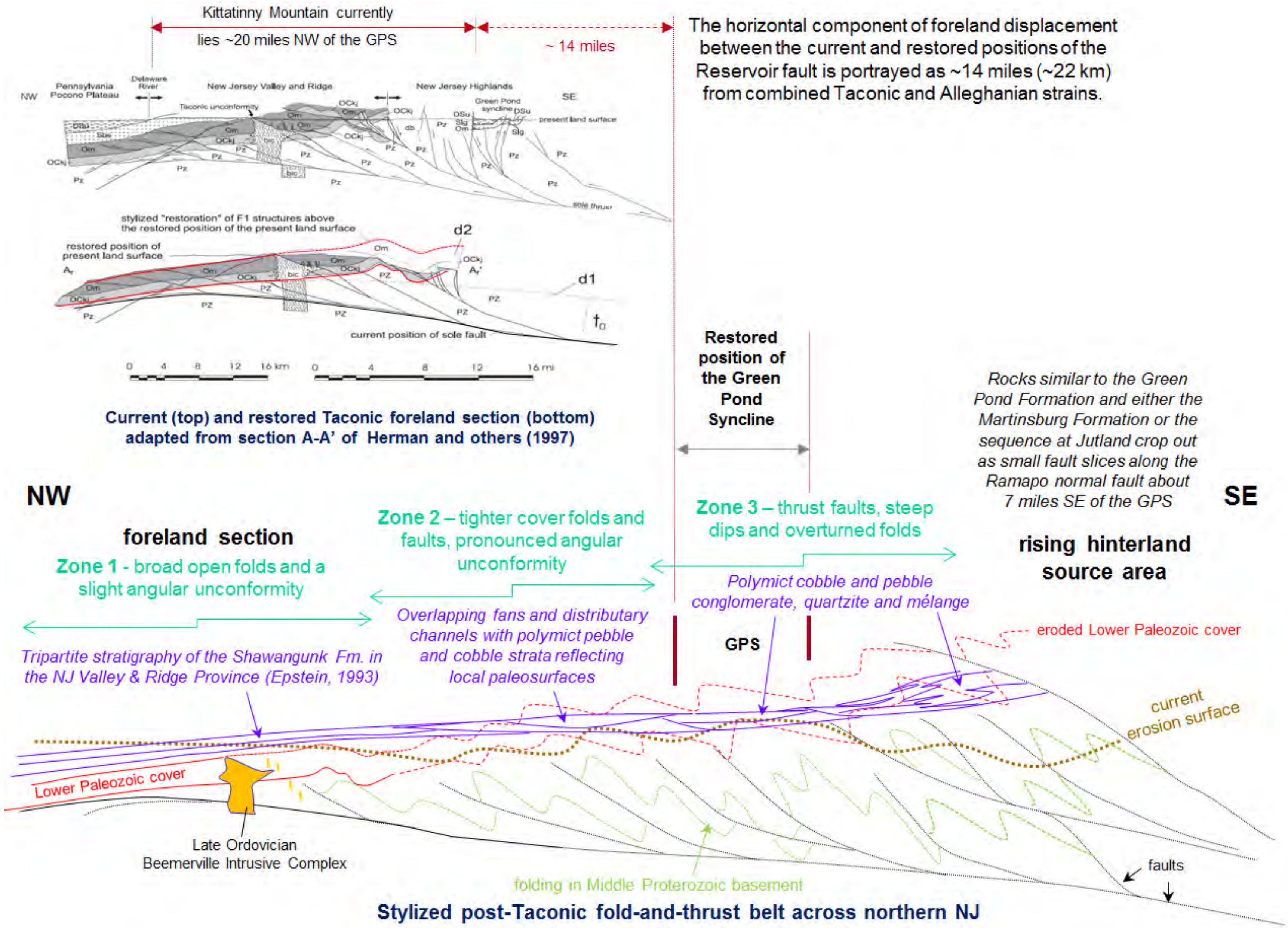


Figure 19. 3D graphic displays looking northeast of geologic and topographic details near 600 Area well field. Image A is shows the well field relative to cross section C-C', a grid with 50-ft (15-m) cells, and oriented bedding ellipses (pink polygons) that were generated at BTV record depths using 300 ft (91 m) major axes and 150 ft (46 m) minor axes. The deepest planes in well AWDF correspond to the Hardyston Quartzite (Ch in the section). Image B is shows the well field relative to ground surface represented by a digital elevation model (N.J. Geological Survey, 1999). Image C is shows the 600 and Mid-Valley groundwater investigation areas relative to cross-section C-C'-C". Profile locations mapped on Figure 13.

later in the Green Pond region than further northwest, where Early Silurian deposition began under "an eastward transgressing sea". But an alternate explanation for the apparent delay of the white zircons in the Green Pond hinges on the accumulation of early, thick, locally sourced materials without the need to invoke west-to-east stratigraphic deposition of the regional Silurian molasse. That is, initial alluvial facies of the Silurian molasse were probably deposited in localized structural depressions first, and then were overlapped by a thick, mature, alluvial cover that grew into the foreland as the hinterland source area culminated over time. In this manner, the basal Green Pond is older, and the Shawangunk becomes coeval with higher sections of the Green Pond.

A more recent description of a Taconic source area includes rift facies, pre-margin material and slope-and-rise rocks of Laurentia (Herman and Mitchell, 1991). The lower, conglomeratic part of Green Pond Formation is probably consolidated piedmont alluvium derived from nearby, deeply-weathered source area rising to the east, but its age is unknown owing to the lack of fossil or radiometric-age data. According to Thomson (1957), the Green Pond conglomerate is composed principally of white quartz and chert pebbles in a matrix of quartz sand and silt containing considerable amounts of hematitic clay, resulting in the deep purplish-red coloration. Sandstones in the lower sections of the formation grade laterally and vertically into conglomerates. The red shale intercalated with red, coarse alluvium strongly suggests a terrestrial origin; initially red sand grains washed by waves on beaches, and by streams on alluvial plains tend to lose their red color (Raymond, 1942). Having brown to light-brown orthoquartzite-conglomerate with only white vein-quartz pebbles on the west side of the syncline, and a red polymictic quartzite-conglomerate on the east limb points to the probability that the east-side, basal conglomerates were deposited within thick alluvial channels near an upland source area with subaerial exposure, deep weathering and soil development. At the same time, marginal-marine sedimentation may have occurred simultaneously along the west margin of the restored GPS where the red-purple rocks first give way to the typical brown, buff, and white colors of the Shawangunk Formation. And so it seems that alluvial and shallow marine deposits of Early to Middle Silurian age in the GPS resulted from the differential erosion of Middle and Upper Proterozoic and Lower Paleozoic rocks that supplied the sedimentary load for distributary channels draining localized uplands. Eventually, a thick blanketing molasse accumulated on the northwest regional slope in a complex transitional marine-continental environment (Epstein and Epstein, 1972) with oscillating marine shorelines in equatorial climates. Finks (1968) argued that the middle-to-upper parts of the Green Pond Formation and the lower parts of the Longwood Shale represent piedmont alluvium and marine sand deposited from a westward-transgressing shoreline.

It seems more plausible that the Green Pond was deposited first closer to a hinterland source, then was later blanketed by more regional, alluvial, and marginal-marine deposits. The Shawangunk Formation is reported as Early to Late Silurian (Epstein, 1993), and possibly Late Ordovician (Epstein and Epstein, 1972), whereas the current published age of the Green Pond Formation is Early to Middle Silurian (Drake et al., 1996, but they query the "Early" designation). The well rounded nature of the zircons toward the source area higher in the section is explained by repeated abrasion in a transitional marine, beach environment near the GPS, and reflects the tendency for Green Pond quartzite to be comparatively more mature than Shawangunk quartzite. It's more likely that erosion and deposition began in the east near the GPS where basal, immature, and thick Silurian alluvium filled local, elongate, structural troughs



Current (top) and restored Taconic foreland section (bottom) adapted from section A-A' of Herman and others (1997)

The horizontal component of foreland displacement between the current and restored positions of the Reservoir fault is portrayed as ~14 miles (~22 km) from combined Taconic and Alleghanian strains.

Stylized post-Taconic fold-and-thrust belt across northern NJ

Figure

before being covered and buried by more mature quartzite and sandstone in a subsiding basin that extended well past the Great Valley to the west.

The stylized nature of the Green Pond Formation in Figure 20 uses a tripartite stratigraphy for the Shawangunk Formation based on the work of Drake and Epstein (1967), Epstein and Epstein (1972), and Epstein and Lyttle (1982). Moving eastward over the Reading Prong, the molasse is shown as having overlapping and interfingered sedimentary lenses of restricted down-slope range meant to portray the infilling of restricted structural troughs and depressions that are aligned with regional strike, and lie about normal to the line of section. Moving farther southeast, the molasse is characterized as overlapping alluvial fans and mélange near the footwall of major Taconic over thrust raising a hinterland source area. However this thrust is probably not Thomson's (1957) "Taconia" root lying further southeast and hinterland of the Huntingdon Valley-Cream Valley fault in eastern PA and Cameron’s line in NY (Figure 20).

Figure 20 also depicts a normal fault having Lower Paleozoic strata dropped down along the ancestral Reservoir fault. This interpretation is consistent with having repeat episodes of slip along older, deeply rooted faults within the Proterozoic blocks, some of which may have been active during Late Proterozoic and Early Mesozoic rifting (Ratcliffe, 1980; Hull et al., 1986). For example, the Reservoir fault has a long, complicated history of slip activity (Hull et al., 1986; Herman and Mitchell, 1991; Malizzi and Gates, 1989; Gates and Costa, 1998). Early normal slip on this fault may help explain the spotty occurrence of Martinsburg Formation on the western limb of the syncline in the Green Pond Mountain region, that must have at one time tied into the Martinsburg Formation in the southern part of the Hudson Valley (Figures 7 and 8). Therefore, in the center of the GPS, it appears that that Martinsburg flysch may have been deposited atop Middle Proterozoic basement because of the lack of other, nearby Lower Paleozoic rock (Herman and Mitchell, 1991; Figure5), although A. A. Drake, Jr., upon review of Herman and Mitchell’s (1991) map, pointed out that this would be a unique occurrence in the Appalachians. It is more probable that the current cross sections underrepresent the presence and thickness of the Paleozoic cover beneath Martinsburg shale in the western, faulted limb of the syncline in NJ, but there is simply no way to know solely based on surface mapping. Where the Martinsburg is first mapped bordering the northeast end of GPS on its northwest side, there are Lower Paleozoic carbonates mapped between the Martinsburg Formation and Middle Proterozoic basement (Offield, 1967; Jafee and Jafee, 1973). But pre-Taconic, arching and open folding of the Lower Paleozoic sequence is well established in the region (Offield, 1967; Epstein and Lyttle, 1987; Herman and Monteverde, 1989; Herman et al., 1997), where early folds in the carbonate platform resulted in restricted, local stratigraphic variations of Middle Ordovician limestone and Upper Ordovician flysch (Monteverde and Herman, 1989).

More work is needed to resolve some issues arising from this work. A more comprehensive assessment of regional subsurface records, like the BTV record shown here (Figure 14), would be very useful for helping in characterizing the lateral stratigraphic heterogeneity and thickness of the Silurian molasse, and the angular discordance about the Taconic unconformity. The AWDF BTV record shows that basal parts of the Green Pond Formation can be locally fine grained near areas where it is also the thickest and coarsest. This area may have been subject to a brief period of post-Taconic relaxation with basement block faulting and local horst and graben structures involving Lower Paleozoic cover rocks, similar to Silurian Connecticut Valley–Gaspé Trough to the northeast (Rankin et al., 1997). In this case, the coarse grained clastics may have originated near fault scarps while more distal, finer alluvium filled more distal parts of local basins.

The Green Pond Formation may be the thickest near Green Pond Mountain NJ (~1,399 ft [426 m]), where the level of Taconic erosion within the GPS was the greatest (Figure 20). The unit thins to the northeast, down to as little as 25 ft (8 m) near Pea Hill, NY,= (Darton, 1894; Ries, 1895), before apparently pinching out. The thickness in the southwest part of the GPS is difficult to tell because of the friable nature of the unit and thick cover, but it may mimic the outcrop expression of the Shawangunk Formation, which generally increases in thickness from the northeast to the southwest across the NY recess (Figure 21). Darton (1894b) reports about 3 ft (0.9 m) of Shawangunk grit at the northeast end of the outcrop belt near the fourth Lake at Binnewater, NY (Figure 21). Darton (1894 a, b) also notes about 290 ft (88 m) at Ellenville, NY, and up to 2,000 ft (610 m) in NJ. Epstein and Epstein (1972) report about 1,800 ft (549 m) near Delaware Water Gap, and it may reach a maximum thickness near Pine Ridge, PA (Figure 21), where the map unit changes from the Shawangunk Formation to the Clinton Formation continuing into the Pennsylvania Salient along strike (Swartz and Swartz, 1930; Epstein and Epstein, 1967). However there are structural complications in the sections from Delaware Water Gap and further southwest that makes an accurate accounting of the unit thickness difficult and imprecise.

The angular unconformity within GPS has only been directly observed in one place, in the subsurface where Green Pond overlies the unit interpreted as Hardyston Quartzite (Figure 14). Both units strike subparallel (northeast-southwest) but at slightly different dip angles (~10° below the unconformity compared to ~30° above). In areas of NJ where the Green Pond overlies Lower Paleozoic rocks, the contact has not been directly observed with certainty, but nearby dip angles vary, from negligible to as much as 18° (see Gould's quarry note above). Where Green Pond Formation overlies Precambrian basement, gneissic layering immediately southeast of the GPS dips steeply southeast in northwest-verging, overturned folds only near the central and northeastern parts of the NJ Green Pond Mountain; further along strike in both directions, basement fold limbs become upright, with layering dipping northwest beneath the northwest-dipping limb of the Paleozoic syncline (Figure 17; and Jafee and Jafee, 1973). It's probably that a main phase of basement folding occurred in the Reading Prong from Taconic orogenesis, and the GPS reflects area-wide, semi-ductile infolding of this age. More work is needed in comparing the geometry of basement folding with that found in the Lower Paleozoic sequence in order to test this hypothesis.

Another aspect arising from this work is the need for more detailed geological maps of Orange County, NY. Only the 1:250,000 scale geological maps for New York are available in digital form, and there are some errors in this coverage in the form of mislabeled (miscoded) polygons for at least the Lower Hudson bedrock coverage. These errors were only detected and corrected in the personal themes needed for generating this report, but they persist in the source themes. Notice of these errors is being sent to the source agency, but users of these data should beware. Also, there are mismatched map units and misaligned unit contacts along the NY-NJ state border that need better definition, as well as those occurring along the quadrangle boundaries at the 1:24,000 scale (for example, see Figure 7). More detailed mapping is also needed in both NJ and NY in and around the GPS for assessing the nature of the late-stage cross faults that cut and offset the Lower Paleozoic rocks. The age and movement on these faults is intriguing and could include Late Paleozoic through Cenozoic movements. The strike of these faults in NY is similar to some cross-faults mapped in the NJ Highlands that may also cut and offset the GPS there, but they are currently mapped as not doing so (see the Mount Hope fault in Figure 4).

In conclusion, the bulk evidence points to the probability that a prominent, Taconic-age structural culmination occurred immediately hinterland of what is now the New York recess, with Taconic root structures now buried beneath Mesozoic cover of the Newark basin and Cenozoic coastal plain sediment laid down on the ensuing passive margin (Figure 1 and 20). It is also likely that these Taconic roots include both 'external' and "internal" basement massifs (Drake et al., 1989), the former including rocks of the Reading Prong and miogeoclinal cover,

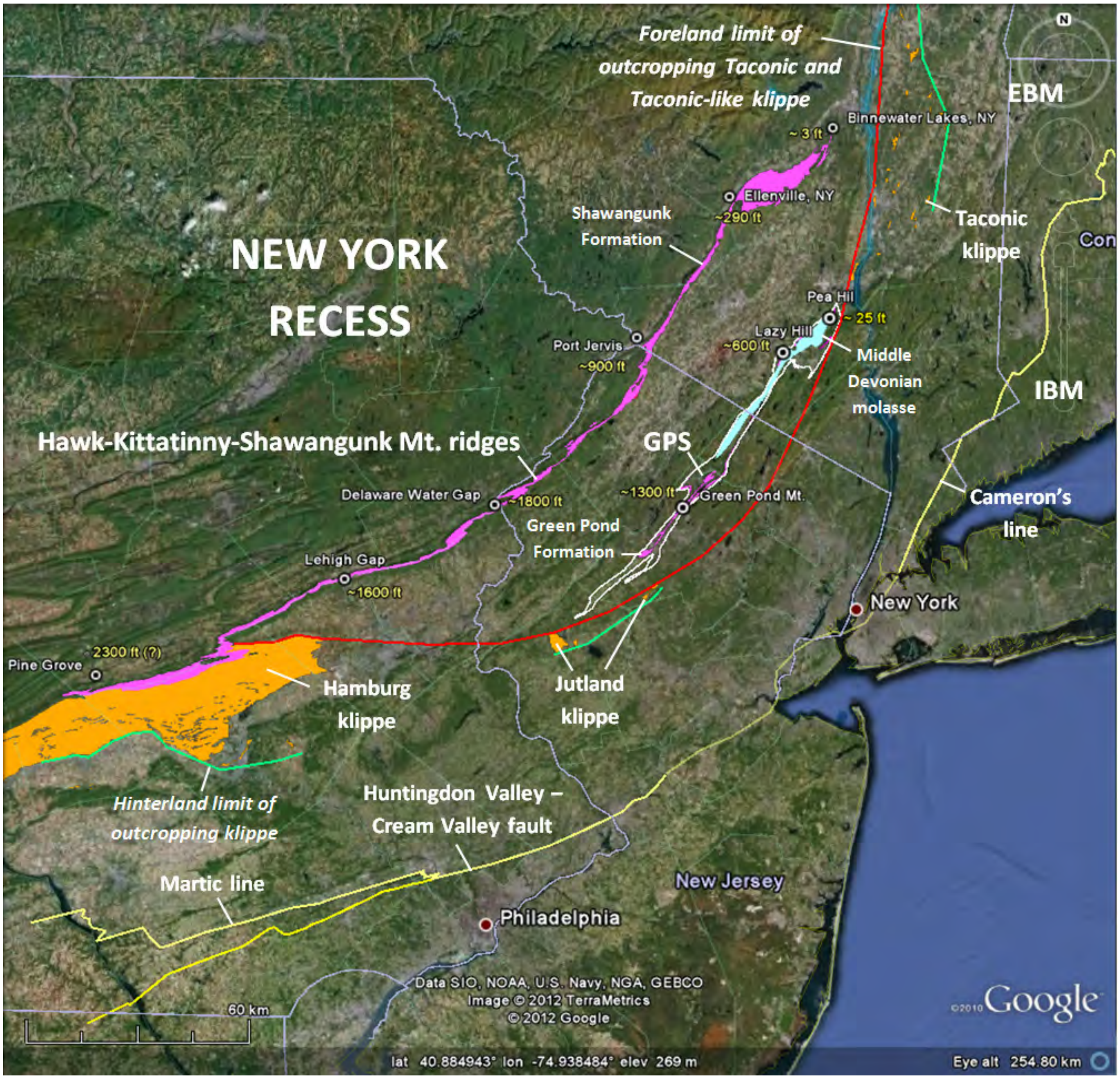


Figure 21. Aspects of the Taconic orogeny around the New York recess summarized using Google Earth. Geological shapes adapted from the US Geological Survey Online Spatial Data; Geological maps of US States (http://mrdata.usgs.gov/geology/state/). Klippe and other terminology after Drake et al. (1989). EBM – Terrain including "external basement massifs" and the foreland basin on the Laurentian margin. IBM – Terrain including "internal basement massifs" and their migeoclinal cover poking through thrust sheets containing eugeosynclinal rocks. The best estimate for the thickness of the Silurian molasse is compiled at a number of places for the Green Pond Formation in the GPS, and for the Shawangunk Formation in the Hawk-Kittatinny-Shawangunk Mountain ridges. See the discussion section for further explanation.

and the latter including abundant mafic rocks, granite, and highly strained eugeosynclinal rocks with “gneiss domes” containing Proterozoic basement like those mapped in New England and the PA Piedmont. These “internides” (Hatcher, 1987) may be the source of Thomson’s (1957) euhedral, white zircons in the heavy mineral fraction of the Silurian molasse. It’s probably more than just coincidence that the Watchung syncline (Figure 1), which contains the thickest accumulation of Early Mesozoic strata in the Newark basin, lies directly southeast of the area of maximum erosion of Paleozoic cover in the GPS. This spatial relationship suggests that the location of maximum structural relief on the New York recess stemming from Paleozoic orogenesis is coaxial with the location of maximum relaxation and normal slip on ensuing Mesozoic faults, including, but not limited to, the Ramapo fault.

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THE BEEMERVILLE ALKALINE COMPLEX, NORTHERN NEW JERSEY

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Introduction

The Beemerville complex is located at the western end (Figure 1) of the Cortlandt-Beemerville magmatic belt (Ratcliffe, 1981). The belt cross-cuts the structural grain of the Appalachians. There is a trend from calc-alkalic and alkalic rocks at the eastern end of the belt to strongly alkalic rocks at the western end. Mafic and intermediate dikes that intrude the magmatic belt show a similar trend in rock composition. Ratcliffe (1968, 1981) concluded that, relative to Taconic dynamo-thermal metamorphism, the Cortlandt complex was emplaced syntectonically while the Beemerville complex was post tectonic. Thin section examination shows no evidence of a metamorphic or tectonic fabric supporting the conclusion that the Beemerville complex is post tectonic.

In this paper I will focus on the geology, mineralogy, and petrography of the Beemerville complex. For a more complete description of the complex in terms of mineral and rock chemistry please consult Eby (2004). A pdf of Eby (2004) is available on request from the author (**nelson_eby@uml.edu**).

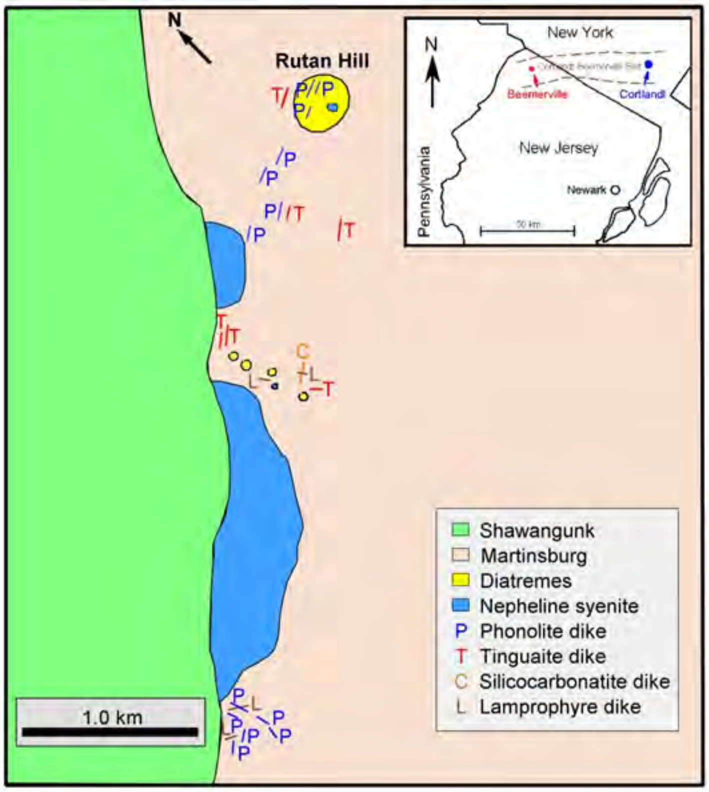

Figure 1. Location and geologic map for the Beemerville complex. Modified from Maxey (1976) and Eby (2004).

Geology of the Beemerville Complex

The following geologic description of the Beemerville complex (Figure 1) is summarized from Maxey (1976) and taken from Eby (2004). The nepheline syenite occurs in two large bodies and as several small bodies, one located in the Shawangunk conglomerate and the other associated with the diatreme of Rutan Hill. The large bodies intrude the Ordovician Martinsburg shale and to the west are overlain by the Silurian Shawangunk conglomerate. The nepheline syenite that crops out in the

Eby, G.N., 2012, The Beemerville alkaline complex, northern New Jersey, *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. 85-91.

Shawangunk is stratigraphically higher than the basal Shawangunk and may represent an intrusion of nepheline syenite from the southern large nepheline syenite body into the Shawangunk. The Martinsburg shale has been metamorphosed to a hornfels near the boundary with the nepheline syenite plutons, but actual contacts between the nepheline syenite and the shale are not observed. The nepheline syenite is medium- to coarse-grained and consists of nepheline, orthoclase, clinopyroxene, biotite, titanite, ±melanite, magnetite, apatite, and trace amounts of pyrite and zircon.

Several diatremes are found in the Martinsburg shale, and the largest comprises Rutan Hill. The diatremes consist of a variety of angular to subangular xenoliths and autoliths in a dark, dense matrix. Xenoliths noted by Maxey (1976) include shale and graywacke (Martinsburg Formation), fine-grained pale-blue dolomite (Kittatinny Formation?), cream-colored, fine-grained limestone (Jacksonburg Formation), and gneiss (similar to that observed in the Reading Prong). Autolithic inclusions are nepheline syenite, micromelteigite, and carbonatite. The matrix consists of an extremely fine-grained groundmass with fine-to coarse-grained megacrysts of biotite, diopside, aegirine-augite, orthoclase, magnetite, apatite, and nepheline. A nepheline syenite plug, approximately 30 m (98 ft) in diameter, intrudes the Rutan Hill diatreme. Fenitization of the greywacke in the Martinsburg is noted in a fracture zone associated with the small diatremes. The fenitized greywacke consists of albite, aegirine, sodic amphibole, and trace amounts of biotite and calcite.

Phonolite, tinguaite and lamprophyre dikes occur in the Beemerville area. Phonolite dikes occur in the southern nepheline syenite body, crosscut diatremes, and intrude the Martinsburg Formation. Dikes vary from a few cm to up to 50 m (164 ft) in width and both fine-grained and porphyritic varieties are noted. The phonolites associated with the Rutan Hill diatreme are extensively altered. Tinguaite dikes are found in both nepheline syenite bodies and the Martinsburg formation. The dikes vary in width from 0.25 to 50 m (10 in to 164 ft). Most are porphyritic and the common phenocrysts are nepheline, orthoclase, clinopyroxene, and titanite. The lamprophyre dikes occur throughout the complex and range in width from 10 cm to 7 m (4 in to 23 ft) and most trend northwest. Many of the dikes are extensively altered and the primary minerals are largely replaced. Where observable, the primary minerals are diopside, aegirine-augite, bioite, nepheline, orthoclase, titanite, melanite, magnetite, and apatite. Ocelli are common in some of the dikes.

Based on gravity data, plus supporting aeromagnetic data, Ghatge et al. (1992) modeled the Beemerville complex as a thin body near the surface that broadened and elongated with depth. The Beemerville body extends to the southwest and plunges at high angle to the southeast. From their data they also inferred the existence of a second, subsurface, intrusive body approximately 9 km (6 mi) southeast of the Beemerville complex.

Petrography

(from Eby, 2004)

Phonolite and Tinguaite

Mineralogically phonolite and tinguaite are the same rock. Historically the distinction was based on the presence of phenocrysts (tinguaite). The term tinguaite is now considered archaic. As used on the geologic map (Figure 1), phonolite indicates a fine-grained dike rock while

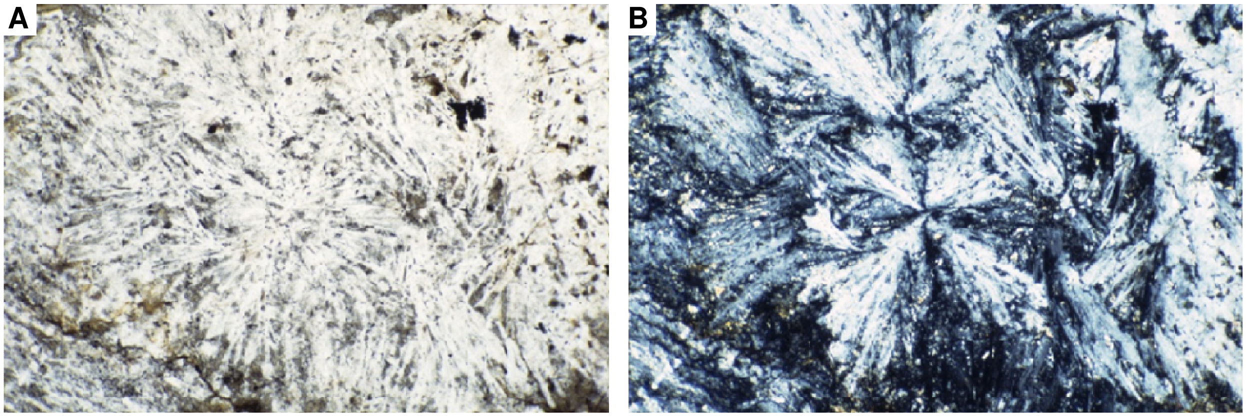

Figure 2. Phonolite dike at base of Rutan Hill (BEM16). Major minerals are nepheline and orthoclase with minor aegirine-augite. Plumose texture indicative of rapid cooling. Width of field, 2 mm. A - Plane light; B – Crossed polars.

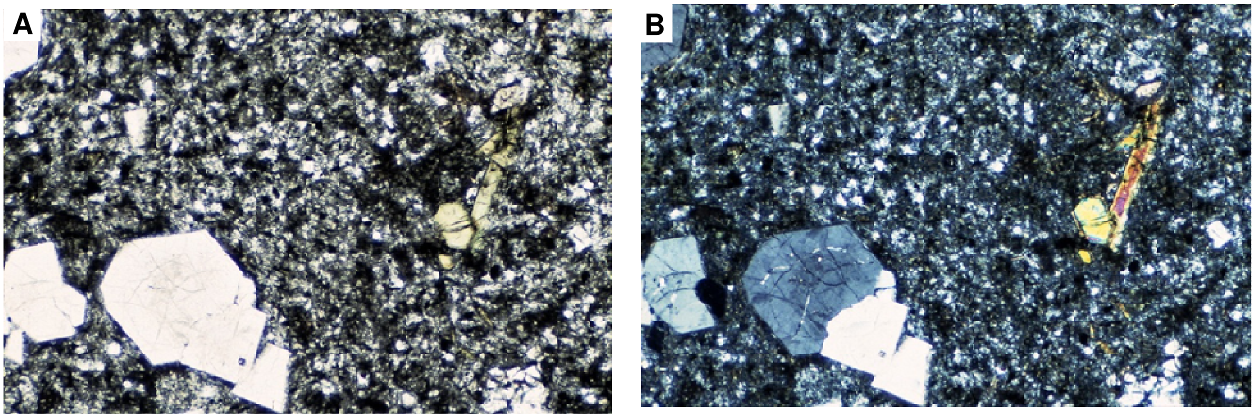

Figure 3. Phonolite (*tinguaite*) dike (BEM19). Nepheline, aegirine, and titanite phenocrysts in a fine-grained matrix of nepheline, orthoclase, and aegirine. Width of field, 5 mm. A - Plane light; B –Crossed polars.

tinguaite indicates the presence of phenocrysts in the dike rock. The major minerals in the phonolites are orthoclase, nepheline, and clinopyroxene. Minor minerals are biotite, titanite, and opaque minerals. A fine-grained phonolite, with a texture indicative of rapid cooling, is illustrated in Figure 2. In the porphyritic varieties, orthoclase, nepheline, clinopyroxene, and titanite are the common phenocryst phases (Figure 3).

Nepheline Syenite

The nepheline syenite is medium- to coarse-grained, equigranular to subporphyritic. Major minerals are orthoclase, nepheline, and clinopyroxene. Minor minerals are biotite, titanite, ±melanite, fluorite, cancrinite, sodalite, calcite, magnetite, and apatite. Based on probe data, the feldspars are orthoclase ($\geq Or_{80}$). Optically, the feldspars do not show unmixing textures. The pyroxenes vary in composition from diopside to aegirine. Zoned clinopyroxenes have diopside cores and aegirine-augite rims or aegirine-augite cores and aegirine rims. Biotite occurs as a minor mineral either replacing clinopyroxene or as discrete grains. Cancrinite and sodalite replace nepheline. Fluorite is a common trace mineral. Figures 4 – 7 illustrate the various types and textures of nepheline syenite.

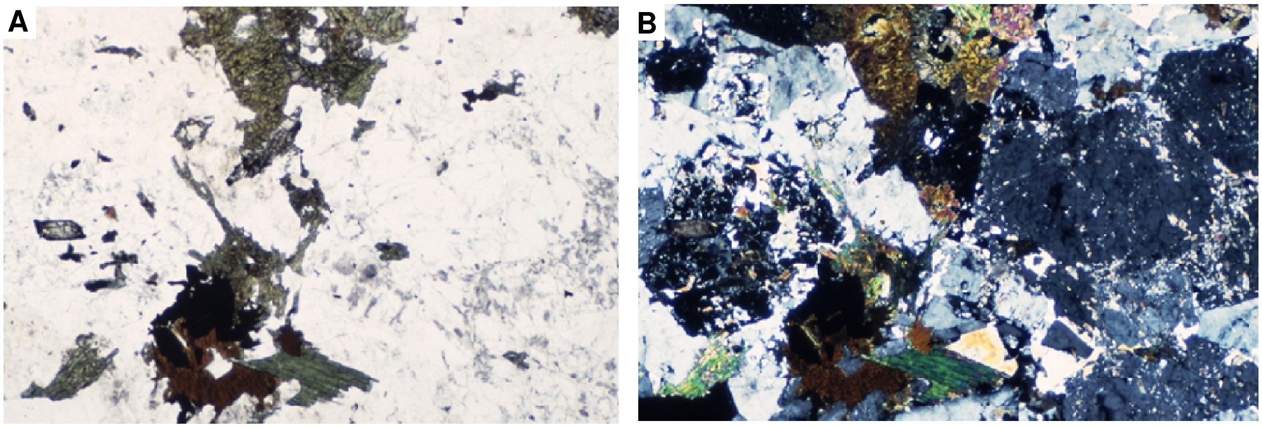

Figure 4. Coarse-grained nepheline syenite (BEM4). Nepheline, orthoclase, aegirine-augite, and minor biotite. Width of field, 5 mm. A - Plane light; B – Crossed polars. Sodalite replaces nepheline (isotropic mineral).

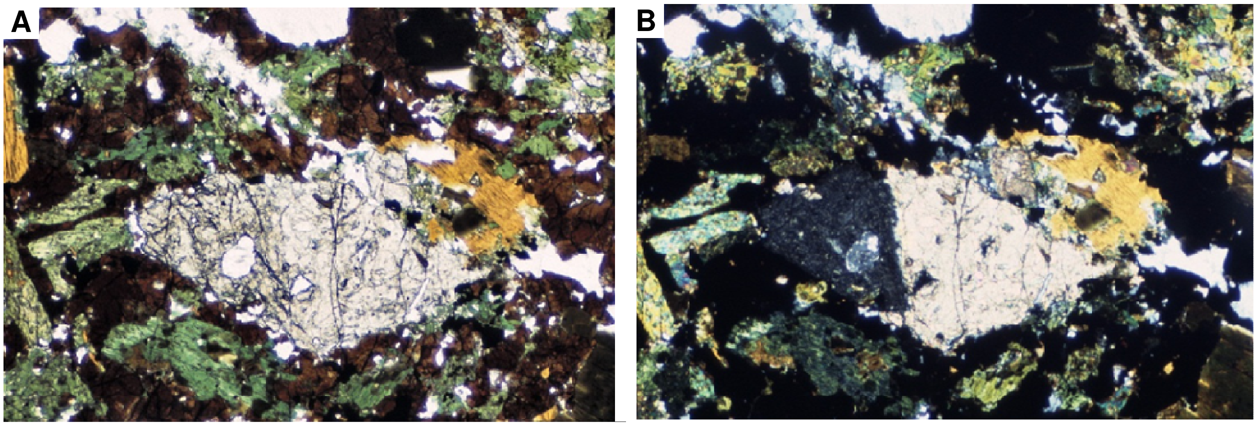

Figure 5. Nepheline syenite (BEM29). Intergrown melanite and aegirine-augite, minor biotite, feldspar, titanite. Width of field, 5 mm. A - Plane light; B – Crossed polars. The high birefringence grain in the center of the field of view is calcite.

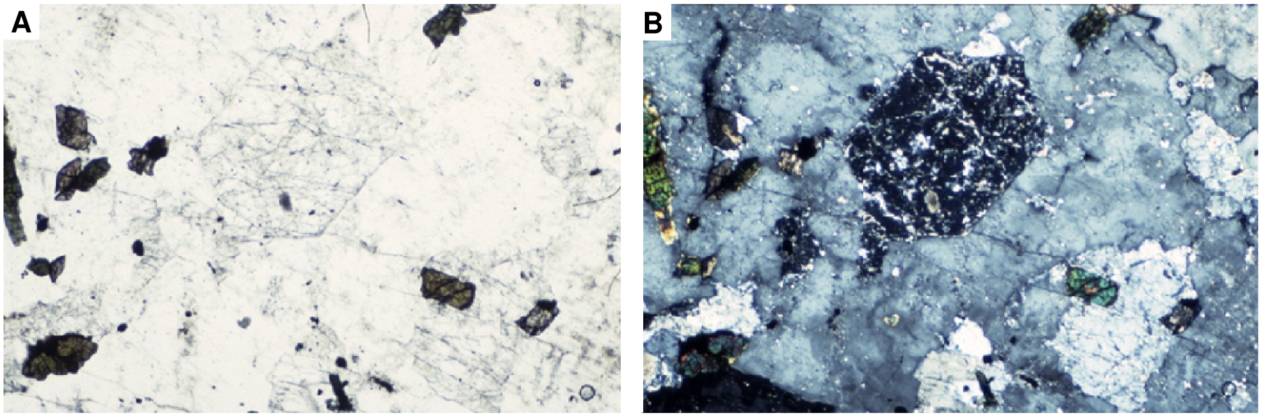

Figure 6. Nepheline syenite (BEM33). Euhedral to subhedral nepheline, aegirine-augite, and titanite in a large orthoclase. Width of field, 5 mm. A - Plane light; B - Crossed polars. Note that the mineral inclusions in the orthoclase are the same as the phenocryst minerals in the phonolite (Figure 3A and B).

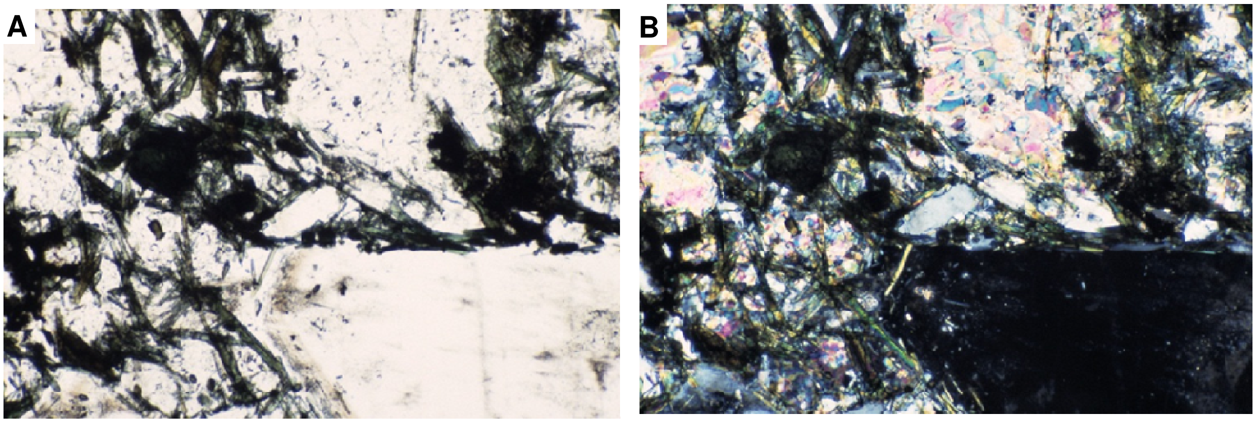

Figure 7. Border phase of northern nepheline syenite body (BEM2). Phenocrysts of nepheline and orthoclase in a fine-grained matrix of feldspar and aegirine. The nepheline has been extensively altered by cancrinite. Width of field, 2 mm. A - Plane light; B - Crossed polars. The high birefringence mineral is cancrinite.

Diatreme Breccia

The diatreme breccias are heterogeneous at all scales and show a wide range of xenoliths and autoliths. Locally calcite is an important component. An example of this carbonate breccia is shown in Figure 8.

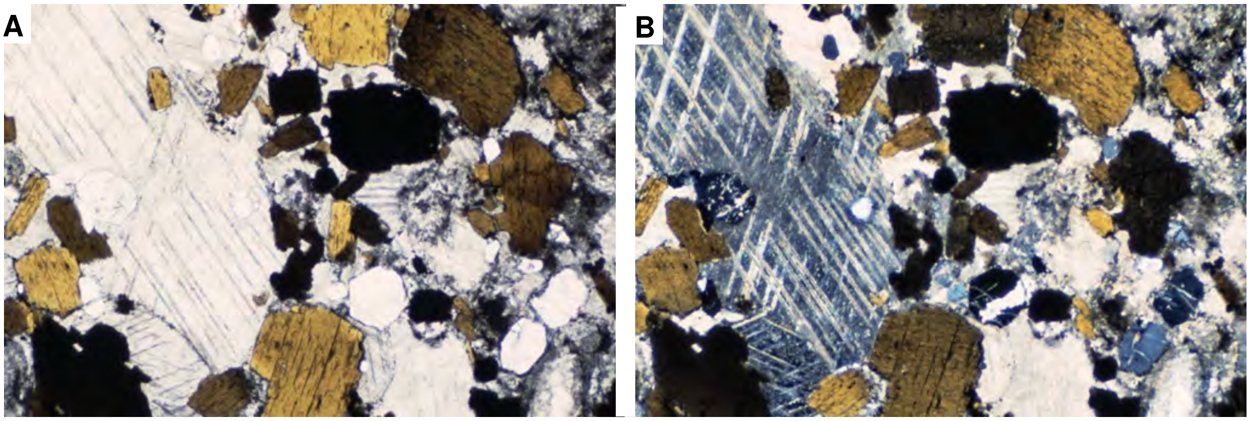

Figure 8. Carbonate breccia from Rutan Hill (BEM11). Biotite, apatite, and opaque minerals in a coarse-grained matrix of calcite. Width of field, 5 mm. A - Plane light; B - Crossed polars.

Lamprophyre Dikes

Many of the lamprophyre dikes are intensely altered obscuring the primary mineralogy. For relatively unaltered specimens the major minerals are diopside or aegirine-augite, and/or biotite phenocrysts in a fine-grained matrix of clinopyroxene, biotite, nepheline, orthoclase, titanite, magnetite, calcite, and apatite. Some of the dikes contain ocelli (Figure 9).

Discussion

The Beemerville complex is of interest because it is the only occurrence of strongly silica-undersaturated rocks of Ordovician age in the northeastern United States. Hydrous minerals

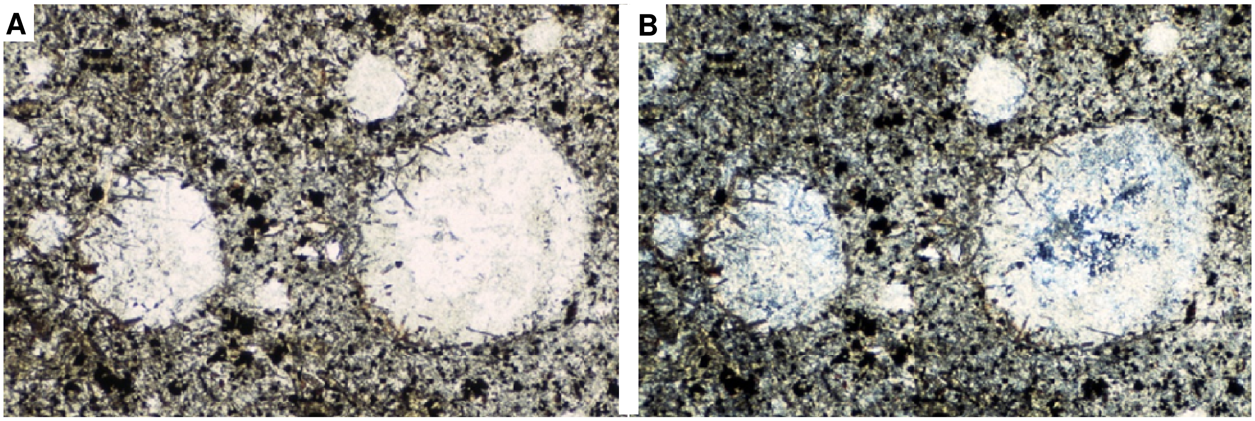

Figure 9. Ocelli in lamprophrye dike (BEM20). Width of field, 5 mm. A - Plane light; B - Crossed polars.

(with the exception of minor biotite) are absent in the nepheline syenites and fluorite occurs as a minor mineral. This suggests that the nepheline syenites crystallized from an anhydrous F-rich magma. On the basis of texture and rock chemistry, it is inferred that the various syenites are largely composed of cumulate minerals (alkali feldspar, nepheline, and clinopyroxene). The only potential solidified liquids, although their chemistry has been modified by hydrothermal alteration, are the phonolites and lamprophyre dikes. The carbonate-rich matrix of the diatreme breccia has chemical characteristics typical of carbonatites.

A number of radiometric ages have been determined for the Beemerville complex. Eby (2004) reported a mean apatite fission-track age of 156 ± 4 Ma and a mean titanite fission-track age of 420 ± 6 Ma. Zartman et al. (1967) reported a K-Ar biotite age of 443 ± 22 Ma (corrected to currently accepted decay constants) for a syenite. Ratcliffe et al. (2011) reported a titanite U-Pb TIMS age of 447 ± 2 Ma for a nepheline syenite. Apatite retains fission-tracks at temperatures less than 120°C, while for titanite fission-track retention starts at temperatures less than ~275°C. Thus the fission-track ages reflect the cooling history of the pluton. The biotite K-Ar and titanite U-Pb ages may represent the age of the intrusion, but it should be noted that the closure temperature for biotite is ~350 °C and the closure temperature for the U-Pb system in titanite is ~450 °C. The older ages can be compared to the currently accepted age of 443.7 ± 1.5 Ma (Gradstein and Ogg, 2004) for the Ordovician-Silurian boundary. Thus one can conclude from the existing geochronological data that the Beemerville complex was emplaced in the late Ordovician. By 420 Ma the intrusion had cooled to ~275 °C, but ambient temperatures of ~100 °C were not reached until 156 Ma. The 27-million-year difference in titanite fission-track and titanite U-Pb ages, coupled with phase equilibria considerations (Eby, 2004), lead to the inference that at least 3 km (1.9 mi), and as much as 6 km (3.7 mi), of rock overlay the Beemerville complex, relative to its present level of exposure, at the time of intrusion. The young apatite fission-track age is most likely related to the unroofing of the Appalachian orogenic belt.

Isotope data are lacking for the Beemerville complex, but the mineralogy and chemistry of the rocks of the complex suggest that the magma originated in the upper mantle at depths at which garnet was a stable phase. The most likely source is enriched lithospheric mantle. The presence of a carbonatitic matrix in the Rutan Hill diatreme breccia also points to a deep lithospheric origin for the magma(s). The emplacement of alkaline silica undersaturated rocks and carbonatites is invariably associated with an extensional (or at least non-compressive) tectonic environment. The Beemerville pluton was intruded during a time of medium to high-grade metamorphism and closure of the Iapetus Ocean. Thus, the intrusion of the Beemerville complex represents a variance from the overall compressive regime for this region during the Ordovician. Ratcliffe et al. (2011) have suggested that the intrusion of the rocks of the Cortlandt – Beemerville belt was controlled by "post-collisonal sublithospheric tears and mantle upwelling oblique to the suture" formed during closing of the Iapetus Ocean.

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GLACIATIONS OF WESTERN NEW JERSEY AND EASTERN PENNSYLVANIA: A VIEW ACROSS THE DELAWARE RIVER

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Preface

The 2012 Pennsylvania Field Conference from Port Clinton, PA to Ellenville, NY will take us through an area that has experienced multiple glaciations over the last two million years. Based on the distribution and degree of preservation and weathering of glacial drift, at least three glaciations have been defined for New Jersey and eastern Pennsylvania. With the exception of eastern New Jersey, each succeeding glaciation stopped short of the older one, preserving a terrestrial record that has kept geologists (at least the good kind) busy for more than a hundred years. The last two million years also included multiple cycles of periglacial weathering where large volumes of colluvium, formed by fragmental disintegration of rock, was shed from uplands, and cycles of temperate to sub-tropical interglacial weathering that was dominated by the formation of saprolite and decomposition residuum.

Starting just outside the glacial border near Port Clinton, PA, the field trip will traverse areas that were glaciated during the pre-Illinoian, Illinoian, and Late Wisconsinan glaciations (Figure 1). The Late Wisconsinan border, in many places marked by a terminal moraine, divides the field trip area into two contrasting landscapes: 1) a southern area marked by extensive colluvium, weathered bedrock and in places patchy, weathered glacial drift; and 2) a northern area marked by extensive fresh to lightly weathered glacial drift and numerous bedrock outcrops.

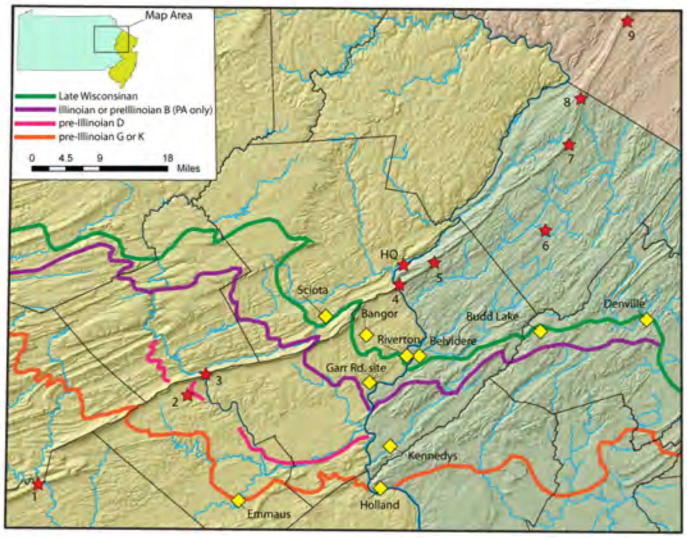

Figure 1. Map showing the extent of glaciations in eastern Pennsylvania and western New Jersey, and location of field trip stops and headquarters for the 2012 Field Conference of Pennsylvania Geologists. Glacial limits from Braun (1996a), Sevon and Braun (1997), and Stone et al. (2002). List of field stops: 1—Port Clinton; 2—Slatedale; 3—Lehigh Gap; 4—Delaware Water Gap; 5—Yards Creek Pumped Storage Facility; 6—Newton; 7—Beemerville; 8—High Point; 9—Otisville; and HQ—Shawnee-on-Delaware.

This is a summary discussion about the glacial history of western New Jersey and eastern Pennsylvania. It could not have been written without

Witte, RW. and Germanoski, Dru, 2012, Glaciations of western New Jersey and eastern Pennsylvania: A view across the Delaware River, *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. 92-117.

the contributions of so many that have labored in the woods and fields since the late 1800s. The earliest investigators, Lewis, Chamberlin, Salisbury, White, Williams and later Leverett and MacClintock wrote detailed reports that laid the foundation for modern studies. What follows is the most current understanding about glacial limits, ages of glaciations, and character of glacial drift. Besides, it's always interesting to discuss geology across state borders.

Introduction

New Jersey’s terrestrial glacial record shows that the Laurentide ice sheet reached New Jersey at least three times (Stone et al., 2002) over the last two million years. These glaciations (Figure 1), following the terminology of Richmond and Fullerton (1986), are from youngest to oldest the Late Wisconsinan (Marine Isotope Stage (MIS) 2), Late Illinoian (MIS 6), and pre-Illinoian G (MIS 22) or older and possibly more than one glaciation. Braun (2004) cited evidence of four glaciations in Pennsylvania: Late Wisconsinan, Late Illinoian or pre-Illinoian B (MIS 12), pre-Illinoian D (MIS 16), and pre-Illinoian G (MIS 22). Similar to New Jersey's oldest glacial deposits, those in Pennsylvania may represent more than one glaciation. There is some disagreement concerning the age of the older glaciations and number of pre-Illinoian glaciations, but there is a remarkable congruency between the glacial limits mapped on either side of the Delaware River. The youngest glacial deposits laid down during the Late Wisconsinan substage provide the clearest record of glaciation. The glacial record, indicated by the Illinoian and especially the pre-Illinoian deposits, is much less clear due to an extensive and complex periglacial and weathering history.

Multiple glacial cycles have greatly modified the Garden State and Penn’s Woods. Valleys were deeply scoured, and bedrock ridges, hills, and slopes were worn down by glacial erosion. In places, glacial ice and drift dammed valleys, rerouting streams and establishing new drainage ways. Most of the eroded debris entrained by the ice sheets was deposited as till and meltwater sediment. Numerous ice-marginal lakes formed in valleys dammed by moraine, ice-contact deltaic deposits and ice. These lakes and their associated deposits, and recessional moraines provide a detailed record of deglaciation. The many unweathered and lightly weathered bedrock outcrops north of the terminal moraine show that most of the pre-existing weathered bedrock and surficial material had been removed by glacial erosion. This area lies in stark contrast to that south of the Late Wisconsinan Glacial Maximum (LWGM) where outcrops are far fewer (Figure 2). The LWGM also divides the largely glacial landscape to the north and the largely colluvial landscape to the south.

Although the effects of glaciation in modifying the landscape are pronounced, these modifications in the older glacial landscapes have been largely masked or removed by periglacial weathering. Based on the sawtooth record of the marine isotope record, Braun (1989) indicated that there may have been as many as ten glaciations of a magnitude sufficient to glaciate or introduce a periglacial climate to Pennsylvania and New Jersey. Glacial/ periglacial periods in New Jersey were short-lived and marked by intense physical weathering. Colluvium, a major weathering product of periglacial climate, was shed off uplands onto the lower parts of hillslopes and onto the floor of narrow valleys and heads of drainage basins. It is chiefly a monolithic diamicton derived from weathered bedrock (chiefly by fragmental disintegration of outcrop and regolith by frost shattering) and transported downslope largely by creep. Over time it accumulated at the base of slopes, forming an apron of thick material, and it also collected on the floors of narrow valleys and in first-order drainage basins. In places it is

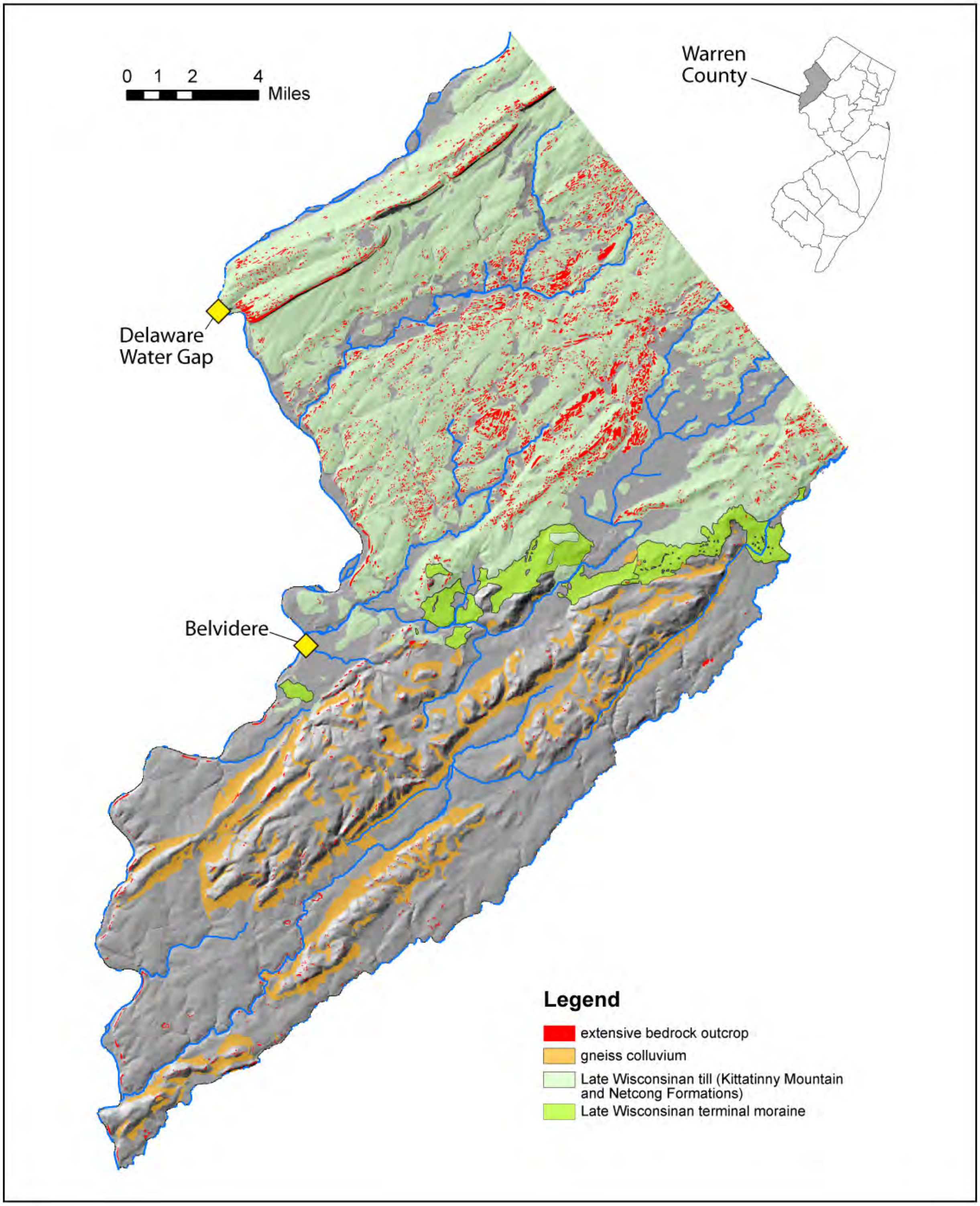

Figure 2. The Late Wisconsinan terminal moraine divides the largely colluvial landscape to the south where rock outcrops are sparse from the glacial landscape to the north where rock outcrops are numerous. Data from Witte and Stanford (1995) and Stone et al. (2002).

greater than 50 ft (15 m) thick and it covers large parts of the landscape. In contrast during the warm interglacials, the relative rate of chemical weathering increased and an extensive cover of deeper-rooted vegetation helped reduce the rate of mass wasting. During these periods thick soils were formed and bedrock was deeply weathered forming saprolite and decomposition residuum. Braun (1999) suggested that sub-till dissolution of carbonate bedrock in the Great Valley has been sufficient to overprint the primary glacial topography, particularly on the oldest till (≥ 850,000 yr BP). Constructional knob and kettle glacial topography, subsequently altered by periglacial processes and bedrock dissolution produced a composite topography that Braun (1999) refers to as “pseudo-moraine”.

Previous Investigations

New Jersey

Cook (1877, 1878, and 1880) discussed the geology of New Jersey’s glacial deposits in a series of Annual Reports to the State Geologist. He included detailed observations on the terminal moraine, recessional moraines, distribution and kinds of drift, and evidence of glacial lakes. Deposits of “older” weathered drift were discussed by Cook (1880) who noted the distribution of quartzose boulders and scattered patches of thin gravely drift in Pohatcong and Musconectcong Valleys in western New Jersey. Most of this material was thought to be “modified glacial drift”, possibly deposited by meltwater and reworked later by weathering and fluvial erosion. On greater inspection (Salisbury, 1893) this “modified glacial drift” was determined to be of glacial origin and called extra-morainic drift because of its distribution south of the terminal moraine.

A voluminous report by Salisbury (1902) detailed the glacial geology of New Jersey region by region. The terminal moraine and all surficial deposits north of it were interpreted to be products of a single glaciation of Wisconsinan age. Salisbury also noted that "in the northwestern part of the state, several halting places of ice can be distinguished by the study of successive aggradation plains in the valleys." South of the terminal moraine Salisbury (1902, Plate XXVIII) shows two deposits of extra-morainic glacial drift. The first, forming a narrow belt just outside the terminal moraine, consisted of glacial drift of late glacial age mixed with material that was older than the terminal moraine. Salisbury indicated that the drift was deposited during a temporary advance of ice beyond the terminal moraine, or was carried out by running water. The second body of extra-morainic drift is largely glacial and much older than the terminal moraine based on its deep weathering and patchy distribution. It lies as much as 20 mi (32 km) beyond the terminal moraine. Salisbury (1902) assigned a Kansan age to the older drift because its deeply weathered appearance suggested it was the product of a much older glaciation than the Wisconsin. Chamberlin and Salisbury (1906) correlated the oldest drift with the sub-Aftonian glacial stage of Iowa, using the term “Jerseyan” as an equivalent stage for the older glacial deposits in Pennsylvania and New Jersey. Bayley et al. (1914) divided the extra-moranic drift into “early glacial drift” that was largely till deposited during the Jerseyan stage and “extra-morainic drift” that consisted of a mix of Wisconsin and early drift.

MacClintock (1940) concluded that there were also three ages of glacal drift in New Jersey, the youngest of Wisconsinan age and two pre-Wisconsian drifts of Illinoian and Kansan age. He largely based his conclusions on the degree of weathering of medium to coarse grained gneiss and pegmatite clasts. Ridge (1983) and Cotter et al. (1986) indicated the youngest glacial deposits in Pennsylvania and New Jersey are Late Wisconsinan age, and are correlative with the Olean drift in Pennsylvania, and Ridge et al. (1990) showed that older and weathered drift in the Delaware Valley north of Marble Mountain is Late Illinoian age and not early Wisconsinan. The only early Wisconsinan deposits were colluvium and fluvial deposits that were observed in the Delaware Valley near Brainards, New Jersey about 4 mi (6 km) downstream from the Late Wisconsinan terminal moraine. Stone et al. (2002) also indicated that the youngest glacial deposits in New Jersey are Late Wisconsinan age, and that the two older drifts are Illinoian, and pre-Illinoian age.

Stanford (1997) suggested that the oldest glacial deposits in New Jersey may be pre-Illinoian K age (2.14 – 2.01 Ma), based on similarity of weathering characteristics, topographic position, and erosional preservation to that of the Pennsauken Formation, a Pliocene age braided stream deposit. Additional evidence for antiquity of these deposits includes the identification of pre-Pleistocene pollen identified in the lower part of a 60-ft (18-m) core from Budd Lake, NJ by Harmon (1968). Sediment sampled (below 45 ft [14 m]) may be laminated clays of pre-Illinoian proglacial lake deposits. It is overlain by late Wisconsinan/Illinoian proglacial lake sediment. Harmon (1968) dismissed the finding of the older pollen because the exotic taxa appeared to have been rebedded prohibiting their use as a trusted indication of Pliocene age.

Ridge (1983) and Witte (1988, 1997, 2001a) detailed the Late Wisconsinan deglaciation for northwestern New Jersey and a small part of northeastern Pennsylvania. Accordingly, deglaciation was characterized by the systematic northeastward retreat of the Kittatinny Valley and Minisink Valley ice lobes (Figure 3). This interpretation was based on the distribution of ice-marginal meltwater deposits (morphosequences) and moraines, and correlative relationships between elevations of delta topset-foreset contacts, former glacial-lake-water plains, and lake spillways. The identification of ice-retreatal positions by mapping morphosequences was first introduced in New England by Jahns (1941) and later refined by Koteff (1974) and Koteff and Pessl (1981).

Pennsylvania

White (1882) described the glacial geology of Pike and Monroe Counties, PA. The terminal moraine of the youngest glaciation was assigned a Late Wisconsinan age by Chamberlin (1883) and mapped in Pennsylvania by Lewis (1884). Williams (1893 and 1894) mapped glacial deposits of pre-Wisconsinan age in the Lehigh Valley. Leverett (1934) also assigned a Late Wisconsinan age to the terminal moraine and the glacial drift north of it, and revised its terminal limit. Crowl and Sevon (1980) remapped the terminal moraine in northeastern Pennsylvania, further refining its distribution and extent of the late glacial limit. They also concluded that the glacial deposits in eastern Pennsylvania consisted of the late Wisconsinan Olean drift, and two older deposits represented by the Warrensville drift of early Wisconsinan age and the Muncy drift of Illinoian age. Braun (2004) indicated that the terrestrial glacial record in northeastern Pennsylvania records at least four glacial advances. The youngest of Late Wisconsinan age (Marine Isotope Stage (MIS) 2 after Richmond and Fullerton (1986), the next oldest Late Illinoian (MIS 6) or pre-Illinoian B age (MIS 12) and two older drifts, the oldest pre-Illinoian G (MIS 22) based on reversed magnetic signal of proglacial lake deposits in the West Branch of the Susquehanna River Valley (Gardner et al., 1994) and a

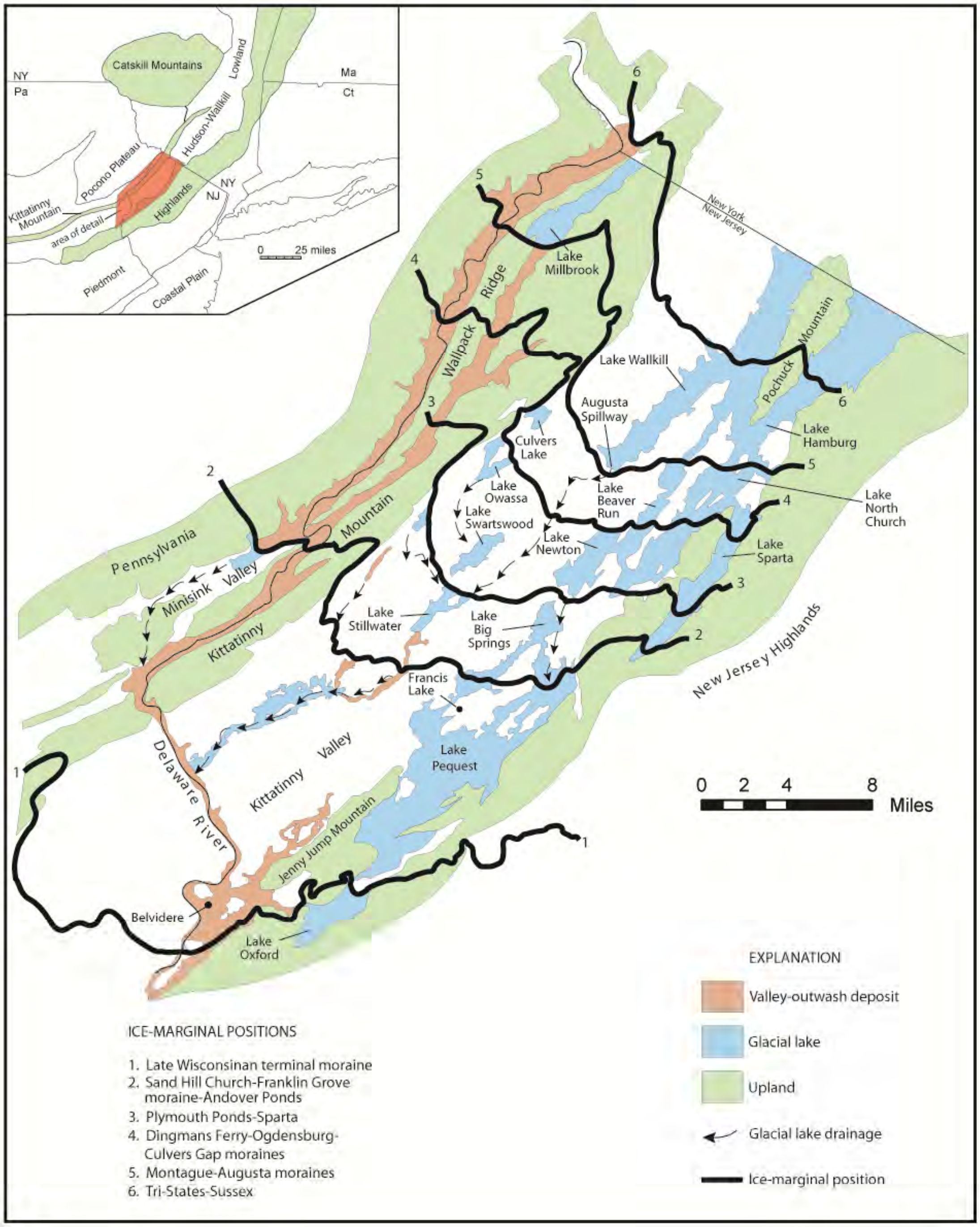

Figure 3. Major Late Wisconsinan ice margins of the Kittatinny and Minisink Valley ice lobes, location of large glacial lakes, and extensive valley-outwash deposits. Figure modified from Witte (1997).

younger pre-Illinoian D (MIS 16) based on a normal magnetic polarity of proglacial lake deposits found between the pre-Illinoian G (maximal glacial limit) and Late Illinoian or pre-Illinoian B limit (Sasowsky, 1994).

Glacial Limits and Deposits

Late Wisconsinan Glaciation

The LWGM is represented in most places by a terminal moraine that forms a nearly continuous, west-trending, low, uneven ridge of boulders and soil that sweeps across the northern part of the state from Perth Amboy to Foul Rift, NJ (Figure 3). In northwestern New Jersey the deposits of this glaciation are represented by meltwater deposits of the Rockaway Formation and till of the Kittatinny Mountain, and Netcong Formations (Stone et al., 2002). These deposits are lightly weathered, generally lie on nonweathered rock, are found in the modern valleys, and glacial landforms exhibit well-preserved constructional topography.

The terminal moraine's course divides New Jersey into two contrasting landscapes (Figure 2). North of the moraine there are many fresh to lightly weathered rock outcrops, thick stony soils, valleys filled with thick deposits of stratified sand and gravel, silt, and clay, and numerous wetlands and lakes. South of the moraine rock outcrops are sparse and weathered, soils are typically more clayey, and wetlands are sparse. Because the terminal moraine was a readily distinguishable feature of New Jersey's landscape, it was well studied around the turn of the 20th century. R. D. Salisbury, in his magnum opus, *The Glacial Geology of New Jersey*, devoted 38 pages to its origin, composition, and topography, as well as several additional pages on recessional moraines. The moraine was tangible evidence that continental glaciation was a very real geologic event. Only fifty years earlier, diluvialist views were accepted as fact in the scientific community. As a sign of the changing times, the terminal moraine and the Ogdensburg-Culvers Gap moraine found their way on New Jersey's first bedrock map (Lewis and Kummel, 1910-1912). This surely caused consternation among the day's geologic elitists, who viewed the study of surficial deposits as a lowly endeavor and not the proper field of study for serious scientists.

The terminal moraine in western New Jersey follows a nearly continuous looping course through Warren County (Figure 2). It consists of non-compact, bouldery, silty-sandy to sandy till with minor beds and lenses of water-laid sand, silt, and gravel (Figure 4 and 5). This material is distinctly different from the more compact, and less stony ground moraine or till that lies near the moraine. Additionally, stratified drift is **not** a major constituent, even in places where the moraine crosses river valleys or former glacial lake basins. The lithology of the moraine is decidedly local in origin. This was noted by Salisbury (1902, p. 254) who reported that "... the lithologic composition of the till varied from point to point, according to the nature of the formations over which the ice has passed."

The age of the terminal moraine and precise chronology of deglaciation are uncertain due to a lack of appropriate organic material for radiocarbon dating, inadequacies of dating bog bottom organic material and concretions, and use of sedimentation rates to extrapolate bog bottom radiocarbon dates. Also, varved lake bottom exposures that can be used for chronology are scarce. However, thick deposits of these annual silt-clay couplets are found beneath swamp and bog deposits in the many glacial lake basins in northern New Jersey (Figure 3), would likely provide information on deglaciation history if they can be sampled.

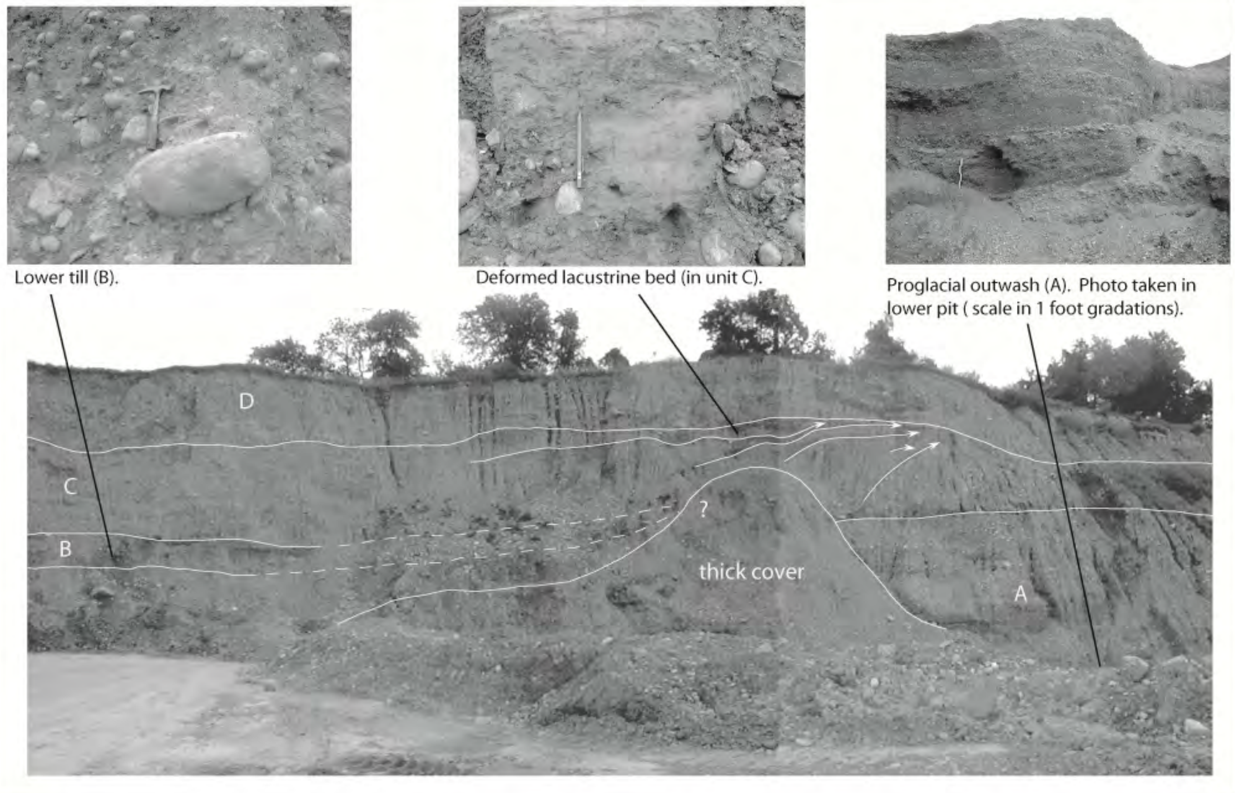

Figure 4. Composite section of the east wall, Foul Rift pit. Units: A—Proglacial outwash; B—Lower till (basal); C—Deformed outwash, arrows denote thrusts; and D—Upper till (Foul Rift moraine). Thrusts typically marked by deformed beds of silt and clay. Figure from Witte (2001b).

There are a few radiocarbon dates that bracket the age of the terminal moraine. Basal organic material cored from Budd Lake by Harmon (1968) yielded an age of 22,890 +/ 720 yr BP (I 2845), and a concretion sampled from sediments of Lake Passaic by Reimer (1984) that yielded an age of 20,180 +/ 500 yr BP (QC 1304) suggests that the age of the terminal moraine dates to 22,000 to 20,000 yr BP. Basal organic material cored from a bog on the side of Jenny Jump Mountain approximately 3 mi (4.8 km) north of the terminal moraine by D. H. Cadwell, New York State Geological Survey (written comm., 1997) indicated a minimum age of deglaciation at 19,340 +/- 695 yr BP (GX-4279). Similarly, basal organic material from Francis Lake in Kittatinny Valley, which lies approximately 8 mi (13 km) north of the terminal moraine indicates a minimum age of deglaciation at 18,570 +/ 250 yr BP (SI 5273) (Cotter, 1983). Based on the assumed age of the LWGM (22 – 21 ka) and deglaciation chronology outlined for northwestern New Jersey, the terminal moraine was deposited during an interval of about 1,000 to 1,500 years. It represents a time when the ice sheet's margin remained in a nearly constant position, neither retreating nor moving forward, except within the narrow zone marked by the moraine.

The Late Wisconsinan recessional history of the Laurentide ice sheet is well documented for northwestern New Jersey and parts of eastern Pennsylvania. Epstein (1969), Ridge (1983), Cotter et al. (1986), and Witte (1997 and 2001a) showed that deglaciation was characterized by the systematic northeastward retreat of the Kittatinny Valley and Minisink Valley ice lobes. This interpretation is based on the distribution of ice-marginal meltwater deposits and moraines, and correlative relationships between elevations of delta topset-foreset contacts, former glacial-

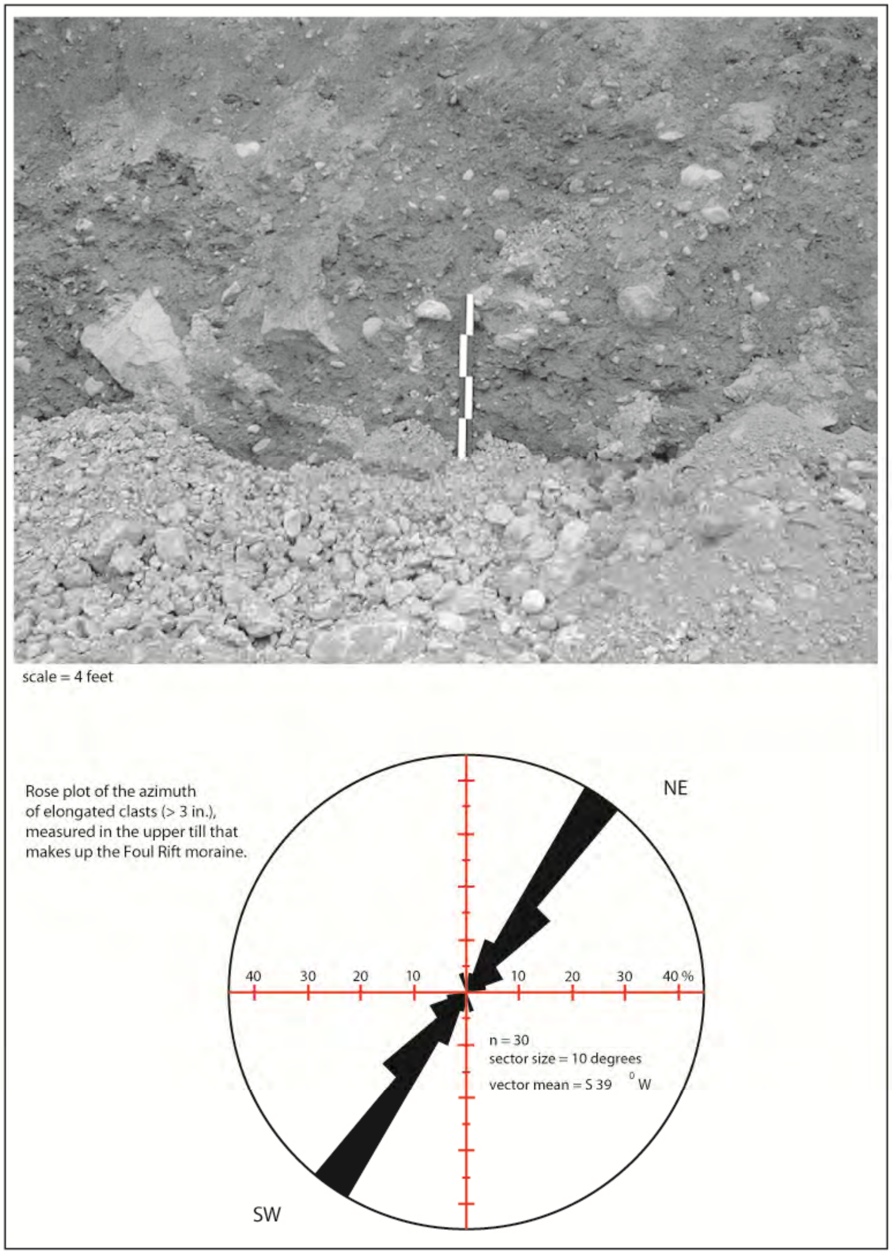

Figure 5. Upper till exposed along the north rim of the Foul Rift pit. Compact, fissile, sandy-silty matrix containing by volume 7 to 10 percent subangular to subrounded stones. Many stones are striated and elongated clasts have a pronounced downvalley fabric. Although the till forms part of the Foul Rift moraine (Late Wisconsinan terminal moraine), it has characteristics of a basal till and it may represent a subglacial till facies associated with a push moraine. Figure modified from Witte (2001b).

Outwash - Planar-bedded gravel and sand (unit 3).

Basal Till - Compact, stony, polylithic diamicton (unit 1).

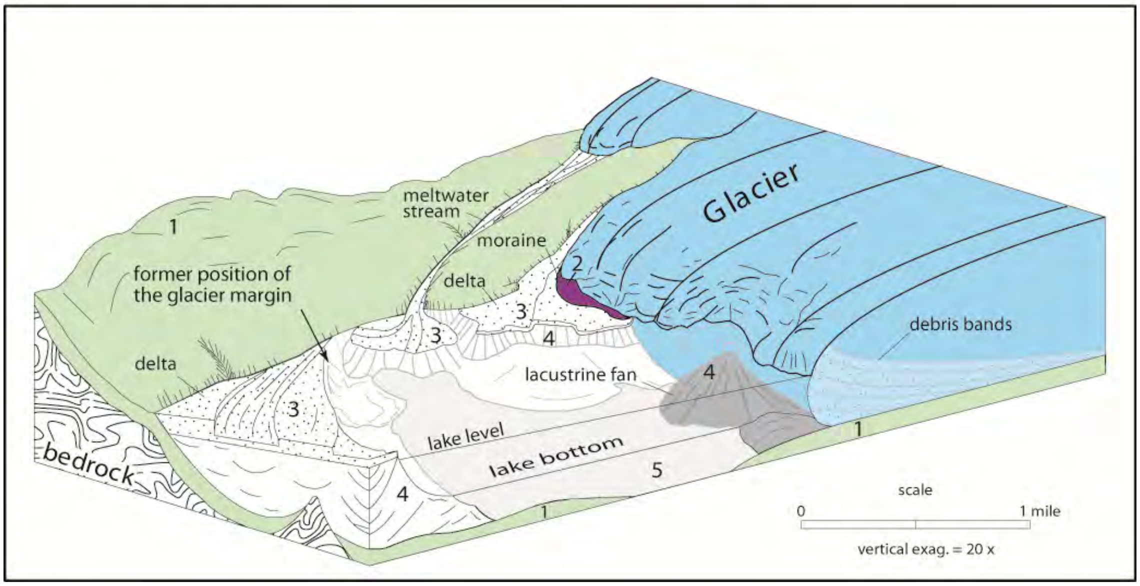

Figure 6. Composite diagram showing the depositional setting of glacial sediments. 1—Basal till; 2—Flowtill; 3—Planar beds of gravel and sand; 4—Inclined beds of sand beds of sand and some gravel; and 5—Laminated beds of silt, clay, and very fine sand.

lake-water plains, and lake spillways. During glacial retreat, meltwater sediment was chiefly laid down in glacial lakes (Figure 6) that occupied valleys now drained by the Pequest River, Paulins Kill, and Wallkill River, and to a lesser extent in small upland basins and valleys (Figure 3). These former lake basins had been dammed by stratified drift, moraine, and stagnant blocks of ice, or by the glacier's margin.

Five ice margins (Figure 3), the Franklin Grove, Sparta, Culvers Gap, Augusta, and Sussex have been identified that mark major recessional positions of the Kittatinny Valley lobe. The Sparta, Culvers Gap, Augusta, and Sussex margins are traceable onto the New Jersey Highlands, and all margins, except Sparta, are traceable westward into Minisink Valley. All appear to represent halts in ice retreat, and some mark minor readvances of the Kittatinny Valley lobe. This pattern of ice retreat is different from the more rapid style of retreat postulated for the lower part of Kittatinny Valley (Witte, 1997). These differences, as well as the close spacing of the Culvers Gap and Augusta margins, their large traceable extent, and correlation with extensive end moraines and ice-contact deltas in western New Jersey may indicate that other factors, besides local topographic control, have influenced the retreat history of the Kittatinny Valley lobe.

Because many end moraines in northwestern New Jersey are nearly continuous belts, they define the edge of the ice sheet both geometrically and temporally. The moraines clearly show that the margin of the Laurentide ice sheet was distinctly lobate at both a regional scale and local scale. Based on the tracing of end moraines from the valley floor onto adjacent uplands, the surface gradient of the Kittatinny Valley lobe varied between 125 and 290 ft/mi (660 and 1,531 m/km) within the first few miles (kilometers) from its margin. In northeastern Pennsylvania, Crowl and Sevon (1980) determined that the slope at the terminus of the Laurentide ice sheet varied from 80 to 405 ft/mi (422 to 2,138 m/km) with a "best measure" estimated at 225 ft/mi (1,188 m/km).

Illinoian Glaciation

The Illinoian glacial maximum (IGM) lies as much as 5 mi (8 km) south of the LWGM, and follows a similar parallel course across western New Jersey (Figure 1). This glaciation is represented by the Lamington (meltwater deposits) and Flanders Formations (till) of late Illinoian age (Stone et al., 2002). These deposits (Figure 7) are moderately weathered, lie on weathered bedrock, and are found in modern valleys at slightly higher topographic positions than Late Wisconsinan glacial drift. Constructional topography is preserved in many places with moraine, delta, valley-outwash plain, and meltwater terrace land forms recognizable. Illinoian deposits in many areas are preserved on low to moderate slopes, whereas the drift on steep slopes has been stripped by erosion. Near the Late Wisconsinan border, Illinoian deposits have been found beneath Late Wisconsinan drift and in the core of some drumlins (Stone et al., 2002). Older soils have been largely stripped, although where buried by younger glacial drift and colluvium, a truncated, red Bt soil (Figure 8) presumably of Sangamon age (MIS 5) may be preserved (Ridge et al., 1990; Stone et al., 2002). Depth of carbonate leaching is as much as 12 ft (4 m), crystalline clasts (mostly gneiss) have moderately thick weathering rinds (Figure 9), and manganese staining is common, especially along the faces of soil joints. Exposed quartzite boulders commonly have a surface coating of ferro-manganese oxide. Late Wisconsinan drift near the LWGM also contains weathered clasts, but there is always fresh material present to distinguish it from Illinoian drift. The "extra-morainic drift" of Bayley et al. (1914) consists of Late Wisconsinan till that extended beyond the terminal moraine, and Illinoian till. Most of this material has been remapped as Illinoian till (Stone et al., 2002).

The southern edge of the Illinoian drift sheet in many places is poorly defined, although in places a terminal moraine and heads-of-outwash mark its southern limit. East of Denville NJ (Figure1), Illinoian deposits have not been recognized, the border covered by Late Wisconsinan deposits laid down by the Passaic ice lobe. In western New Jersey, heads-of-outwash and remnants of a terminal moraine mark the Illinoian border in the larger valleys. Elsewhere, patches of till and ice-contact stratified deposits (largely deltaic) define the border.

The similarity in the course of the Illinoian and late Wisconsinan drift borders shows that the Illinoian deglaciation proceeded similarly as the late Wisconsinan with glacial lakes forming in the valleys. An end moraine in Pequest Valley below Townsbury, NJ is the only Illinoian recessional moraine identified in western New Jersey. Bayley et al. (1914), and Ridge (1983) indicated this feature was Late Wisconsinan age, based on their finding a few lightly weathered dolostone boulders on its surface. However, closer inspection has shown that the dolostone clasts were only found near dolostone outcrops on the western side of the ridge. The dolostone clasts may have also been derived from ice-rafted debris laid down in Lake Oxford in Late

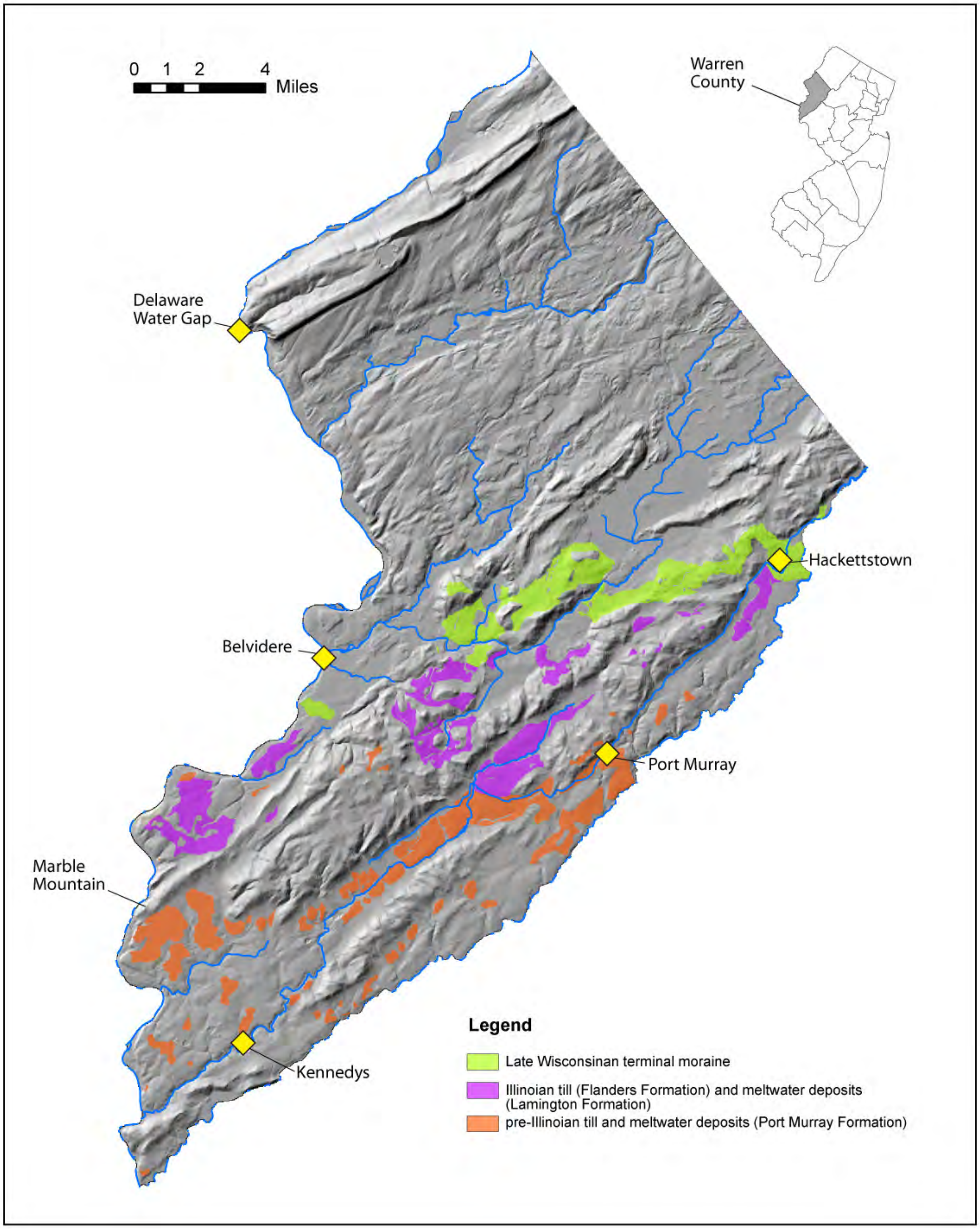

Figure 7. Distribution of Illinoian and pre-Illinoian glacial drift in Warren County, NJ. Data from Witte and Stanford (1995) and Stone et al. (2002).

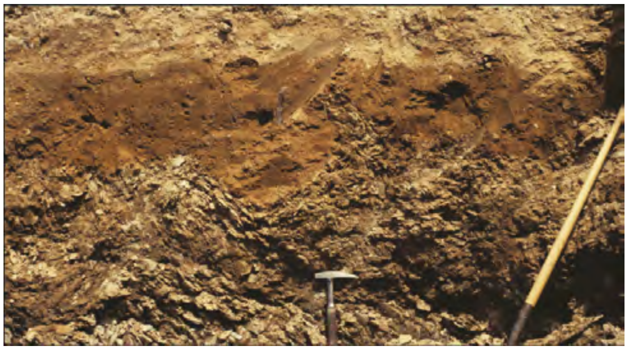

Figure 8. Truncated red Bt horizon developed in Illinoian till (Flanders Formation) overlying frost involution surface developed on weathered and colluviated Martinsburg Formation. Pit location is approximately 2 mi (3 km) outside the Late Wisconsinan limit, near Hackettstown, NJ.

Figure 9. Medium to medium-thick weathering rinds developed in gneiss cobbles (except for chert pebble in upper left). The clasts were collected from Illinoian till (Flanders Formation) that makes up a small recessional moraine in the Pequest Valley, approximately 0.5 mi (1 km) outside off the Late Wisconsinan glacial limit.

Wisconsinan time. Additionally, a 12-ft (4-m) deep trench dug at the crest of the moraine showed moderately-weathered till devoid of carbonate clasts. Based on the lack of carbonate material, the advanced degree of weathering of crystalline clasts, and pervasive ferro-manganese staining, this material compares favorably with other till in the area that has been mapped as Illinoian. An exploratory boring located near the crest of the moraine shows that the drift there is 52 ft (16 m) thick and provides additional evidence that this cross-valley ridge is a moraine rather than thin till perched on carbonate bedrock.

Pre-Illinoian Glaciation

Figure 10. Till of the pre-Illinoian Port Murray Formation overlying deeply weathered Martinsburg Formation (below dashed line) exposed in an old clay pit near Port Murray, NJ. Fully decomposed gneiss cobble by arrow. The inclined contact may represent relief on the Martinsburg surface. The underlying unit may also be glaciotectonized, frozen substrate formed when the pre-Illinoian glacier overrode deeply weathered Martinsburg more than 800,000 years ago.

New Jersey's oldest glaciation is represented by the Port Murray Formation (Stone et al., 2002) (Figure 1), which replaces the term "Jerseyan". The formation consists of till, till-stone lag, and meltwater deposits. It is deeply weathered, thin and patchy, and it lies on weathered bedrock (Figure 10). Deposits are generally only preserved in valleys in areas of low relief protected from erosion and more rarely in uplands where deposits have been trapped on low topographic saddles and broad low-relief surfaces. In places, these older deposits have been found beneath colluvium. In western New Jersey, most of the Port Murray Formation is preserved on weathered dolomite and slate in the Pohatcong, Musconectong, and Delaware Valleys (Figure 8). It is typically less than 15 ft (5 m) thick. Constructional topography is not preserved. The drift is not found in the modern valleys, more often lying as much as 100 ft (31 m) above modern valley floors in areas that are protected from mass wasting and fluvial erosion. In most places these older deposits appear to be till. However, after a long and complex weathering history most of these polymictic materials become clayey, slightly stony diamictons. Original characteristics are often difficult to discern. However, the strong scientific consensus is that these materials are of glacial origin, based on clast provenance and position on the landscape

The southern limit of the pre-Illinoian glaciation (pIGM) is based on the most southerly occurrence of thin, deeply weathered patchy till, till-stone lag, and a few stratified deposits and erratics. In most places it is poorly defined, its trace a "best guess" between patches of the Port Murray Formation and erratics. The pIGM lies as much as 15 mi (24 km) south of the IGM, following a westward trending course from Denville to Holland, NJ (Figure 1). Similar to the Illinoian deposits, pre-Illinoian glacial deposits have not been recognized east of Denville.

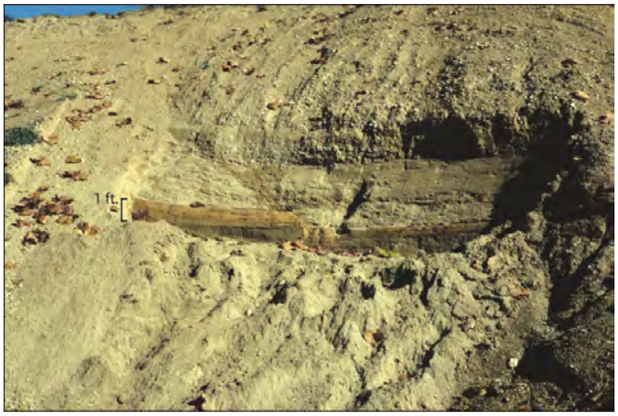

Figure 11. Weathered silty clay bed of the Port Murray Formation exposed in a small gravel pit near Kennedys, NJ. The 10-in (25-cm) thick bed was shown to have a reversed magnetic polarity indicating that it is older than 788 ka (J. C. Ridge, Tufts University, written comm., 1998). The planar-bedded material here may also be of non-glacial origin possibly deposited by the Delaware River when its course was farther east than its present configuration. The small normal fault (center of photo) may have formed because of glacial collapse or it is neotectonic in origin.

The age of this oldest and most extensive glaciation is uncertain. The Port Murray Formation is correlative with the oldest glacial deposits in eastern Pennsylvania, which are older than 788 ka based on the reversed magnetic polarity of lake-bottom deposits cited in Braun (2004). As previously discussed, Braun (2004) assumes a pre-Illinoian G (850 ka) age for these deposits whereas Stanford (1997) favors a pre-Illinoian K (2.1 Ma) age. Samples collected from a silty-clay bed in a deeply weathered glaciofluvial deposit in the Pohatcong Creek valley near Kennedys (Figure 1 and Figure 11), show that these sediments were laid down during a period of reversed magnetic polarity (J.C. Ridge, Tufts University, written comm., 1998). This places the age of the deposits at older than 788 ka. Based on the correlation of continental glaciations in the northern hemisphere with the offshore oxygen isotope record this deposit may have been laid down during Late Pliocene (2.1 Ma) or during the middle part of the Pleistocene (1.1 or .85 Ma). If the deposit is not outwash, but rather alluvium laid down by Pohatcong Creek or the Delaware River, its position within the belt of older glacial drift shows that the older drift is the same age or older than the suspected outwash.

Due to the scant distribution and poor preservation of the Port Murrayan deposits, and lack of recognizable recessional deposits, the history of the pre-Illinoian deglaciation is problematic. If deglaciation proceeded as it did in the late Wisconsinan, then ice-recessional positions may have been marked by the heads-of-outwash of glaciofluvial deposits laid down in the Musconetcong and Pohatcong Valleys, and ice-contact deltas laid down in glacial lakes in Kittatinny Valley. Except for a few high-standing remnants in the lower parts of the Musconetcong and Pohatcong Valleys (Witte and Stanford, 1995) all pre-Illinoian stratified deposits have been removed by erosion.

In eastern Pennsylvania thick belts of older glacial material and a few ice-contact stratified deposits near Emmaus and Hellertown define the terminal edge of the pre-Illinoian ice sheet.

Lake clays observed by Williams (1893) near Emmaus and Allentown, PA confirmed the existence of an ice-dammed lake named glacial Lake Packer in the lowland now drained by Little Lehigh Creek. A lake would have also existed in Saucon Valley up until the time Saucon Gap was uncovered by ice and the lake drained into the Lehigh Valley. Because glacial lakes provide much of the basis for deglaciation chronologies in New Jersey and Pennsylvania there may be an opportunity to define part of the pre-Illinoian deglaciation in eastern Pennsylvania, an opportunity that's lacking in western New Jersey.

Tracing Glacial Limits into and across Eastern Pennsylvania

Glacial limits in western New Jersey (Stone et al., 2002) are largely accordant with limits in Pennsylvania (Braun, 2004) with the exception of the third oldest (pre-Illinoian D) glaciation, which is not recognized in New Jersey (Figure 1).

Late Wisconsinan

In New Jersey the outer edge of the terminal moraine marks the LWGM in most places. The moraine follows a nearly continuous looping course through western New Jersey. Morainal topography is typically distinct and easily recognized by its well-formed ridge-and-trough and knob-and-kettle topography. In a few places, where steep topography constrained its formation, morainal topography is only faintly noticeable. R.D. Salisbury and H.B. Kummel (Salisbury, 1902) described in detail the course of the moraine across New Jersey. Their excellent description of its trace through the southern part of Kittatinny Valley and across the Jenny Jump outlier stands today, except for a few areas in the Pequest and Delaware Valleys where outwash was mapped as part of the moraine. Clearly, the moraine's course was strongly influenced by topography, extending more southward in areas of lower elevation, and as it approaches the central axis of Kittatinny Valley. In some places a narrow belt of Late Wisconsinan till extends as much as 3,000 ft (914 m) beyond the terminal moraine. Tracing the LWGM into eastern Pennsylvania, there is a very close accordance with the limit showed in Braun (2004).

Similar to the Late Wisconsinan terminal moraine in New Jersey, the terminal moraine traces a lobate westward and northwestward course through Pennsylvania. In most places it marks the LWGM, sharply separating the lightly weathered, drab-looking glacial drift to the north of it with the weathered, brighter-colored glacial drift to the south. The moraine is generally characterized by constructional hummocky topography throughout most of eastern Pennsylvania (Figure 12) except where ice crossed Kittatinny Mountain, Godfrey Ridge, and other significant bedrock landforms (Epstein, 1969). From Riverton (located across the Delaware River from Belvidere, NJ), the moraine trends northwest near the Villages of Ackermanville, Bangor and Rosetto (Braun and Ridge, 1997). The

Figure 12. Hummocky constructional moraine topography, Late Wisconsinan terminal moraine, Riverton, PA.

Figure 13. Stone row south of Kittatinny Ridge dominated by Shawangunk cobbles and boulders (note Bloomsburg Formation cobbles in center of photo).

Figure 14. Poorly sorted Late Wisconsinan till near Bangor, PA (rock hammer in center of photo for scale).

Figure 15. Fresh to lightly weathered shales and siltstones in kame pit north of Saylorsburg, PA.

moraine forms a reentrant northwest of the Big and Little Offsets in Kittatinny Mountain and crosses the ridge near Fox Gap (Epstein, 1969). The moraine follows the north flank of Kittatinny Mountain southwest to Saylorsburg (Epstein, 1969), where constructional knob and kettle topography is also well developed. The LWGM curves north to Sciota and then northwest towards Tamaqua (Braun, 1996a). Glacial till varies in thickness from being too thin to map over the crest of Kittatinny Ridge at Fox Gap (Epstein, 1969), to thicknesses greater than 100 ft (31 m) in valleys (Braun and Ridge, 1997). South of Kittatinny Ridge, cobbles and boulders in till are dominated by the Shawangunk quartzite, with scattered clasts derived from the Bloomsburg Formation present in most localities (Figure 13). The moraine is marked by higher concentrations of cobbles and boulders, but is characteristically poorly sorted (Figure 14). Till and meltwater deposits deposited north of Kittatinny Ridge are dominated by locally derived Devonian lithotypes including weathered shales, siltstone, sandstones, and carbonates (Figure 15).

Outwash terraces and valley trains have been mapped in many of the major drainages extending away from the ice margin including Oughoughton and Martins Creek (Ridge, 1983; Ridge et al., 1992; Braun and Ridge, 1997) and the Delaware River (Crowl, 1971; Ridge, 1983; Witte, 2001a; Medford et al., 2011). Stratified fluvioglacial deposits associated with deglaciation are present south of Kittatinny Mountain in the Jacoby Creek watershed northwest of Portland, PA (Ward, 1938; Epstein, 1969) and north of Kittatinny Mountain in Cherry Valley between Kittatinny Mountain and Godfrey Ridge (Epstein, 1969). Ice disintegration kames are common both as large mounds in the center of the valley (Figure 16) and also as kame terraces deposited between stagnant ice and the valley sides (Figure 17). Kames consist of stratified sand and gravel (Figure 17) and have been mined for aggregate by individual landowners

Figure 16. Kame (low hill, photo's center) in Cherry Valley, PA.

Figure 17. Stratified kame sand and gravel exposed in a kame terrace deposited against the south flank of Godfrey Ridge in Cherry Valley, PA.

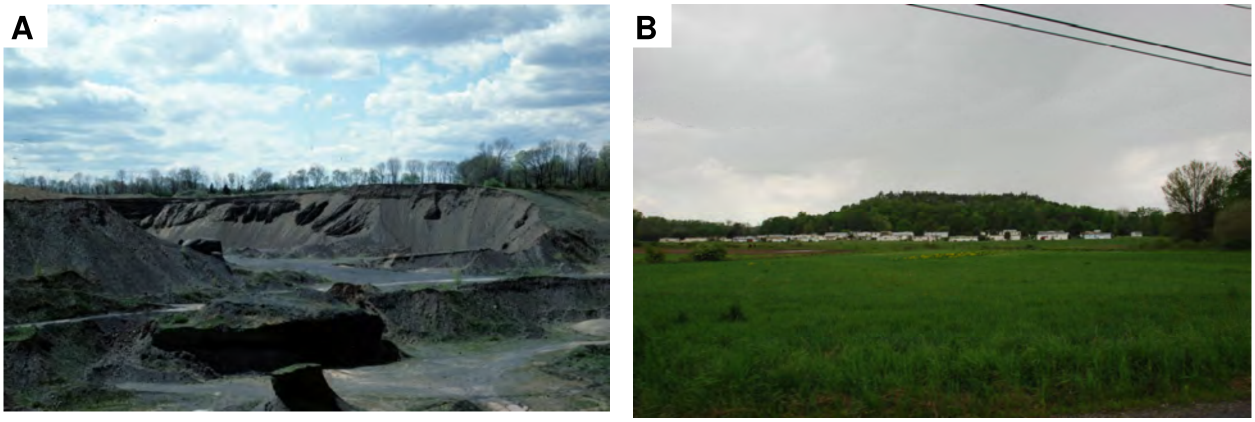

Figure 18. A—Ice-contact ("kame") delta near Sciota, PA; B—Esker 'upstream' of kame delta shown in A, Sciota, PA.

(Cherry Valley) and commercially (Jacoby Creek). Ice flow was clearly influenced by these prominent ridges during the LWGM, and the topographic influence likely became more pronounced as the ice sheet thinned. As the ice sheet wasted towards the northeast during deglaciation, the ridges may have stranded ice south of Kittatinny Mountain in the Jacoby Creek Valley and also in Cherry Valley between Kittatinny Mountain and Godfrey Ridge. Whether the kames represent heads of outwash associated with temporary ice margin positions, or whether there were multiple ice blocks is not entirely clear, but the elongate nature of several of the kames suggests that ice wasted towards the northeast as a solid mass (Epstein, 1969).

The most impressive stratified deposits in the area consist of a large ice-contact ("kame") delta and esker near Sciota (Epstein, 1969; Epstein and Epstein, 1969; Figures 18A and B). The esker is discontinuous and most pronounced immediately upstream of the delta (Figure 18B). The delta (originally a lacustrine fan) prograded from a subglacial meltwater tunnel into glacial lake Sciota, an ice-marginal lake formed between the terminal moraine and the retreating ice margin (Epstein, 1969; Epstein and Epstein, 1969). Although the delta-esker pair shown in Figures 18A and 18B is the largest and most prominent, Epstein (1969) mapped and described multiple ice-contact ("kame") deltas that prograded into a dynamic Lake Sciota whose level decreased as lower outlets were uncovered by ice retreat.

Illinoian

The Illinoian ice sheet (Figure 1) reached its most southerly limit on the north side of Marble Mountain during the late Illinoian stage. In western New Jersey Illinoian till is represented by the Flanders Formation. (Qit) is preserved on many hillslopes, and it lies in the modern river valleys. In some places its surface is marked by a truncated red soil of presumably Sangamon age. Elsewhere, the soil has been stripped by colluviation. Generally clasts and matrix material are moderately weathered, and dolostone and limestone clasts are leached to depths of at least 12 ft (4 m).

Well preserved, moderately weathered till and ice-contact outwash delineate the IGM in the Delaware Valley and the northwestern edge of the New Jersey Highlands. The location of high-standing meltwater deposits underlain by thick clay and silt north of Marble Mountain and Chestnut Hill show that the Marble Mountain Gap was probably blocked by a tongue of ice during the Illinoian maximum. This resulted in the formation of a high-standing glacial lake during the early phase of glacial retreat from the Illinoian terminal position. Illinoian deposits in the Delaware Valley in the vicinity of Marble Mountain appear significantly more weathered due to rubification of matrix material and staining of clasts than deposits farther east in the New Jersey Highlands. These differences result from differences in parent material with the more carbonate-rich drift in the Delaware Valley appearing to be more weathered than the crystalline-rich (gneiss and granite) drift found in the Highlands. Also, insitu weathering of drift in the Highlands was highly attenuated due to colluviation in areas of higher relief, s compared to the moderately flat valley floors.

Tracing the IGM into Pennsylvania, there exists a close accordance with the limit showed by Braun (1996a, 2004), based on Illinoian (MIS 6) deposits (or pre-Illinoian B (MIS 12)) mapped near Easton, PA. The Illinoian limit in eastern Pennsylvania is defined by heads-of-outwash in valleys and patchy till on uplands, the limit generally paralleling the LWGM and as much as 7 mi (11 km) beyond. Deposits are deeply weathered (10 m or more) and constructional topography has been removed or greatly subdued by erosion Braun (2004). Overall these deposits appear to be weathered greater than equivalent deposits in western PA (west of the Salamanca re-entrant) (Braun, 2004) and western NJ (personal commun, 1987). Based on degree of weathering and preservation Braun doubts that only 150,000 yrs. have passed since deposition and favors a pre-Illinoian B age (440 ka). Nonetheless, our examination of till mapped in Eastern Pennsylvania by Braun (1996a) as possibly pre-Illinoian B, appears to be too fresh to be 440,000 yrs. old. Weathering differences of the Illinoian till are largely due to lithologic variation and that much of the Illinoian in eastern Pennsylvania (Lehigh Valley) was deposited on the Martinsburg Formation where it was more easily eroded by colluviation and congeliturbation.

The Illinoian drift in Pennsylvania is well represented just south of Mud Run in Forks Township, PA, where large concentrations of boulders from the till have been assembled in large continuous stone rows. The cobbles and boulders in these stone rows are clearly more weathered than those found in stone rows developed from tills of Late Wisconsinan age, however they are remarkably unweathered if one were to assume they were pre-Illinoian B age (Figures 19A and B). The Garr Road site in Forks Township overlies carbonate rocks situated approximately 700 to 1,000 ft (213 to 305 m) south of the contact with the Martinsburg escarpment. This is the exact same geologic setting as exists near Riverton, PA where the

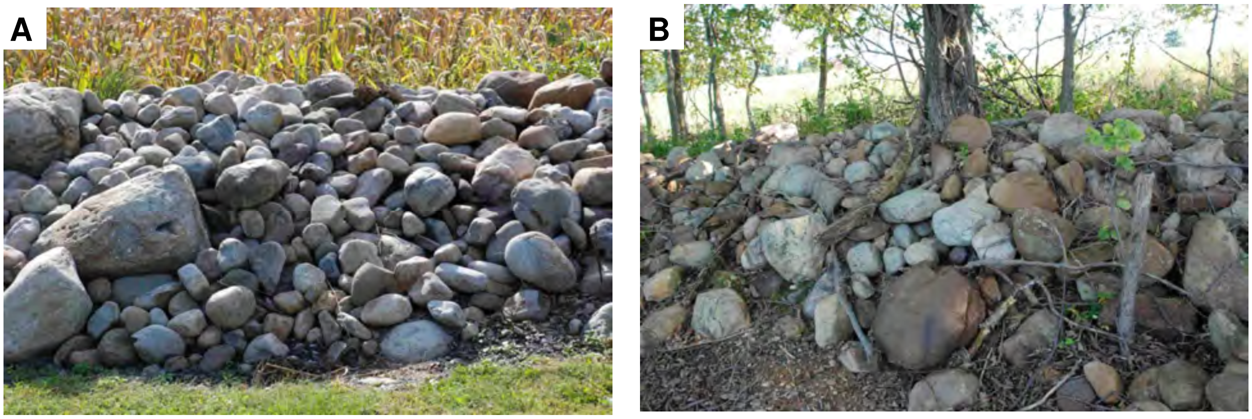

Figure 19. A—Typical stone row composed of Late Wisconsinan boulders (west of Riverton, PA on Martins Creek-Belvidere Highway); B—Stone row composed of Late Ilinoian boulders (Forks Township, PA on Garr Rd.). Note ferromagnesian weathering rind on many boulders.

LWGM deposits are extensive (overlying carbonate rocks situated approximately 700 to 1,000 ft (213 to 305 m) south of the contact with the Martinsburg escarpment). Because the Wisconsinan and Illinoian ice sheets would have overrun the same lithologies in each location, these sites provide a good opportunity to compare the degree to which weathering has altered the rocks without the typical complication of comparing the weathering of disparate lithotypes. We sampled 93 rocks in stone rows at each of these locations selected at 10-in (25-cm) intervals in four 43-ft^2 (1-m^2) grids (some grid intersections landed on vein quartz, shattered Martinsburg slate, or two grid intersections covered the same rock). The majority of the lithologies sampled at each site were Shawangunk or other sandstone cobbles, and four clasts of the Bloomsburg Formation were included in each sample. Weathering rinds were measured at the mm scale on all specimens that had clear oxidation rinds. Cobbles that were weathered through were arbitrarily assigned a rind thickness of 35 mm to separate them from the rocks having discrete rinds. Figure 20 left shows the frequency distribution of rind thicknesses at the two sites and Figure 20 right, shows a representative sample of specimens from each of the two sites included in the rind data along with a set of cobbles collected in till in Bethlehem Township Pa, well south of the Late Illinoian border. Although the samples collected at the Mud Run site are clearly more weathered than those from the LGWM site in Riverton, they are far less weathered than those collected further south in Bethlehem Township.

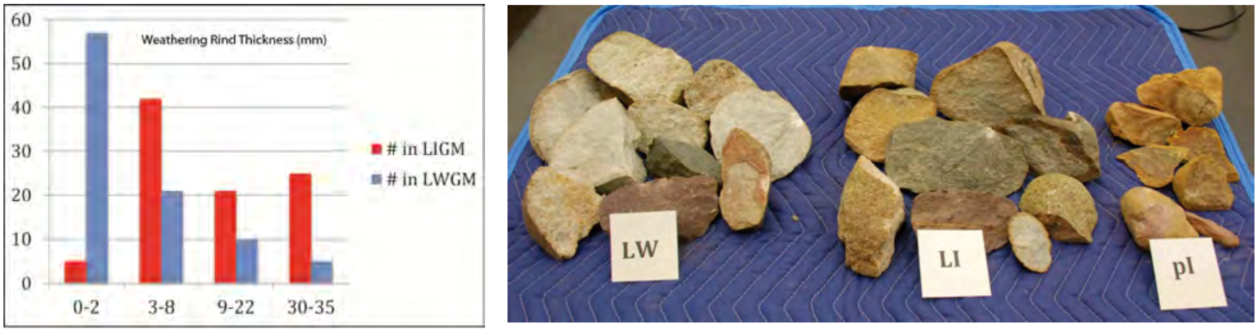

Figure 20. Left—Weathering rind thickness on clasts collected from stone rows near Riverton, PA (LWGM deposits) and near Mud Run (LIGM deposits). Clasts labeled 30-35 mm are actually weathered throughout the interior; Right—Examples of samples represented in Figure 20a. Note the relatively fresh nature of specimens labeled as late Illinoian relative to those labeled pre-Illinoian. The labels are situated on a Bloomsburg clast for comparison for each group.

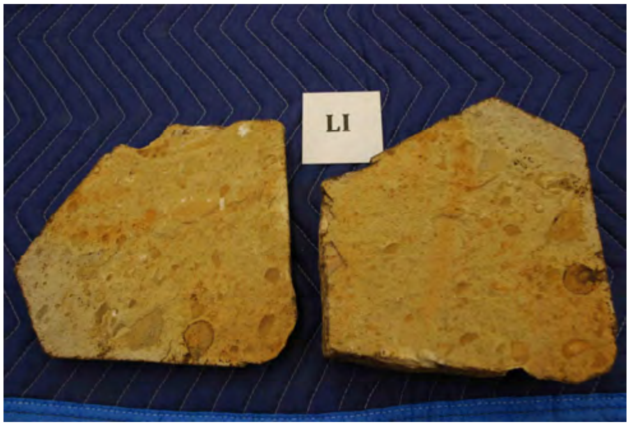

Figure 21. Fossiliferous specimen of the Middle Devonian Hamilton group from Illinoian till near Mud Run. Fossils are very well preserved in this sample.

Morris Metz, the landowner at the Mud Run site, collected a partially weathered fossiliferous cobble in the field adjacent to the stone row that contains a fossil assemblage characteristic of the Middle Devonian Hamilton that only crops out north of Kittatinny Ridge (Andy Bush and David Sunderlin, Pers. Comm., 2012). The rock is weathered, but too fresh, we believe, to represent a till stone of pre-Illinoian B age (Figure 21). Therefore, based on the high concentration of relatively unweathered cobbles and boulders near the glacial border in the Mud Run drainage basin, the similarity in weathering between these cobbles and those mapped in New Jersey as Late Illinoian, and the disparity in weathering compared to rocks picked from till approximately 6 mi (10 km) south in Bethlehem Township, we believe the border mapped as Illinoian or pre-Illinoian in Figure 1 is most likely late Illinoian in age rather than pre-Illinoian B.

Pre-Illinoian

The pre-Illinoian glacial maximum (pIGM) in New Jersey is based on the most southerly occurrence of thin, deeply weathered patchy till, till-stone lag, and a few stratified deposits collectively known as the Port Murray Formation (Stone et al., 2002) and erratics. In western New Jersey the limit lies just south of Musconectong Mountain crossing the Delaware River near Holland, NJ (Figure 1). Weathered deposits of Triassic fanglomerate make the identification of pre-Illinoian glacial drift in this area difficult. Alternatively, patches of weathered till just north on Musconetcong Mountain (New Jersey Highlands) show a maximum glacial position nearby.

Tracing the pIGM into Pennsylvania, there exists a close accordance with pre-Illinoian boulder and cobble lags mapped by Braun (1996a), near Monroe, PA. Similar to New Jersey, the identification of glacial drift in areas of fanglomerate is problematic. Alternatively, some of these lags may be weathered pre-Illinoian outwash given their position along and above the Delaware River. Farther west the limit is traced to the pseudo-moraine areas in Saucon Valley and the Lehigh Valley (Braun, 2004).

Braun (2004) also defines a second pre-Illinoian limit in the Lehigh Valley based on a thick belt of drift about 6 mi (10 km) north of the glacial maximum. Similar to the older deposits farther south they are deeply weathered and poorly preserved. However, in a few places pseudo-moraine topography is persevered. Tracing the limit eastward it wraps around the north end of Morgan Hill, PA crossing the Delaware Valley just south of Phillipsburg, NJ. Continuing an eastward trend and adjusting for topography, the limit would fall near the reversed polarity site (discussed previously) near Kennedys, NJ, too close to determine its location inside or outside of the limit. In New Jersey, thick deposits of pre-Illinoian glacial drift and/or pseudo-moraine topography have not been observed in areas underlain by dolomite and limestone. This limit is untraceable in New Jersey. For now it's an unresolved issue of whether there existed a pre-Illinoian D glaciation.

In Pennsylvania evidence of a glacial event that extended to the position of Braun's pre-Illinoian G margin was recognized as early as 1893 by Williams. Williams also postulated the existence of proglacial Lake Packer, an ice dammed lake formed between the ice margin on the northeast in Lehigh Valley and the Reading Prong hills to the southwest in the Little Lehigh drainage basin. He based Lake Packer on lacustrine clays that he called the Packer Clay and topographic enclosure related to ice damming. Williams (1893) and Leverett (1934) mapped a moraine that, more or less, mirrors Braun's (1999) pre-Illinoian G margin, based on tills and stratified drift. The Saucon Valley drainage basin is bounded by Reading Prong basement blocks such as South Mountain on the north and other Reading Prong blocks on the west, south and east, and drains to the northeast through a narrow gap between South Mountain and Green Hill, into the Lehigh River. Early workers *(*Leverett, 1934; Miller et al., 1939) mapped a moraine looping across the south central portion of Saucon Valley through the south end of Hellertown and Bingen. Based on topographic and drainage relationships, and clays mapped in the Saucon Valley, Braun (1999) suggested that a proglacial Lake bounded by the ice margin to the north and the reading Prong Hills to the south and west, formed in the Saucon Valley similar to Lake Packer to the west. One of us (Germanoski) encountered clean clays beneath the colluvial wedge prograding from the south side of South Mountain in a heat pump well drilled near Summit Lawn that that may be representative of these lacustrine clays. This ice-marginal lake would have formed as ice advanced into the Saucon Valley, blocking the South Mountain-Green Hill gap. The lake sediments were probably overlain by till as the ice advanced to its maximum southernly extent (pre-Illinoian G), with a spillway over the southern drainage divide into Cooks Creek (Braun 1996b). As ice retreated out of the Saucon Valley, the lake would have persisted until the drainage outlet was breached at the South Mountain-Green Hill gap. This corresponds with Braun's pre-Illinoian D boundary (Figure 1). Therefore, as Braun (1999) acknowledges, his pre-Illinoian D boundary may represent a recessional position of the pre-Illinoian ice sheet. This interpretation may also explain the lack of a well-defined counterpart to this ice margin in western New Jersey where pre-Illinoian proglacial lakes have not been identified.

The Pre-Illinoian G ice margin is reasonably well marked in Pennsylvania by a number of ice-contact stratified deposits that may be ice-contact ("kame") deltas in the Hellertown and Allentown East quadrangles (Braun, 1996b, 1996c, 1999). One of the more striking deposits is exposed between Emmaus and the northwest flank of South Mountain (Braun, 1999). This delta would be a pre-Illinoian G analog to the Late Wisconsinan Sciota proglacial delta described earlier, except that this proglacial lake was trapped between the ice margin and bedrock topography rather than an ice margin and a terminal moraine. Material in the Emmaus deposit (Figure 22) is deeply weathered, far more so than the Late Illinoian material and other pre-Illinoian material described in this summary. Individual clasts, lack physical strength and matrix was largely derived from the weathering of primary

Figure 22. Deeply weathered material in a kame delta between South Mountain and Emmaus (photo courtesy of Frank Pazzaglia, Lehigh University).

materials (Braun, 1999). These deposits are heavily weathered in part because they were originally coarse, permeable sand and gravel.

Summary

There is a remarkable consistency between glacial margins mapped on either side of the Delaware River given that the scope of work here spans more than 130 years and includes the work of many geologists. Dates of glaciations have changed as more has become known of continental glaciations in North America. Current thinking indicates that eastern Pennsylvania and New Jersey have been glaciated at least three times over the last 2.1 million years. These are the Late Wisconsinan (21 ka), Illinoian (150 ka), and pre-Illinoian (855 ka or older). Comparison of Illinoian till and outwash across the river from New Jersey to Pennsylvania shows highly variable weathering, an indication that composition, topographic position, and permeability greatly influence apparent age. In studies where these differences were kept to a minimum (Garrs Road site), measured weathering rinds suggest a more likely Late Illinoian age (150 ka) rather than the pre-Illinoian B age (440 ka) for the glaciation that lies just outside of the LWGM. However, it must be said that without absolute dates it comes down to "in the Delaware Valley, Illinoian clasts look too fresh to be sitting around for 440,000 years and they nearly occupy the same topographic position as Late Wisconsinan glacial drift."

The lack of a pre-Ilinoian D margin in New Jersey suggests that the margin mapped in Pennsylvania behind the glacial maximum limit may be a pre-Illinoian G recessional position. A study on the magnetic polarity of proglacial lake sediments in the Lehigh Valley area could resolve the legitimacy of the p-ID margin and age of the oldest glacial deposits (p-IG or older). Similarly, a re-investigation of the proglacial lake sediments beneath Budd Lake in New Jersey may establish the age of the oldest glacial deposits

Lastly, the terrestial record in terms of glacial landforms has been consistent from glacial episode to glacial episode. The strongly developed northeast-southwest topographic grain of eastern Pennsylvania and western New Jersey has shaped ice flow dynamics and the nature of the glacial deposition by channeling ice into lobes, forming moraines along lobate glacial margins, stranding ice during deglaciation to varying degrees, and in particular facilitating the development of proglacial lakes and deposition of ice-contact (kame) deltas. Except for a few moraines, these lake deposits provide the clearest record of terminal limits and deglaciation and although this record is greatly obscured in areas of older glacial episodes, parts of it remain. What little we do know suggests that glaciation proceeded in the same manner regardless of age and that long interglacial periods of weathering and erosion have made the history of pre-Late Wisconsinan glaciations a challenge to understand.

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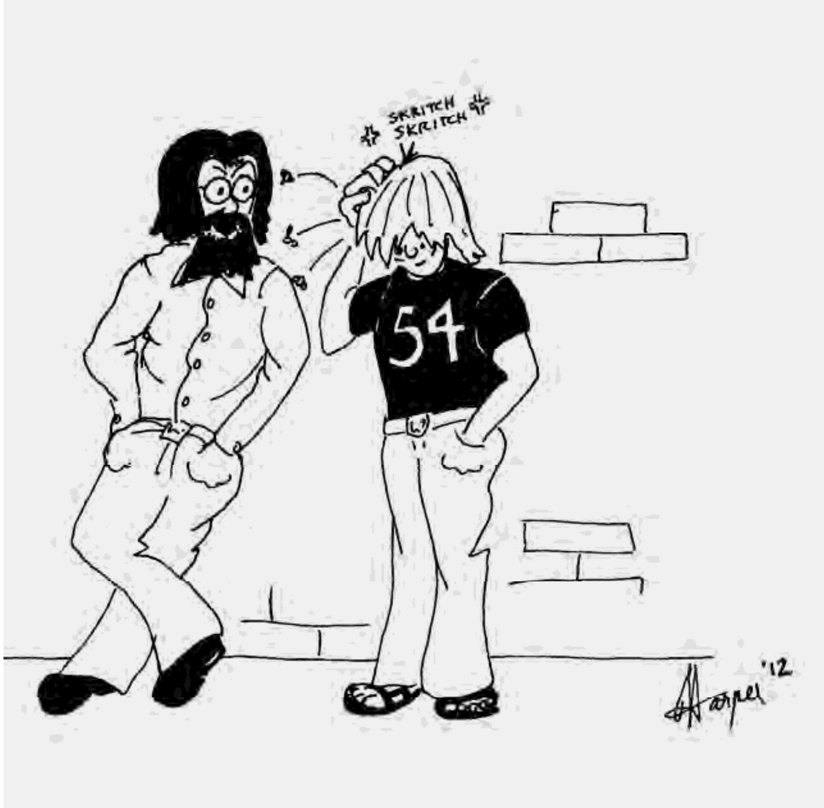

Hey, man, quit buggin' me!

BREACHING THE MOUNTAIN BARRIER: HISTORY AND ENGINEERING GEOLOGY OF THE SHAWANGUNK MOUNTAIN RAILROAD TUNNELS, ORANGE AND SULLIVAN COUNTIES, NEW YORK

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Introduction

Shawangunk Mountain in New York constitutes the northern 44 mi (71 km) of a remarkable topographic ridge that bounds the northwestern margin of the Appalachian Great Valley for 244 mi (388 km) from Franklin County, PA, ~10 mi (~15 km) north of the Maryland State Line, to Rosendale, Ulster County, NY. The 144 mi- (232 km-) long ridge in Pennsylvania, breached by numerous water gaps (see Stops 1, 3, and 4 of this guidebook), is called Blue Mountain. The 34 mi- (55 km-) long ridge in New Jersey, known by the very appropriate Lenni Lenape Indian name of Kittatinny ("Endless") Mountain, extends northwest from Delaware Gap into New York State, deeply notched only at Culvers Gap, a prominent preglacial wind gap in Sussex County (see Witte, 2001). Shawangunk Mountain is an uninterrupted homoclinal ridge (with a few wind gaps) northeast from the New Jersey State Line for 30 mi (48 km) to near Ellenville, Ulster County, but from there to its termination broadens out as a result of several Alleghanian folds. (Shawangunk is also apparently of Lenni Lenape derivation, meaning "there is smoky air" and perhaps referring to the Dutch burning of a Munsee Indian fort in 1663 [Wikipedia, 2012c; but see Fried, 2005].) Throughout its entire length, the Blue-Kittatinny-Shawangunk Mountain ridge is underlain by Silurian Tuscarora-Shawangunk Formation quartzite and conglomerate on its summit and northwest slope and Ordovician Martinsburg Formation shale and sandstone on its southeast slope. (The above statement must be modified slightly by pointing out that at one point at least, in the Town of Mount Hope, Orange County, NY, the Martinsburg lies at the crest of the mountain.)

Over the last two centuries a number of proposals have been made to bore transportation tunnels through Shawangunk Mountain in New York, the mountain ridge being a significant barrier between the Hudson River valley and New York City on the east and the economically important Catskill foothills and Neversink-Basher Kill-Mamakating valley on the west. However, in all this time only two such tunnels have been dug (Figure 1). The High View Tunnel was among the earliest successfully completed in the Northeast. The Otisville Tunnel was bored nearly 50 years later when tunnel technology was considerably more advanced.

Early Proposed Tunnels

In the 1820's, 10 years before railroads entered the transportation picture, a group of Orange County businessmen lobbied for the planned Delaware and Hudson (D&H) Canal to

Inners, J., Skye, S., Epstein, J., Bierly, A., and O'Hara, A., 2012, Breaching the mountain barrier: History and engineering geology of the Shaqwangunk Mountain railroad tunnels, Orange and Sullivan Counties, New York,, *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. 118-129.

HISTORICAL CHRONOLOGY

(Wakefield, 1970; Inners et al., 2002; Houck, 2006; Skye, 2009; Wikipedia, [undated], 2012a, 2012b, 2012d, 2012e.)

1828	**Delaware and Hudson (D&H) Canal completed between Honesdale, PA, and Kingston, NY. (Construction of the canal was initiated in 1825.)**
1832	**(April 24) The New York and Erie Rail Road is chartered in New York, the line to connect Piermont, NY, north of New York City and west of the Hudson, with Dunkirk, NY, on Lake Erie.**
1836	**Construction of the Erie Rail Road begins.**
1847	**The New York and Erie Rail Road cuts through Shawangunk Mountain at Otisville, NY. The line opens to Port Jervis in January 1848.**
1861	**The New York and Erie Rail Road is reorganized as the Erie Railway.**
1868	**The New York and Oswego Midland Rail Road is organized. The mainline runs from Weehawken, NJ, to Oswego, NY.**
1871	**The New York and Oswego Midland Rail Road completes the High View Tunnel through Shawangunk Mountain between Wurtsboro on the west and Bloomingburg on the east.**
1878	**Brick tunnel-liner installed in parts of the High View Tunnel.**
	Due in part to the earlier financial machinations of Jay Gould, the Erie Railway goes bankrupt and is sold off, becoming the New York, Lake Erie and Western Railroad.
1880	**The New York, Ontario and Western (Ontario and Western, O&W) Railway takes over the mainline of the New York and Oswego Midland Rail Road.**
1895	**The New York, Lake Erie and Western Railroad goes into bankruptcy, and then emerges as the Erie Railroad.**
1906-08	**The Erie Railroad bores the Otisville Tunnel through Shawangunk Mountain.**
1947-48	**Last passage of steam trains through the High View Tunnel.**
1953	**(September 10) Last O&W passenger train passes through the High View Tunnel, bound for Roscoe to the west.**
1957	**Last trains run through the High View Tunnel. The tunnel is abandoned. (Sometime later the tracks are removed.)**
	(March 29) The O&W Railway is liquidated, and all assets are auctioned off.
1960	**(October 17) The Erie Railroad merges with the Delaware, Lackawanna and Western Railroad to form the Erie-Lackawanna.**
1976	**The Erie-Lackawanna becomes part of Conrail.**
1983	**The Metro-North Railroad is formed to take over commuter operations of Conrail in New York State, operating the Port Jervis Line through the Otisville Tunnel.**
1999	**Conrail system is split up, with the Norfolk Southern (NS) Railroad taking over the old Erie line through Otisville. Metro-North leases the NS tracks for commuter operations down to the present day.**
2003	**Metro-North leases the NS tracks for commuter operations, with the possibility of outright purchase in the future.**
2005-2006	**New York Highway Department undertakes attempt to dewater the High View Tunnel because of concerns about subsidence beneath new NY Route 17 being constructed over the mountain above the tunnel.**

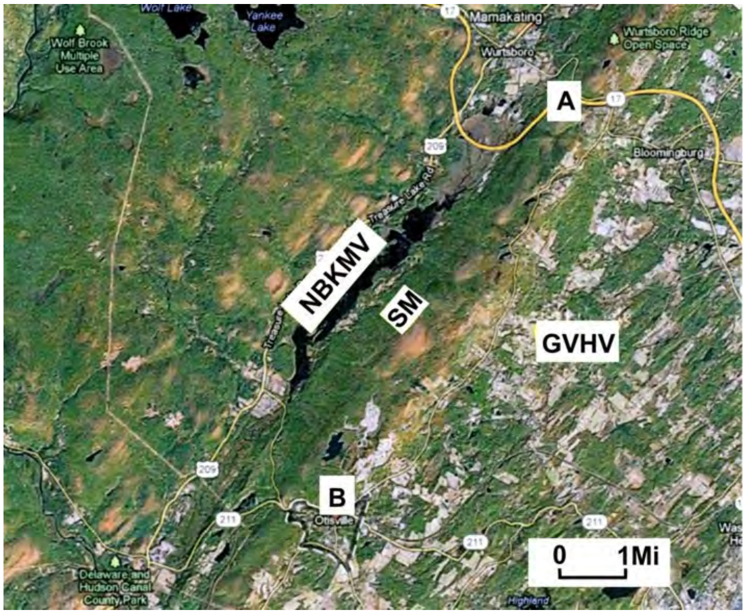

Figure 1. Map showing the locations of the High View (A) and Otisville (B) Tunnels in relation to the Neversink-Basher Kill-Mamakating Valley (NBKMV), Shawangunk Mountain (SM), and the Great Valley-Hudson Valley (GVHV) in Orange and Sullivan Counties, NY.

cross Orange County. In 1825 these gentlemen proposed that a tunnel be dug through the Shawangunk ridge and that a canal be built through Orange County to Newburgh where it would join the Hudson River. Since one of the strong backers of the D&H Canal was George Duncan Wickham, a prominent citizen of Orange County and a member of the D&H Board, the D&H Board of Managers had to treat the proposal seriously. Wickham made a motion to the Board to explore alternatives to the planned route up the valley west of Shawangunk Mountain to Kingston on the Hudson and the board approved (Skye, 2009). Benjamin Wright, the nation's foremost canal engineer was asked to explore alternatives to the Kingston route. Wright evaluated the proposed Orange County route and determined that a tunnel two miles long would be needed and that the additional cost would be prohibitive. It is worth noting that the black powder blasting technology available at the time would surely have delayed the completion of the canal well beyond the actual completion date of 1828 when the canal was opened to Kingston (Skye, 2009).

Ten years after Wright rejected the ideal of a D&H Canal tunnel, he had to consider the idea of a Shawangunk tunnel again. Wright had become the chief engineer for the Erie Railroad and had to decide whether the Erie should cross the Shawangunks at Otisville by going over the top or through a tunnel. He opted for a deep cut through the Deerfield Gap at Otisville in the route plan he completed in 1835. He did not support the idea of a tunnel at the time since the amount of traffic expected could not justify the expense of a tunnel he estimated would have to be over half a mile (>0.8 km) long. He did state in his report to the New York Secretary of State that in 20 years time the increase in the railroad's business would demand that such a tunnel be built. In 1847 the railroad finally accepted Wright's recommendation and built the line through Deerfield Gap (Figure 2; see Stop 9). In 1873 the Erie reconsidered its decision on building a tunnel, but nothing came of that effort (Skye, 2009).

Figure 2. Abandoned Erie Railroad cut through Shawangunk Mountain in the wind gap at Otisville, looking east (GPS 41°28'32.4"N/ 74°33'05.9"W). The cut is 0.15 mi (0.24 km) south of the later tunnel ~100 ft (~30 m) higher in elevation. The beds exposed are northwest-dipping (~30°) quartzitic conglomerate and sandstone of the Shawangunk Formation, the unconformable contact with the Martinsburg Formation being exposed at the east end of the cut (STOP – of this guidebook, p. ----).

Engineering Geology of the Shawangunk Tunnels

The High View Tunnel

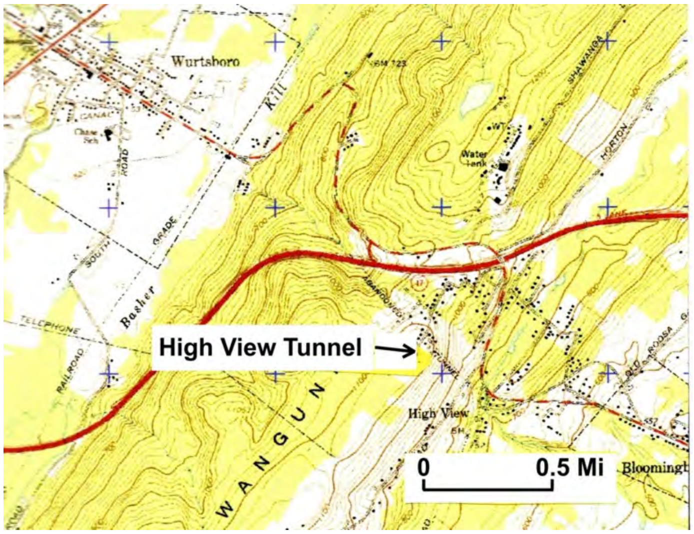

Figure 3. Location map of the O&W Railroad's tunnel through Shawangunk Mountain between High View and Bloomingburg,

In 1868, more than 20 years after the Erie rejected the idea of a tunnel, Clinton Stephens designed a tunnel through the Shawangunk ridge between Wurtsboro on the west and Bloomingburg on the east for the New York and Oswego Midland Rail Road (later the Ontario and Western [O&W] Railway). Stephens had previously done considerable work on the Erie Canal and had also contracted with the Erie Railroad. Construction of the so-called High View Tunnel began in 1868 and was completed in 1871. Work was started at both ends of the tunnel simultaneously. When both teams met in the middle, they were only a few feet off. This was quite an engineering feat at the time, especially since the tunnel is curved near the east portal (Skye, 2009).

The now abandoned High View Tunnel cuts through Shawangunk Mountain just south of a high wind gap ~1 mi (~1.5 km) southwest of Wurtsboro, Sullivan County (Figure 3). Elevation of the floor of the gap is about 1000 ft, the mountain rising to knobs ~1200 ft (~365 m) immediately to the northeast and southwest. Just to the southeast, and also on the line of the tunnel is a narrow spur-ridge ~100 ft (~30 m) higher than the floor of the gap. The elevation of both portals is ~840 ft (~255 m), and therefore ~250 ft (~75 m) of rock lie above the deepest part of the tunnel. Original length of the tunnel was 3,857 ft (1,176 m), cut through solid rock. The rock was excavated using steam-powered drills and black powder.

Figure 4. Southeast portal of the abandoned O&W tunnel at High View (GPS ~41°33'30.3'N/-74°27'30.6"W). Bedding in the Martinsburg shale and sandstone in the immediate vicinity of the portal is very gently west dipping.

The southeast portal of the tunnel (Figure 4) is situated several hundred feet (scores of meters) northeast of the former High View Station (Figure 5). The Martinsburg Formation exposed at the portal and in cuts to the south is predominantly evenly interstratified, thin-bedded gray shale and siltstone, exhibiting only slight internal deformation. Bedding strikes N35-65E and dips rather uniformly 10-15NW. Attitude of cleavage in the shales is ~N75E/20SE. Attitudes of the most prominent joints are N75E/90, N28E/87SE, and N2W/83E.

The present northwest portal is on the

Figure 5. High View Station, now an elegant residence, along the abandoned railroad grade a few hundred feet (scores of meters) from the east portal of the O&W tunnel. In the late 1960's, the station "brood[ed] hauntingly over a field-like thicket, a vandalized shell, nothing more than a shelter for a flock of chickens" (Wakefield, 1970, p. 38). Things have since decidedly improved.

Figure 6. Northwest portal of the abandoned O&W tunnel, about 0.8 mi (1.3 km) east-southeast of Wurtsboro (GPS 41°34'00.0"N/74°28'05.7"W). Bedding in the Shawangunk conglomerate here strikes N33E and dips 26NW. Note the brick lining (with stone facing at entrance) and water flowing from pipe in foreground.

mountainside directly downslope from the westbound lanes of recently constructed new NY Route 17 (Figure 6). Well exposed at the portal and in the rock cut to the northwest is medium - to thick-bedded, light-gray to white Shawangunk quartzitic sandstone and conglomerate. Bedding is relatively uniform, striking N33E and dipping 26 NW. Numerous large, angular quartzite blocks fill the cut just beyond the existing portal, a result of a "botched attempt" to block the original portal that shortened the tunnel ~ 20 ft (~6 m) (Houck, 2006).

The High View Tunnel was originally "jerry-built" with little regard to safety and geologic conditions (Wakefield, 1970, p. 45). Particularly troublesome were a pocket of clay encountered in the course of construction (probably related to deep weathering in the Martinsburg at the northwest-dipping contact with the Shawangunk), the fractured (jointed) nature of the Shawangunk quartzite, and constant water problems. In 1878 the Midland installed brick lining in parts of the tunnel (Figure 7), but leaving large rooms of solely rock bore construction between three lined segments (Wakefield, 1970, p. 45; Houck, 2006). In 1897, seventeen years after taking over the tunnel from the Midland, the O&W Railway attempted to further strengthen the arching of the tunnel. (The local press reported, however, that the men performing the work were exposed to almost unbearable gas and smoke conditions [Wakefield, 1970, p. 47].)

Bearing testimony to the tunnel's constant water problems are the large pool of

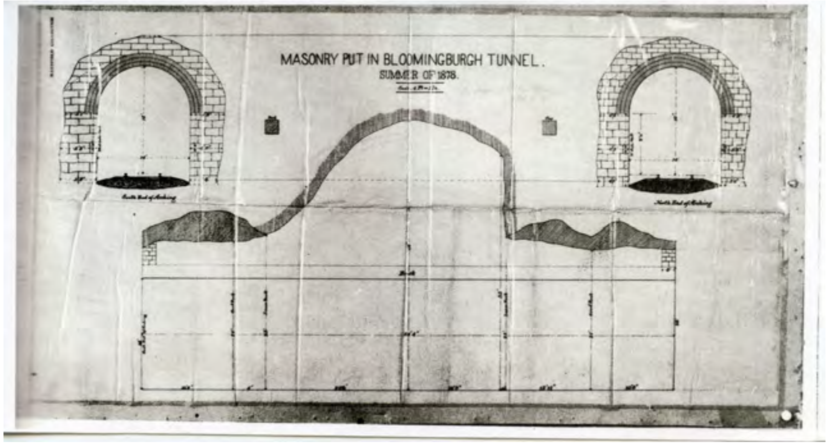

Figure 7. Engineering department drawing showing details of brick lining built to protect trains from persistent roof rock-falls in the O&W's High View-Wurtsville ("Bloomingburgh") tunnel. The August 30, 1878, Liberty (NY) Register reported "the Midland is doing a good job in the tunnel, laying a solid brick arch which will make it save for all trains to come" (Wakefield, 1970, p. 47).

Figure 8. Close-up of the southeast portal of the O&W tunnel's east portal showing gently west-dipping bedding, water in tunnel (a constant problem during railroad operations), and lack of lining at portal.

water at the southeast portal (Figure 8) and the water flowing from a similar pool into a pipe at the northwest portal (see Figure 6). The pipe was emplaced about a half-dozen years ago during construction of new NY Route 17, when New York Highway Department engineers and geologists became concerned that "the standing water in the tunnel would hasten the further deterioration of the rock bore [and thereby increase the likelihood of additional rock falls and subsidence above the line of the tunnel bore]" (Houck, 2006).

Though suffering periodic safety, engineering and geologic problems, the High View Tunnel continued to operate effectively throughout the first half of the 20th century until the tunnel was abandoned and the O&W Railway was liquidated in 1957.

The Otisville Tunnel

The idea of an Erie Railroad tunnel at Otisville lay dormant until 1906 when work finally began on the long awaited tunnel. Troubles beset the tunnel builders as they worked their way through the mountain in 1906. In August fighting broke out within the African-American crew that was digging the tunnel. The local Justice of the Peace and his constables had to be summoned to restore order. In September a blast of the explosives being used to excavate the tunnel caused the tunnel roof to collapse, killing one workman and trapping a number of others. That same month it was reported that the new tunnel was causing local water "veins" to dry up. This resulted in farmers' wells running dry and in large amounts of water spilling into the tunnel (Skye, 2009). As inscribed on the east portal, the tunnel was completed in 1908.

The Otisville Tunnel trends WNW-ESE through Shawangunk Mountain at Deerfield Gap, a short distance north of the original Erie grade over the ridge just west of Otisville, Orange County (Figure 9). The elevation of the gap is ~850 ft (~260 m) at the east end, rising gently to ~900 ft (~275 m). At the west end a mountain spur juts into the gap from the northeast, sloping off from an elevation of ~1,090 ft (~330 m) to ~1,025 ft (~310 m) at an imposing quartzite cliff high

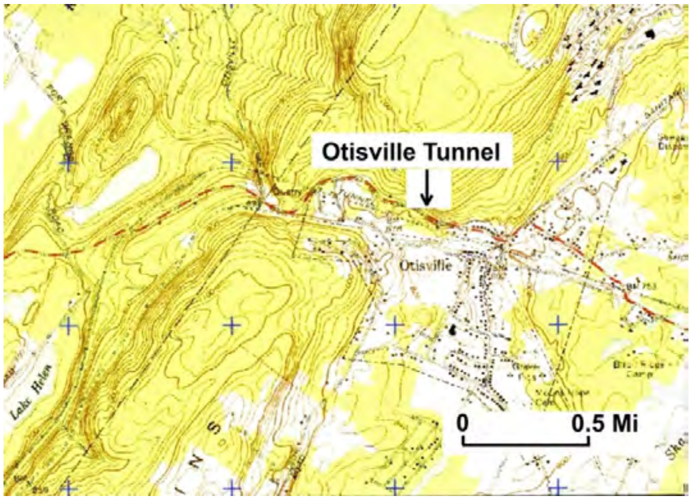

Figure 9. Location map of the Erie Railroad's tunnel through Shawangunk Mountain at Otisville, Orange Co., NY (Otisville, 7.5' quadrangle).

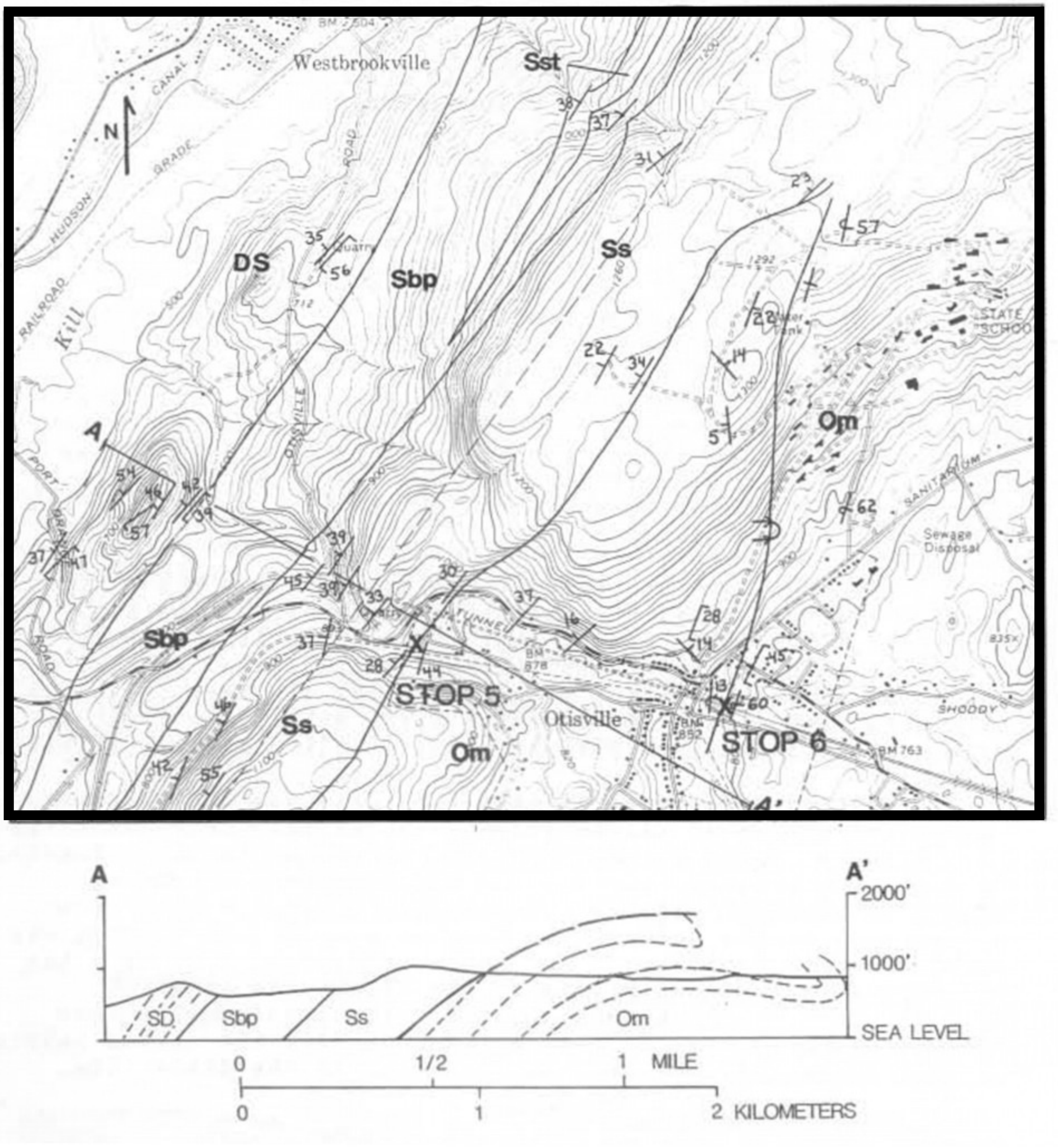

Figure 10. Preliminary geologic map and section of the Otisville, NY, area, showing the angular unconformity between the Shawangunk and Martinsburg Formations, the overturned syncline overlapped by the Taconic unconformity, and location of STOPS 5 and 6 (1987 NYSGA). Standard structure symbols used for bedding, cleavage, and axial tract of syncline. DS = Schoharie Formation through Bossardville Limestone; Sbp = Poxono Island Formation and Bloomsburg Red Beds; Ss = Shawangunk Formation; Om = Martinsburg Formation. Base from Otisville 7.5' topographic quadrangle, 1969. (Epstein and Lyttle, 1987, fig. 16)

Figure 11. East portal of the Erie Railroad tunnel at Otisville (GPS 41°28’25.1”N/74°32’13.2’W). Intensely deformed Martinsburg shale and sandstone are exposed on both side of the cut

over the tunnel. Elevation of both portals is ~780 ft (~240 m). Therefore, the eastern 0.75 mi (1.2 km) of the tunnel is only ~100 -120 ft (~30-35 m) beneath the floor of the gap, but under the spur ridge at the west end nearly 250 ft (76 m) of rock lies overhead. The tunnel is 5,314 ft (1,620 m) long (Wikipedia, 2011). At the west portal the 1908 grade curves to the south and joins the 1847 grade ~2 mi (~3 km) to the southwest.

Figure 10 is a preliminary geologic map of the Otisville area, showing the areal geology in the vicinity of the old Erie Railroad Tunnel and the structure at the portals (Epstein and Lyttle, 1987).

The Martinsburg Formation at the east portal of the Otisville Tunnel (Figure 11) is spectacular exposed in cuts on both sides of the tracks leading into the portal. While generally within the open-fold Taconic frontal zone in the Otisville area, the Martinsburg at the east portal is complicated by a faulted overturned fold (Figures 12 to 14). The formation here consists of shale and interbedded thin- to thick-bedded graywackes. Sole marks (grooves, flutes, and loads) are prominent on the undersurfaces of bedding in the overturned limb (Figures 15 to 18). Cleavage is well developed and is axial-planar to the fold. The axis of the fold trends about N10E and is overlapped by the Shawangunk ~1.3 mi (~2.1 km) to the north. Because the Shawangunk does not appear to be folded at the unconformity, the fold, faults, and cleavage in the Martinsburg here must be Taconic in age. Outside the area of this fold, cleavage is generally not developed (Epstein and Lyttle, 1987).

The west portal of the Otisville Tunnel is quite picturesque, being cut into the Shawangunk ridge beneath wooded cliffs high above and a deep roadcut on NY Route 61 just

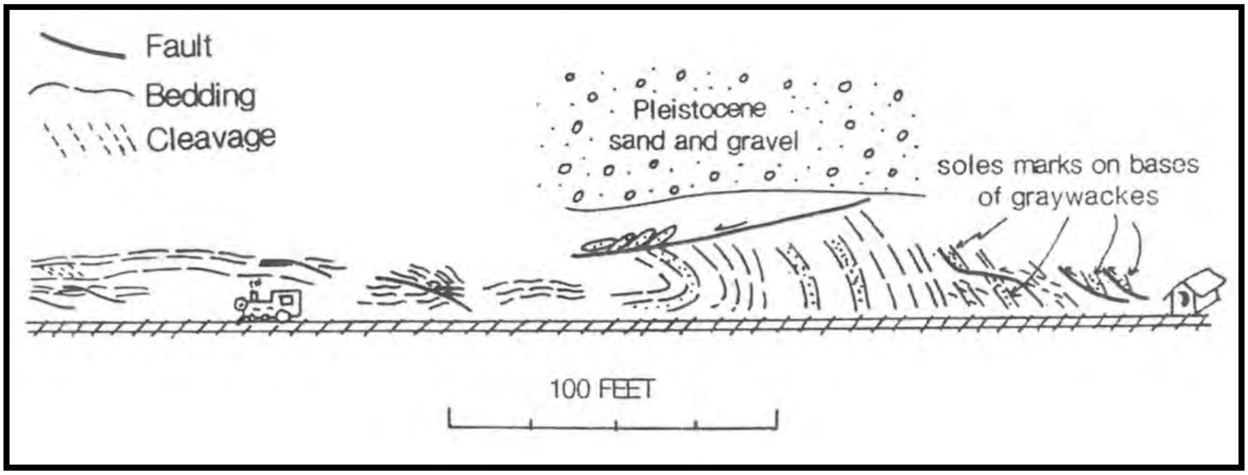

Figure 12. Field sketch (looking to north) of faulted overturned syncline along old Erie (now Norfolk Southern) Railroad at the east portal of Otisville Tunnel (Epstein and Lyttle, 1987, fig. 17).

Figure 13. West-verging, overturned (recumbent) syncline predominantly in sandstone on the north side of the cut at the east portal of the Otisville Tunnel.

Figure 14. The west-verging overturned syncline as expressed in shaly Martinsburg strata on the south side of the cut. Note the overlying west-dipping fault, movement on which is presumably to the west (see Figure 12).

Figure 15. Steeply dipping, overturned Martinsburg beds with sole markings on the north side of the tracks near the east end of the cut. Attitude of bedding is N25E/62 SE (overturned). Jeff Chiarenzelli for scale.

Figure 16. Groove and flute casts on the base of overturned Martinsburg sandstone bed at

Figure 17. Shallow load casts on the base of overturned Martinsburg sandstone bed at Figure 15 locality.

Figure 18. Large load casts on thick overturned Martinsburg sandstone bed at Figure 15 locality. Attitude of bedding is N25E/62 SE (overturned).

Figure 19. Cliffs of Shawangunk conglomerate at crest of Shawangunk Mountain high above the west portal of the Erie Railroad tunnel at Otisville and just north of the earlier rock cut through the wind gap.

Figure 20. West portal of Erie Railroad tunnel at Otisville (GPS 41°28'41.6"N/74°33'19.9"W). Note outcrop of Shawangunk conglomerate to left of portal. The inscription reads "19—Otisville—08," the year of completion of the tunnel.

overhead (Figure 19). Bedding in the Shawangunk quartzite on the north side of the tracks at the portal (Figure 20) strikes N47E and dips 45 NW. The tunnel is lined for ~100 ft directly in from the concrete portal (Figure 21), then unlined for ~750 ft (~230 m). The unsupported rock bore apparently extends to some point just west of the Shawangunk-Martinsburg contact, with concrete and corrugated metal lining from there through the Martinsburg to the east portal.

The Otisville Tunnel remained in the hands of the Erie Railroad until 1960, when the financially strapped Erie merged with the Delaware, Lackawanna and Western Railroad to form the Erie-Lackawanna Railroad. In 1976 The Erie Lackawanna became part of Conrail; and finally in 1999, on the split up of Conrail, the Norfolk Southern Railroad took over the line through the tunnel (Wikipedia, 2011, 2012a, 2012e). In 2003 the Metro-North Railroad began leasing this "Port Jervis Line" for commuter service from Suffern to Port Jervis, NY.

Figure 21. Unlined west part of the Erie Railroad tunnel at Otisville. The Shawangunk conglomerate here forms a ragged, but solid, arch that does not require lining.

NOTE WELL: Metro North runs frequent New York-bound and Port Jervis-bound trains every weekday, as well as on weekends. This is in addition to the Norfolk Southern freight trains operating on the tracks (Wikipedia, 2012d).

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Acknowledgments

Inners and O'Hara gratefully thank Dave Valentino and Jeff Chiarenzelli for granting us a few hours off from our rigorous responsibilities with the SUNY Oswego Delaware Valley Geologic Field Camp to examine the Martinsburg cuts at the east portal of the Otisville Tunnel in late May 2012.

Appendix—Structural Data from Cut in Martinsburg Formation at East Portal of Otisville Tunnel (measured by A. O'Hara)

Overturned Bedding

Strike	Dip	Dip direction
040	47	E
018	42	E
046	52	E
022	54	E
010	67	E
022	62	E
027	71	E
023	68	E

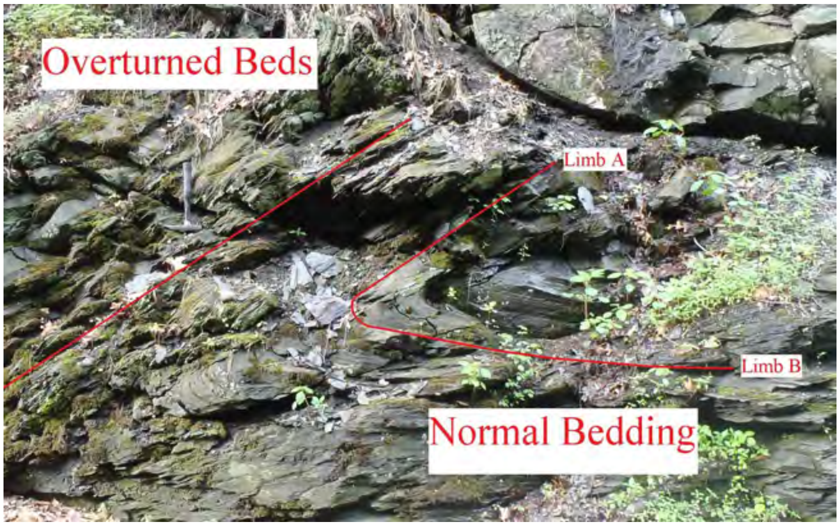
Fold

Limb A

Strike	Dip	Dip direction
036	36	E

Limb B

Strike	Dip	Dip direction
030	02	E



BLUE MOUNTAIN BOULDER COLLUVIUM

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Introduction

Blue Mountain is a unique feature in the geology of PA. The mountain forms a Ridge and Valley Province physiographic boundary that separates the Great Valley Section from the Appalachian Mountain and Blue Mountain Sections to its north. Blue Mountain (BKM), called Kittatinny Mountain east of Wind Gap, extends southwestward from the Delaware River to the Maryland state line and is broken only by several water gaps that cut through the mountain. This trip is concerned with the mountain only from the Schuylkill River northeastward and this discussion will focus mainly on the mountain a few miles southwest and northeast of the Lehigh River.

The crest of BKM is underlain by the Silurian age Shawangunk Formation, a unit of mixed rock types, but of particular importance are white sandstones and conglomerates that are the most erosion-resistant rocks in PA. Southwest of the Schuylkill River, and particularly in the Appalachian Mountain Section, these rocks are called the Tuscarora Formation (TF), or more commonly, the Tuscarora quartzite. Considerable information on the SF is presented in this guidebook and an excellent reference is Epstein and others (1974) and the several Epstein and Epstein references cited therein. A simplified geologic map of PA shows the Shawangunk and Tuscarora (S-T) as one continuous unit from the Delaware River to Maryland (Figure 1).

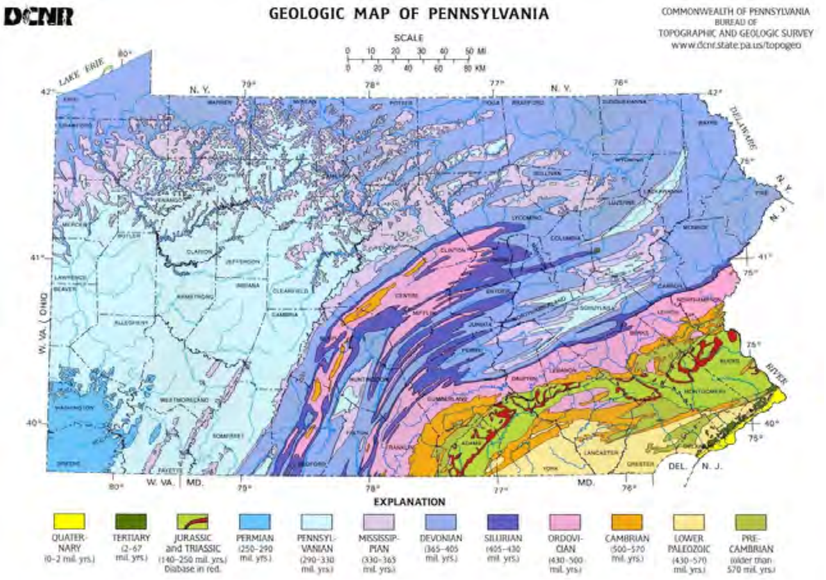

Figure 1. Simplified geologic map of PA. Copied from PA Geological Survey post card.

Sevon, W.D., 2012, Blue Mountain boulder colluvium, *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. 130-138.

East of the Susquehanna River, the S-T is exposed only on BKM because folding during the Alleghany orogeny put the S-T at considerable depth and it does not outcrop again in PA. In the Appalachian Mountain Section of the Ridge and Valley Province SW of the Susquehanna River, the TF forms the crests of several ridges as the result of anticlinal folding that brings the rock unit to the surface.

The Rocks

The rocks that comprise the south-facing slope of BKM above the unconformable contact with the underlying shales of the Penn Argyl Member of the Martinsburg Fm. (MF) are those of the Shawangunk Fm. (SF). The contact of the SF and MF is topographically defined by a marked change in slope from steep (SF) to gentle (MF) (Figure 2). The rocks of the SF comprise four members that are, in descending order, the Tammany, Lizard Creek, Minsi, and Weiders. All of the members contribute to the south-slope colluvial deposits, but the lower three members, and possibly mainly the lower two members, contribute the most. The Lizard Creek is the thickest member at 1,225 ft (373 m) at the Lehigh River water gap and frequently the crest and/or the upper south slopes of the mountain. The unit consists of shale, siltstone, sandstone, conglomerate, calcareous sandstone, and scattered red beds. Bedding thickness is variable and the various lithologies are intermixed.

Figure 2. Blue Mountain steeper BKM slope underlain by SF contrasting with gentler slopes developed on the MF, here defined by greener leafing-out trees.

The Minsi Member consists dominantly of white, planar-bedded to cross-bedded conglomeratic quartzite with variable bedding thickness. Some scattered, 0.5-3 in. (1.3-7.5 cm) thick, argillite beds occur. The unit is 225 ft (68.6 m) thick at Lehigh River water gap.

The Weider Mbr. consists dominantly of white, cross-bedded, planar-bedded, and massive conglomerate and quartzite. The conglomerates are up to 3 ft (0.9 m) thick. The quartzite occurs in 1-6 in. (2.5-15 cm) thick beds. About 3 percent of the member consists of thin argillite beds. The member is 220 ft (67.1 m) thick.

All of the members have abundant bedding-normal joint planes that were formed during the Alleghany orogeny. Figure 3 shows a large outcrop of SF on the east side of Lehigh River water gap. Both bedding and joint planes are apparent. The spacing of the planes is suggestive of the size of the boulders and blocks that result from breakdown of the outcrop and become the surface debris. The crest of the mountain and much of the outcrop is Lizard Creek Mbr. The lower right part of the outcrop has a prominent, laterally continuous, white, massive unit that is

Figure 3. SF sandstones and conglomerates on the east side of the Lehigh River water gap. BKM crest and much of slope is Lizard Creek Mbr. Lower white ledge is Minsi Mbr.

Figure 4. Remnants of SF outcrop at crest of BKM now broken into boulders and blocks.

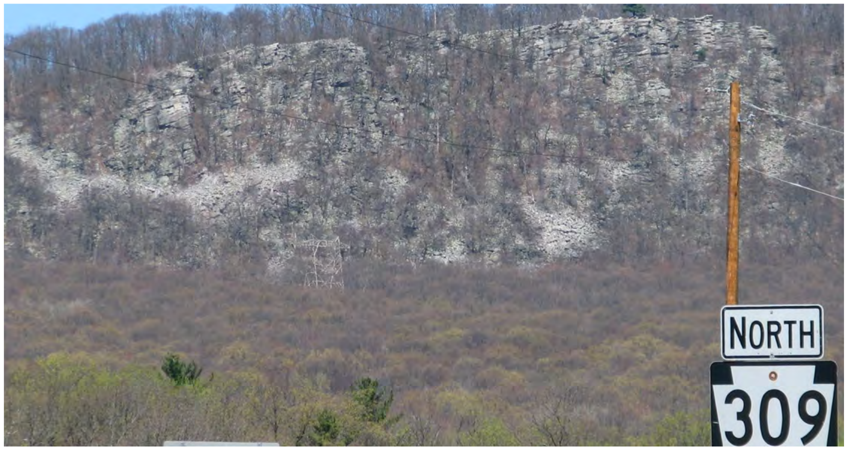

Figure 5. Large area of SF outcrop just east of where BKM is crossed by US Rte 309. Best exposed large area showing features. Note bedding and fracture planes and the large amount of BC on slope.

Figure 6. BC on the upper steeper slope of BKM where no GLs occur.

the Minsi Mbr. These rocks plus the underlying Weiders Mbr. are the source of much of the rock that covers the south slope of BKM.

Boulder Colluvium

The south-facing slopes of BKM are covered with abundant rock debris called boulder colluvium (BC). This BC results from the physical breakdown of rocks of the SF into boulders (rounded to subrounded, >10 in. (256 mm) diam.) and blocks (angular to subangular, > 10 in. (256 mm), and generally larger than nearby boulders) of various size controlled by the variable spacing of the bedding and joint planes. Figure 4 shows an area at the crest of BKM where an outcrop has been totally broken down at the surface by physical processes. Figure 5 shows a very large area of mixed outcrop and BC lower on the BKM slope. Much of the BKM slope is covered with too much vegetation for the large extent of BC to be readily apparent.

Physical breakdown of the SF was intense during the Pleistocene when periglacial activity dominated the non-glaciated areas of PA. Such activity was definitely associated with the pre-Illinoian, Illinoian, and Late Wisconsin glaciers that crossed NE PA and crossed BKM in different places NE of the Schuylkill River. The southwesternmost crossing was that of the pre-Illinoian glaciation that crossed BKM southwest of the Lehigh River and deposited glacial materials in the New Tripoli quadrangle (Braun, 1996). Subsequent BKM glacial crossings were farther NE. The closeness of glacial ice intensified the periglacial activity in nearby areas and resulted in the abundance of BC in areas close to but SW of the ice crossing, e.g., Figure 4. In areas where the ice crossed BKM, much material was removed by the ice and the resultant amount of BC is less.

On the steeper upper BKM slopes the BC forms a relatively uniform covering of boulders and blocks with essentially no surface form other than the irregularity caused by variations in size of the rocks (Figure 6). The lack of surface morphology results from downslope movement caused primarily by gravity. This all changes when the contact between the SF and MF is reached. The shallower slopes associated with the MF impeded gravity caused flow and periglacially aided down-slope flow took over. The periglacial flow involved water and ice as well as gravity.

This periglacial flow, working through freeze and thaw action, gradually moved debris down the lower gradient slopes. As it did so, it created a lower angle slope that varied from very low angle to nearly flat to slightly depressed in places. The debris accumulated as an elongated mound at the front of the moved mass. The frontal mass had either a relatively straight or lobate front. The front of the lobate mass was steeper than the surface in front or behind. The individual elongate mass is called a 'gelufluction lobe' (GL).

The fronts of the GLs are only a few feet high and can be missed as significant geologic features, particularly in wooded areas, by one who does not know their significance. Figure 7 is a LIDAR image of part of the New Tripoli quadrangle showing the fronts and backs of a number of GLs, both moderately to very lobate. The dark area at the north side of the GLs is the steep slope of BKM underlain by the SF. The GLs occur on the slopes of the MF.

Figure 8 shows the subtle front and top of a GL with almost no surface boulders. The angle of the frontal slope of the GL shows best near the left margin of the photo. A similar GL front is shown in Figure 9. The boulders and blocks in these GLs by the finer grained matrix material. In contrast, Figure 10 shows the front of a lobe composed entirely of boulders and

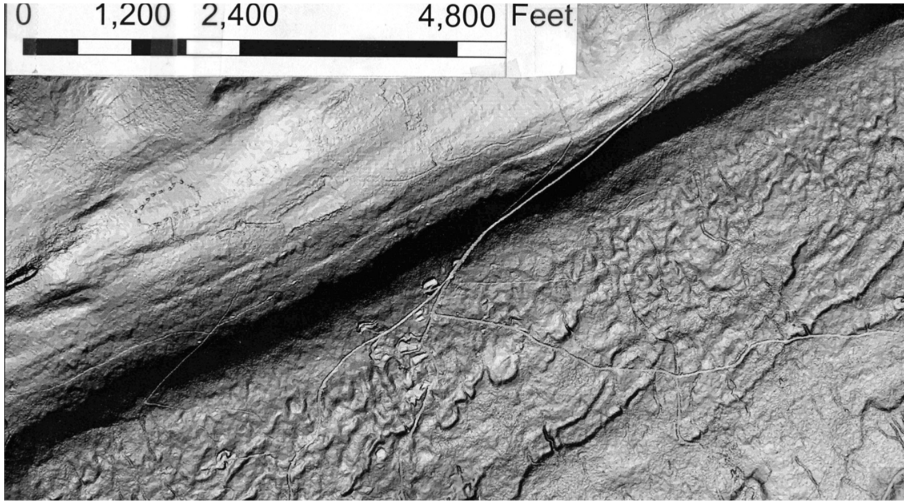

Figure 7. LIDAR image of part of the New Tripoli quad. Showing moderately to very curved GLs. Note the well defined GL fronts. Dark area north of GLs is the BKM south slope.

Figure 8. Front and top of a GL with almost no exposed boulders or blocks. Slope of GL front best shown on the left side of the photo.

Figure 9. Front end and laterally continuous top of a GL with no exposed boulders or blocks.

Figure 10. Front end and crest of a GL composed totally of boulders and blocks. Front slope both on the left and towards the viewer.

Figure 11. Typical surface of the north-sloping side of BKM showing minimal surface debris and no BC similar to that on the south-facing side of BKM.

blocks. Note the lack of boulders on the surface in front of the GL. That area presumably contributed its rocks to the next down-slope GL.

Hopefully this discussion, the LIDAR image, and the photographs will make these topographic forms more clear and recognizable when encountered in the field.

Mention should be made of the north-facing slopes of BKM. These slopes are dip slopes that parallel the slope of the SF as it disappears underground. The slopes are underlain in part by the uppermost part of the SF and for the most part by the overlying Bloomsburg Fm. (BF). Because of the dip slope and the general softness of the BF red sandstones, siltstones, and shales, the amount of debris on the north-facing slopes is minimal and the debris is much finer grained than that on the south-facing slopes of BKM and BC is absent. Figure 11 shows a fairly typical example of the nature of that surface.

Devil's Potato Patch

The flat area of the floor of Little Gap in BKM NE of the Lehigh River is a boulder field called the Devil's Potato Patch. Braun (1997) calls this an area of boulder colluvium, which it is in sense, but, because of the flatness and breadth of surface, I prefer to call it a boulder field. Figure 12 shows well the flatness, width, and partial length of the accumulation of boulders. Figure 13 shows the angular character of the blocks and boulders as well as the almost total lack of rounding of any of the rocks. The rocks are all derived from the slopes on the sides of the gap.

The boulders and blocks were physically broken away from the SF and moved into their present position periglacially. This had to have occurred after the gap itself was eroded and after the pre-Illinoian glaciation had occurred. The Illinoian and Late Wisconsin glaciations were sufficiently close to have had considerable periglacial affect on the gap area.

Noticeable in Figure 13 is the vertical to sub-vertical orientation of many of the elongate boulders/blocks. Why? I don't really know, but I suggest that when an elongate rock mass reached the bottom of the side slope through gravity processes, it became encased in ice and was moved onto the boulder field in that orientation. The same would hold true for rocks in

Figure 12. View of the Devil's Potato Patch showing flatness, length, and general nature of the boulders and blocks.

Figure 13. Close-up view of the boulders and blocks forming the Devil's Potato Patch. Note the vertical orientation and angularity of many of the blocks.

other orientations. Note in both Figures 12 and 13 the lack of rounding of any of the rocks and the lack of any visible matrix material. This angularity is a total contrast to the Hickory Run Boulder Field (Hickory Run State Park, Carbon Co., PA, about 18 mi. (29 km) north of Little Gap) where rounding of boulders is extensive (Sevon, 1990). Obviously, the two boulder fields have considerably different histories.

Origin of Blue Mountain Wind and Water Gaps in the Field Trip Area

In 1979 I pointed out the direct correlation between the position of water gaps in BKM and the former position of Paleozoic input centers through which came the sediment that filled the Appalachian basin (Sevon, 1979). Despite the temptation to suggest a simple drainage reversal following the Alleghany orogeny, the whole history of the Mesozoic discounts that idea. Instead, the best explanation is Mesozoic and post-Mesozoic headward erosion by streams that originated both on the north side of the Birdsboro basin (Faill, 2003) and on the new coastal margin of North America following its separation from Africa.

The first headward-eroding stream was the Triassic precursor to the Schuylkill River that eroded into the Anthracite basin that was once up to 5.9 mi. (9 km) higher as the result of Alleghany orogeny overthrusting (McLachlan, 1985; Faill, 1998). This headward erosion brought sand and gravel southward into the north part of the Birdsboro basin and formed the Hammer Creek Fm. (Glaesser, 1966; Faill, 2003). Although basically unstudied for correlation to this concept, late Triassic Birdsboro basin conglomerates marginal to both the Delaware and Susquehanna Rivers suggest that headward erosion by those streams may also have been underway at an early date.

Why have the headward-eroding streams chosen to cut through BKM at sites correlative with the former sediment-input centers where the hardest and coarsest rocks, sandstone and conglomerate occur? This is a particularly relevant question because most if not all, of these coarser, harder rocks, e.g., the Pottsville on the Schuylkill River, the (in descending order) Duncannon, Clarks Ferry, Berry Run, and Packerton Mbrs. of the Catskill Fm. on the Lehigh River, and the SF on the Delaware River, are central to these former input centers and change laterally through facies change to finer grained, more erodible rocks. To me, the only logical explanation is the erosion-susceptibility of the combination of bedding planes and orogenically produced fracture planes that have greatest concentration in the coarser and harder rocks that occur in the former sediment-input centers.

Wind gaps in the field trip area occur only at Little Gap and Wind Gap, the site from which the geologic term originated. There seems to be little doubt that streams once flowed through each of these gaps and that these streams were long ago beheaded by tributaries to larger streams on the north side: Aquashicola Creek, tributary to the Lehigh River in the case of Little Gap, and Cherry Creek, tributary to the Delaware River, in the case of Wind Gap.

Final Words

I hope that this commentary and particularly some of the illustrations will be an illumination of some of the geology that occurs not only here in this field trip area, but also in other parts of PA. The gelufluction lobes are widespread and particularly noticeable one you know what to look for. All the slopes of BKM and those of South Mountain in Franklin and New Cumberland Counties are very demonstrative of these features.

The trip does not stop at the Devil’s Potato Patch, but it does pass through Little Gap and the boulder field can be seen in passing. There’s a good parking area on the SW side if you want to come back.

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KARST SUBSIDENCE PROBLEMS ALONG THE BUSHKILL CREEK, NORTHAMPTON COUNTY, PENNSYLVANIA

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Introduction

During the period 1999 through 2006, both banks and the floodplain of the Bushkill Creek in the Stockertown area (Figure 1) were affected by an inordinate amount of sinkhole activity. Consequently, existing highways and nearby residential areas were impacted

Figure 1. The Stockertown area; Nazareth 7.5-minute quadrangle. Coordinates for the former SR 2017 bridge at the Bushkill Creek, 40° 44'55.51", 75°15'44.43". BC = Bushkill Creek, BW = Brookwood Community, ST = Stockertown, LBC = Little Bushkill Creek. North is up.

The story is a complex weave of karst geology, surface mining, hydrogeology, stream geomorphology, engineering, land development and the weather. Combine all these variables with a handful of geo-technical firms, state and federal government agencies, municipal government officials, legislators, the general public and the story takes on serial proportions.

Although not a stop in this year's Field Conference, the events that took place during this time period provide an interesting aside into the geotechnical problems associated with karstic subsidence. It is suggested that what has been observed along the Bushkill can serve as a model case study for the geologist and engineer.

Regional Karst Geology

The Bushkill Creek has its headwaters to the north at Blue Mountain, a ridge of siliciclastic Lower Silurian-aged bedrock. As it flows south of the ridge, the creek crosses Ordovician slates and shales of the Martinsburg Formation then across mixed shales, shaley limestone and limestone of the Jacksonburg Formation, and finally across interbedded

Kochanov, W.E., Karst subsidence problems along the Bushkill Creek, Northampton County, Pennsylvania, *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. 139-152.

limestone and dolostone of the Epler Formation (Aaron, 1971; Drake, draft; and Epstein, 1990). A generalized geologic map is shown in Figure 2.

Bedrock structure is complex. Bedding generally strikes in an east-west direction with variable dips that reflect low to high-angle folding. High-angle joints strike north south with variance of 20° to 30° towards the east. One feature worth noting is the "Stockertown Fault," or fault complex (Epstein, 1990). It is interpreted as one of a series of imbricate folded thrusts in this general area (Epstein, 1990). Based on the east-west strike orientation of faulting observed in the nearby Hercules limestone quarry, the general straight-lined nature of the Bushkill Creek, and borehole data (SAIC, 2002), it is suggested that the "Stockertown Fault" or fault complex may extend along the Bushkill Creek from the Hercules Quarry to the Little Bushkill.

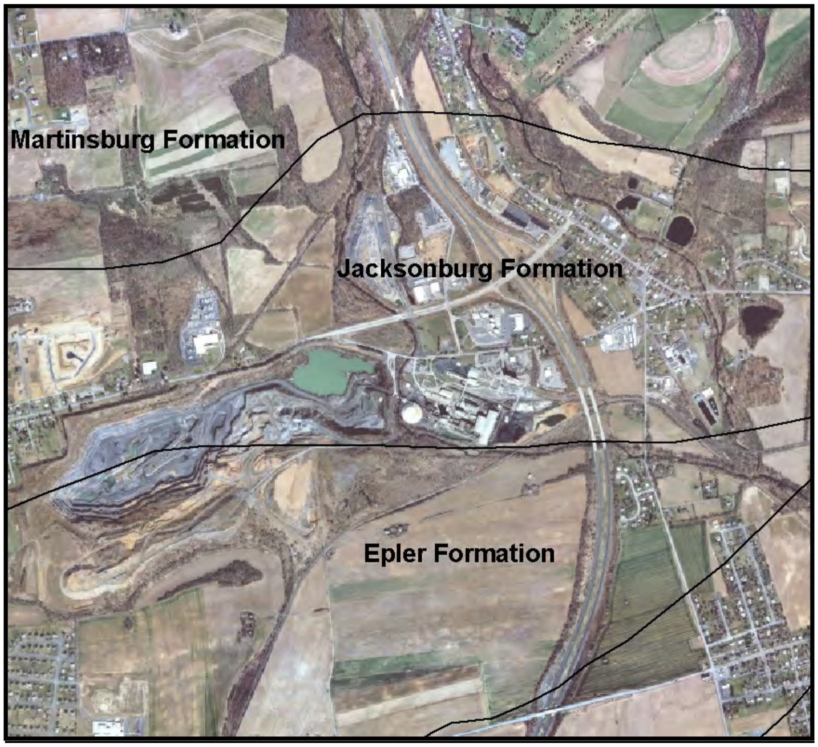

Figure 2. Generalized geologic map of the Stockertown area. Geology from Aaron (1971) and Drake (unpublished).

Surficial geologic mapping by Braun (1996) shows pre-Illinoian glacial till and lag deposits over much of Northampton County. The tills tend to lie in the often straight-lined drainages that are oriented with regional bedding and joint patterns (Kochanov, 2005). Till is commonly exposed within the channel and in sinkholes along the Bushkill Creek between the Hercules Quarry and the Little Bushkill Creek (Figure 3).

Surface Features

The topographic surface of the limestone belt in eastern Pennsylvania exhibits a relatively low-relief karstic surface. Surface depressions are the dominant features ranging upwards of 328 ft (100 m) in diameter and 3 to 10 ft (1 to 3 m) in depth. This low, undulating surface is the result of being covered by a variable thickness of alluvial, colluvial, and glacial sediments making it appear "flat" in many areas. Coupled with land disturbances from urban and rural activities, surficial evidence for karst subsidence features can be difficult to discern from the ground level.

Statistically the Ordovician Epler Formation, along with the Cambrian Allentown Formation, account for 85 percent of recorded sinkholes (Wilshusen and Kochanov, 1999) and have the highest number of karst surface features per unit area in the eastern third of the Great

Valley Section (Kochanov, 1993). The Ordovician Jacksonburg Formation, on the other hand, has the lowest rate per unit area.

Sinkholes on average can range in size from 3 to 22 ft (1 to 7 m) in diameter and the same in depth. Bedrock is rarely observed within sinkholes inferring that the sink structures are the result of voids propagating upward through the regolith.

Figure 3. Sinkhole along the north bank of the Bushkill Creek showing coarse glacial till (T) overlain by finer alluvial sediment (A)

Although the Epler Formation is highly karstic, the degree of karstification can vary regionally. Density patterns on recent mapping shows that the Epler can exhibit areas with a high density pattern yet have low-density areas or areas lacking observable karst surface features within the same outcrop belt (Kochanov and Reese, 2003; Reese and Kochanov, 2003). Even though lithologic composition is an important variable in karst development, structural deformation is the key component in determining the pathways for groundwater movement. It is the orientation of bedrock discontinuities that directs the groundwater and thus determines areas of preferential dissolution. Additionally, dolostones are more brittle than limestone and would be more fractured as a result of structural deformation, allowing more groundwater to move through those discontinuities. This can make some dolostones more karstic than limestones even though the limestone may be more soluble. The interbedded nature of the Epler and Allentown, where more soluble limestone is in contact with more fractured dolostone, would also help to direct and enhance the carbonate dissolution process. The geographic distribution of these limestone-dolostone sequences could account for the distribution pattern of sinkhole occurrences within the Epler and Allentown Formations throughout the Lehigh Valley.

In this section of the Lehigh Valley, the carbonate belt straddles the mapped glacial border. This raises the question as to whether identified surface depressions are karstic or glacial/periglacial features. Braun (1994, 1996) discusses surface depressions occurring within the slate and shale belt of Lehigh County both inside and outside the glacial limit inferring that they are periglacial features. Smaller-scale periglacial depressions have also been observed superimposed atop larger-scale karstic dissolution features in the carbonate belt of the Lehigh Valley (Braun, 1996). These periglacial depressions however, commonly contain wetlands and perennial ponds and differentiate them from the surrounding karst landscape.

Records based on marine oxygen isotopes and radiometric dating of terrestrial volcanic and glacial deposits suggest that as many as ten glaciations may have approached the late Wisconsinan terminus and four probably reached beyond that limit (Braun, 1999); the late Wisconsinan advance destroyed nearly all traces of previous advances right up to the late Wisconsinan terminal margin (Braun, 1999).

With this many periods of glacial advance and retreat the karst surfaces that had developed during warmer, interglacial periods probably had been eroded away. However, with the rise and fall of local and regional base levels associated with these glacial/interglacial periods, *subsurface* conduits were probably preserved and continually modified with regard to connectivity, extent, and the amount of sediment moving through the conduit network.

These conduits are static features as chemical and mechanical weathering and erosional processes continually deepen and widen these zones over long periods of time. Water pathways through the regolith may be initially small, filling the interstitial spaces between soil granules and within macropores. Over the course of time they continually change course and evolve into more complex water insurgence systems linking with other pathways that eventually lead to the conduits developed in the soluble bedrock. These insurgences mimic the function of fractures and bedding partings in the carbonate bedrock in that they provide a means for water to flow (Kochanov, 2005).

Ponors, or swallow holes, can be considered the end result of this linkage process between surface drainage and the water table. Ponors are dynamic fixtures in the karst plumbing system and vary in size, shape and location within the regolith, changing with the seasonal fluctuations of groundwater and insurgent water. One of the most common forms is the alluvial ponor as discussed by Milanovic (1981) where water is gradually lost along the length of a surface stream through the unconsolidated sediment lining the streambed.

The Bushkill Creek is an alluvial ponor. A significant percentage of the stream waters is lost through alluvial and glacial sediments that cover a well-developed karstic bedrock surface (Kochanov, 2005). Monitoring data concluded that the Bushkill Creek was losing approximately 70 percent of its water between the SR 33 bridges and the SR 2017 bridge (D. Zeveney, U.S. Army Corps of Engineers, pers. comm.).

Sinkhole History

Historical evidence for sinkholes along the Bushkill Creek can be traced from aerial photographs as far back as the late 1930s. Perlow (1985) documented sinkholes along the SR 33 corridor during its construction, as well as surveys for the Lehigh Valley by Kochanov (1987).

Sinkholes began to be reported by local residents along the stream and within the floodplain of the Bushkill Creek in 1999. The main areas of occurrence were at the SR 2017 bridge, within the channel of the Bushkill Creek and along the south bank of the creek adjacent to the Brookwood Community.

In the fall of 2000, one residential property within the Brookwood Community had a large sinkhole open in the backyard with over $20,000 in remediation costs. Continued subsidence eventually forced the residents to abandon the house. Over the course of the next few years, sinkholes continued to open within the Creek and along the banks of the stream eventually compromising the SR 2017 bridge and undermining the approach roadway to the bridge (Figure 4). Individual sinkholes around the 2017 bridge coalesced to make one large subsidence area (Figure 5). Sinkhole activity was not limited to the 2017 area but also upstream and in the medial area of SR 33. In April 2001, large sinkholes opened along the south bank of the Bushkill with a portion of the Norfolk Southern railroad bridge being damaged.

During January of 2004, sinkhole activity focused around the abutments of the northbound span of SR 33 bridge. It was during this time that the SR 33 bridge suffered serious structural

Figure 4. A—A large sinkhole on the south bank of the Bushkill Creek in 2001; B—The SR 2017 bridge in October 2002.

damage, was razed and a new span constructed. In a proactive measure, the southbound span was also replaced. Replacement cost exceeded $30 million.

Concurrent with the damages to the bridges, a small drama was unfolding along the north bank of the Bushkill Creek near SR 33. Two sinkholes opened, coalesced, and created a nick point along the bank allowing the Creek to develop a small meander bend (Figure 6).

Figure 5. Coalescing sinkholes along the SR 2017 bridge in 2002. Photo courtesy of the Brookwood Group.

The formation of the small meander loop was intriguing and resulted in much speculation as to the end result of the stream breach. It was hypothesized that the stream might be attempting to revert back to a previous channel configuration. This goes back to the construction of SR 33 (late 1960s through early 1970s). At that time the channel of the Bushkill Creek was split around a mid-stream gravel bar (Figure 7A). As part of the construction activity, the southern channel of the Bushkill was filled and the entire stream flow was directed into the northern channel (Figure 7B). The hypothesis was that the stream would play out a game of connect-the-dots, where the the stream would link

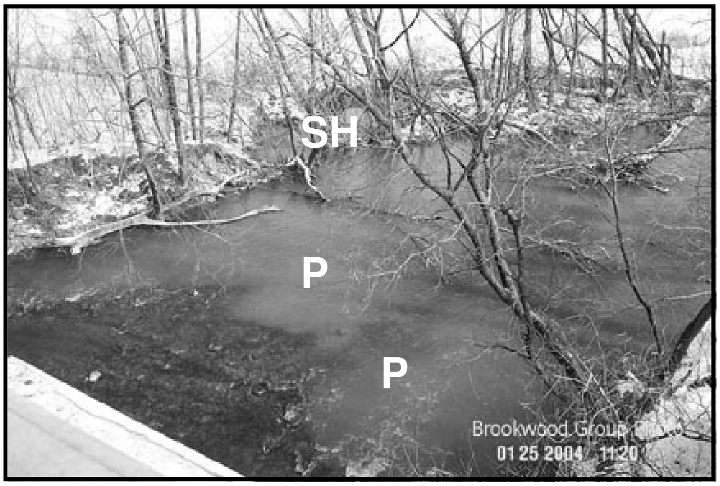

Figure 6. View from the SR33 bridge in January, 2004 showing the location of sinkhole pools (P) in the bed of the Bushkill Creek. A sinkhole (SH) had opened along the bank and has started to divert water from the stream. This diversion helped to form a small meander loop. Photo courtesy of the Brookwood Group.

Figure 7. A—Aerial photograph from 1939 on the left shows the island bar on the Bushkill Creek with the channel split circumventing the island; B—The 1971 photo on the right shows the location of SR 33 and the modified channel of the Bushkill Creek. Flow of the Bushkill is from left to right, north is up.

to new and existing sinkholes, starting with those in the field and finally connecting to sinkholes at the SR 2017 bridge. By doing so it would create a new island and have the split channel reform. What really happened, however, was that the stream did connect up with sinkholes but the stream ended up going in a different direction (Kochanov, 2005). During the summer of 2004 the remnants of Hurricane Ivan dumped approximately 7 in (18 cm) of rain in the Northampton County area. The resulting flood wiped out the remaining meander "neck" creating a new recessed bank edge (Figure 8A). This recession brought the stream closer to an existing sinkhole that was located in the field (Kochanov, 2005).

In December of 2004, a breach developed connecting the sinkhole in the field and the Bushkill channel (Figure 8B). In the following week, additional sinkholes opened in advance of the prograding stream as the stream was pirated across the field. The stream had nearly advanced across the field and threatened to link up with one recently activated sinkhole near the SR 2017 highway and potentially affect the approach to the SR 2017 Bridge (Figure 8C).

A thin finger of land was serving as a partial barrier during these events (Figure 8D). It was plain that if this neck of land failed then the major flow of the Bushkill would have followed the route across the field. This prompted a rapid response to temporarily fill in the new stream segment (Figure 9) to prevent further deterioration of private property and potential damages to SR 2017 (Hill, 2005). This action by the State Department of Environmental Protection put an end to the progradation of the Bushkill Creek across the field at this time and put a stopper in this interesting case of sinkhole piracy.

Discussion

The overriding thought throughout this case history is what was the primary cause for the dramatic sinkhole occurrences to occur in this particular area? A number of variables come into play, each adding their own weight at any one time.

One simple version is that:

1. The area is underlain by carbonate bedrock. Sinkholes occur in areas underlain by carbonate

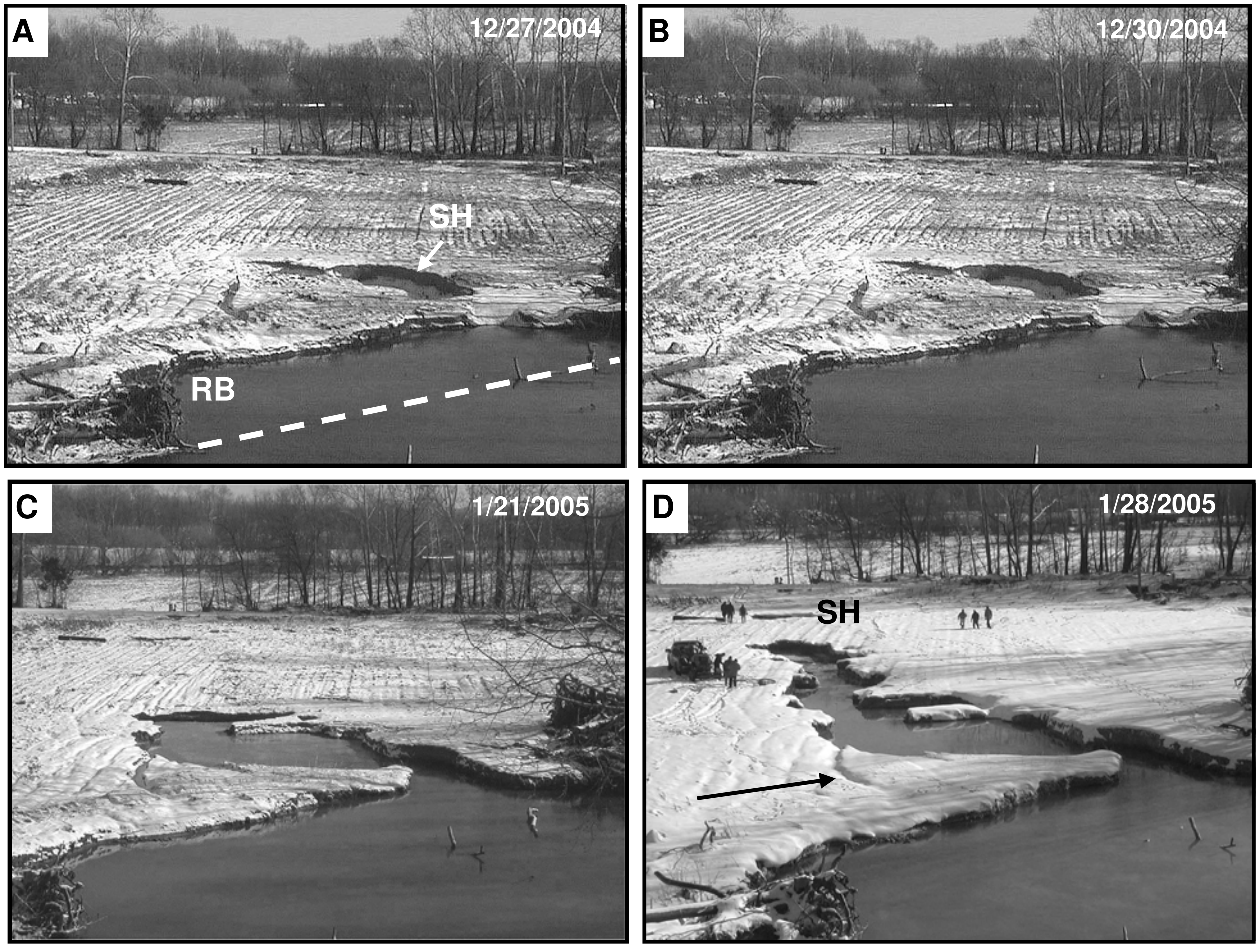

Figure 8. Photographic sequence showing the progradation of the Bushkill Creek across the field. A—Note the recessed bank (RB) and the nearby sinkhole (SH) in the field; B—Shows the breach in the bank (arrow) allowing stream water to enter the sinkhole; C—Shows the beginning of stream progradation across the field; D—Shows the stream almost to another sinkhole (SH) and SR 2017 (line at the top of SH letters). Also note in D the finger of stream bank (arrow) serving as a tenuous barrier. The outline of curving tension cracks can also be seen (arrow). All views are looking east.

Figure 9. Drained segment of the "new" Bushkill channel. It was subsequently filled with soil and shot rock as part of the rapid response plan.

bedrock. It was just this areas turn on the big wheel.

Evidence from borings and geophysical surveys indicate that a deeply weathered zone exists in the vicinity of the SR 33 bridge. In addition, borehole data along the Bushkill Creek show depths to bedrock ranging from 7 to 50 ft (2 to 15 m) indicating a pinnacled bedrock surface. For example, on the northbound segment of the SR 33 bridge, the depth to bedrock ranges from approximately 80 ft (25 m) on the south side of the creek to over 330 ft (100 m) on the north side of the creek (K. Petrasic, PDOT, pers. comm.). Sinkhole distribution is reflected in the regional attitude of bedding and joints.

Borehole camera views filmed by PA DEP showed a cave invertebrate in monitoring well 3 located on the south side of the Bushkill along SR 33 at depths of approximately 100 ft (30 m) below stream level. Core from a borehole on the north side of SR 33 depths of over 425 ft (130 m) showed rounded limestone gravels similar to pebbles observed in cave streams (pers. obs.).

Add in the fact that the Bushkill is a losing stream between SR 33 and SR 2017, it is quite apparent that the area is karstic. But what was the trigger?

Much of Pennsylvania was in the grips of drought during the period September 1995 through November 2002. The drought years were followed by a period of above-normal precipitation. What is noteworthy was that the drought lasted beyond the onset of sinkhole activity along the Bushkill. Additionally, high precipitation events due to Tropical Storms Dennis (2 in [5.5 cm]) and Floyd (6 in [16 cm]) in 1999 were also coincident with the onset of sinkhole activity.

Drought conditions can exacerbate sinkhole development. As the soil dries out, clays will shrink with desiccation and cracking of the soil would result in the development of more pathways for surficial water to enter the subsurface. In addition, drought conditions would have depressed the water table.

Depending on the cohesive properties of the regolith, infiltrating surface water can play an important role in promoting instability. Residual sediment typically has minimal interstitial cement holding the grains together and would have a low liquid limit. As water comes into contact with such loosely cemented material, cohesion is lost and liquefaction occurs. This is commonly observed during drilling where fluids are often lost at the soil-bedrock interface where the residual rind from the dissolution process is typically encountered. In another instance, the rise and fall of a potentiometric surface could also increase and decrease soil pore pressure and the effective stress between soil particles causing liquefaction and create sinkholes.

Over time, dewatering and the lowering of the potentiometric surface (i.e., during a drought) creates a temporary base level as equilibrium is reached. Sinkhole activity is generally low during equilibrium phases. Sudden changes in this equilibrium, such as what occurs during extreme swings in precipitation amounts (i.e., dry to wet times), can be the trigger that affects the hydraulic gradient to such a degree that sinkhole activity is high until the next plateau of equilibrium is reached.

2. Mining activity was concurrent with the onset of sinkhole activity. The affected area was compromised by the cone of depression developed by pumping during the mining process.

Sinkholes and limestone quarries are as acid mine drainage and coal mining; one often occurs with the other. Connections between quarry operations and sinkhole occurrence has been discussed in the literature (Foose 1953; Knight, 1970; Foose and Humphreville, 1979; Newton, 1987; Kochanov, 1999; Langer, 2001).

Dewatering, or the removal of water from sediment, commonly occurs during mining. The high pumping rates involved with removing groundwater from a mine can lower the water table and increase the zone of influence for miles (kilometers). Changes in the potentiometric surface from pumping can affect hydrostatic pressure and in turn cause gradual or sudden removal of support for the land surface. As this support is removed, the land surface sags, creating a depression and increasing potential for collapse.

A nearby quarry (approximately 6,070 ft [1850 m] west of southbound SR 33) has been in operation since 1919 primarily mining the Jacksonburg limestone and argillaceous limestone. On an average they pump 20-25 million gallons per day (mgd) (76-95 million liters per day [mld]) ranging to 32 mgd (121 mld) during periods of high precipitation out of the active pit and return it to the Bushkill Creek (DEP, 2000). Hydrographs of the pumpage rates during the period of increased sinkhole activity indicate that there has been a steady increase in pumping over time (DEP, 2000). However, one would think that sediment-laden water would be observed in the water being pumped out of the quarry with each sinkhole collapse. This was not always the case and leaves room to speculate that sediment could be traveling in some other direction or simply that the finer sediment never made its way back to the quarry. The observation of cave invertebrates, cave-type of sediment observed in deep core returns, and significant water loss between SR 33/SR 2017, leaves the investigator with some degree of certainty that a subsurface conduit system of some undefined extent is present in the Bushkill-Brookwood-SR 33 area.

Two other quarries (~1.7 mi [~2.7 km] SW of the SR 33 bridge) were also operating during the same time period. It was felt that the cone of depression for the three quarries overlapped at some point but the precise location of the combined cone of depression was indeterminate (S. Hill, DEP, pers. comm.).

Although no direct hydrologic connection has been determined quantitatively by means of a dye trace, it is generally assumed that there has been significant impact from the nearby mining activity and that the water table has been lowered significantly in the vicinity of the SR 33/SR 2017 stretch.

Dewatering and the lowering of the potentiometric surface with an increase (or decrease) in pumping rates could create a temporary base level and somewhat artificial groundwater equilibrium. A disruption of this equilibrium by increased pumping could remove the hydraulic support of the land surface and cause sinkholes to occur.

3. The construction of SR 33 set the stage for sinkhole development at the SR 33 and SR 2017 bridges as well as the sinkholes between SR 33 and SR 2017.

It is interesting to note that the onset of sinkhole activity began in the area where the Bushkill channel had been modified through the construction of SR 33. It would appear that the change of the Bushkill channel had some influence on stream processes.

Straight banks are not the norm for any significant distance but can contain many of the channel features common to meandering streams (Ritter, 1986; Leopold and others, 1964).

Typically, straight reaches contain sediment that accumulate along alternating sides of the stream as alternate bars with the thalweg, or deepest part of the channel, migrating back and forth (Ritter, 1986). The sediment within the Bushkill channel is generally a poorly sorted mixture of sand and cobbles and the channel is reflective of the dynamics of the stream flow rate and volume. The base of the channel alternates with a series of shallow riffles and deep pools basically directing the flow of water from side to side of the channel as it flows towards the Delaware River (Kochanov, 2005).

Pools in the Bushkill appear to be directly linked to sinkhole development within the stream channel. Keller (1971) observed that that as discharge increases, the velocity in the pool approaches that of the riffle and from this he suggests that in bankfull discharge conditions, the velocity in the pool will exceed that of the riffle. During periods of high flow, the pools are scoured, with sediment being deposited on "high" reaches of the stream. These topographic highs correspond to places where bedrock is closer to the surface. As stream energy dissipates during the waning of a flood event, the coarser sediment falls out while the finer sediment is transported and deposited to the next pool.

Kochanov (2005) suggested that sinkhole pools in the Bushkill Creek have had a major impact on determining flow direction. Within the main streambed, a sinkhole can serve as a deflector, forcing the water laterally towards the banks as well as directing water downward within the sinkhole pool (Figure 10). Once deflected, erosional processes along the banks would be more focused. Changes in sediment pore sizes, such as what would be encountered with the poorly sorted glacial sediment, can result in more turbulent groundwater flow and enhance erosion. As the banks are undercut, connections are made to voids and other subsurface drainageways and promote new sinkhole development ahead of the prograding stream (Figure 11).

Within the channel pool, the downward deflection of water may increase the size of the sinkhole or shift its location through erosion. In the case of the Bushkill reach between SR 33 and SR 2017, sinkholes within the channel appeared to approach a certain maximum size, roughly 10 ft (3 m). Sinkholes within the stream channel went through cycles of opening and filling in with sediment over time (Kochanov, 2005).

Summary

Since the fall of 1999, increased sinkhole activity south of the Borough of Stockertown had resulted in significant damage to public and private property. To date, three houses, three highway bridges, one railroad support, hundreds of work hours plus materials for other related sinkhole remediation, stream monitoring, borehole drilling, geophysical testing, along with dozens of cookies courtesy of Aunt Sylvia, contributed to making this case truly unique.

In karst areas, it may take a relatively long period of time to set the stage for a subsidence event, and when it does occur, it can proceed rapidly. Aerial photography established that the catastrophic sinkhole that occurred in the Borough of Macungie in 1987 (Dougherty and Perlow, 1987; Kochanov, 1987b) was related to a large sinkhole that had been filled some 30 years earlier. Sinkholes can recur in the same location due to variables such as precipitation, water table fluctuations, surface drainage alteration, and repair methods (if applicable). In that instance, the large sinkhole noted in the 1964 aerial photographs was filled and subsequently farmed. It is unknown whether the historical account for this occurrence was recorded. It took

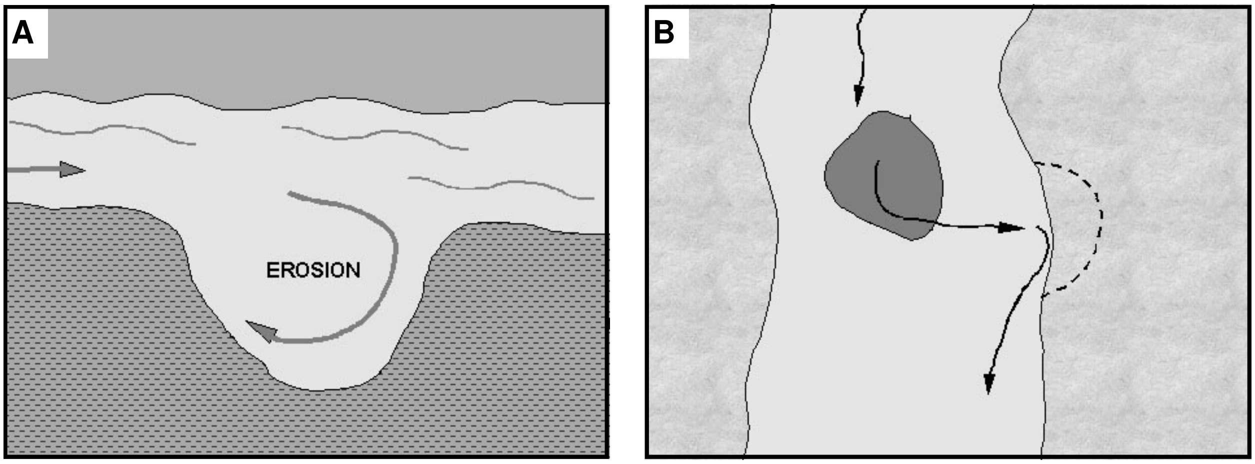

Figure 10. A sinkhole can serve as a deflector, forcing the water downward within the sinkhole pool (A) or directing water laterally towards the banks (B).

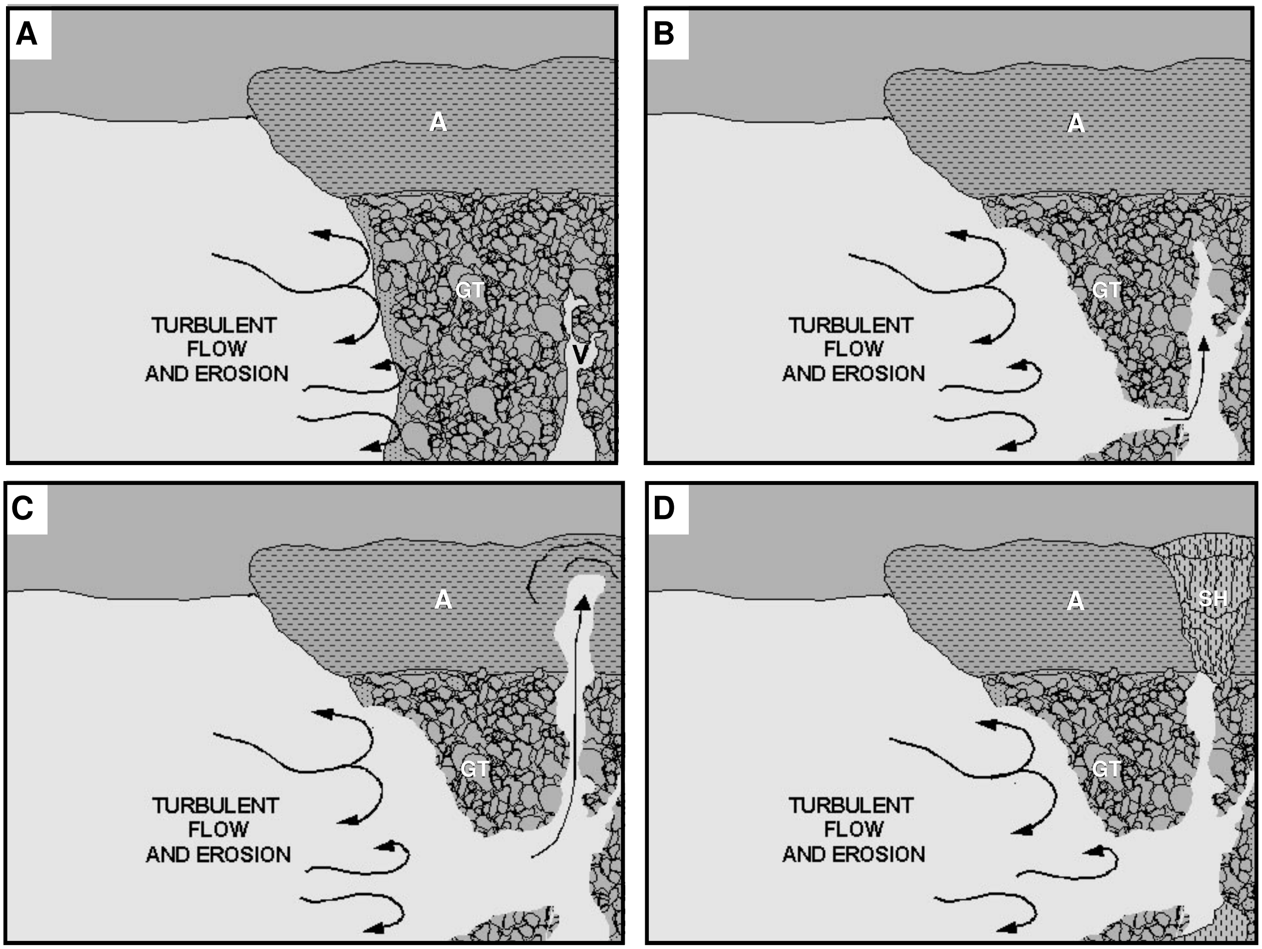

Figure 11. As stream water is deflected towards the bank and encounters poorly sorted glacial sediment (GT), more turbulent groundwater flow and enhanced erosion can occur. As the banks are undercut, connections are made to voids (V). Increased hydrostatic pressures (arrows) within pore spaces and within the voids can flush out sediment more easily and promote new sinkhole (SH) development.

decades for the sinkhole to be rejuvenated but when it did, it opened in a residential area and not rural farmland. Parallels could be made with the sinkhole activity at Stockertown. The construction of SR 33 and the modifications to the Bushkill channel occurred 25 years before the onset of the more recent activity. Mining surely had its influence as well as the impact of swings in precipitation amounts. It was probably a combination of factors that contributed to the Stockertown events, each adding their own weight at any one given time.

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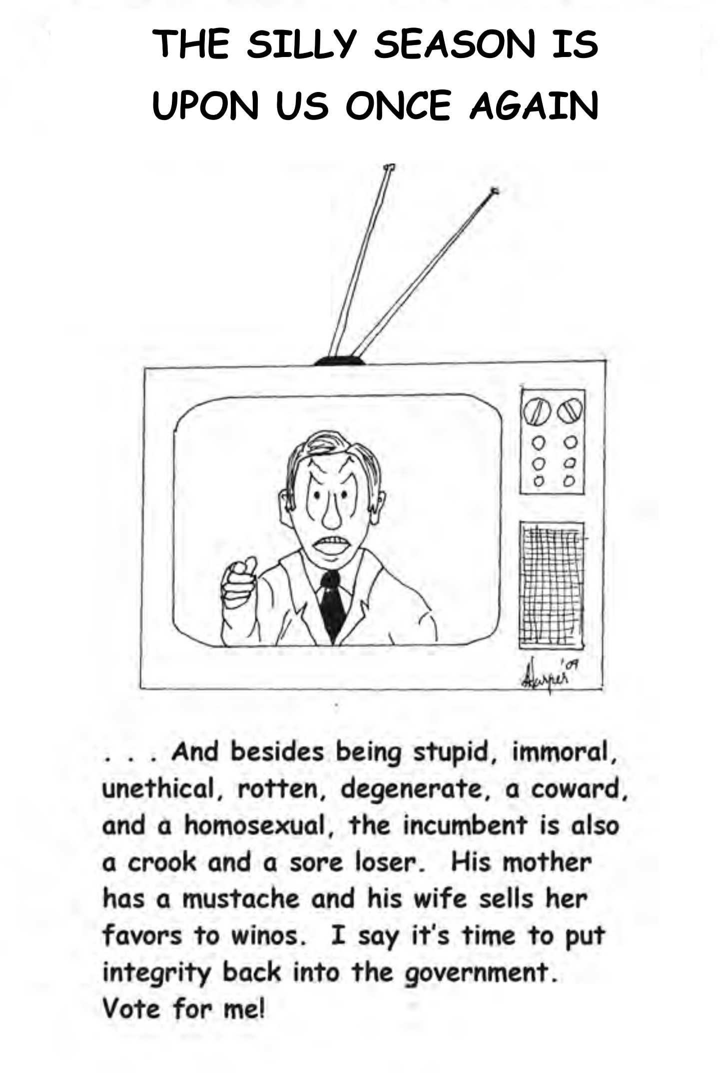

A HISTORY OF DELAWARE WATER GAP AND ITS RESORTS*

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** Published online by the Antoine Dutot Museum and Gallery, Main Street, Delaware Water Gap, Martin Wilson, East Stroudsburg University Pa. (http://www.dutotmuseum.com/history.htm), taken from his 1984 East Stroudsburg University Master's thesis.*

As a sunflower seed needs fertile earth, an adequate supply of water, mild temperatures, and plenty of sunlight to grow, so too, a resort community, in order to flower, requires specific conditions. For Delaware Water Gap, those conditions existed during the last half of the nineteenth, and the first third of the twentieth centuries. During that period, America's vacation habits and the limitations of transportation, coupled with the scenic beauty of the area and the entrepreneurial spirit of some local residents, conspired to transform the tiny borough into the heart of one of the most popular inland resort areas in the eastern United States. Each summer during that period its year-round population of about 400 was augmented by approximately 2500 visitors, many of whom stayed the entire season.

Life before indoor plumbing, super highways, and air-conditioning is hard to imagine for those of us who did not experience it. Summer, for city dwellers especially, must have been unpleasant and even unhealthful. Depending on individual economic circumstances, urbanites responded to unbearable summer heat in a number of ways. The wealthiest escaped for the entire season to Bar Harbor, Newport, or to other playgrounds of the rich. Working class and lower middle class Philadelphians traveled to Atlantic City to enjoy the cool sea breezes and the ever-present holiday atmosphere. For New Yorkers, Coney Island served as the destination of choice every year. Not everyone,

Wilson, M.W., 2012, A history of Delaware Water Gap and its resorts, *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. 153-165.

though, preferred the excitement and noise of these two seaside playgrounds. Many more prosperous middle-class city dwellers opted for the refreshing mountain air and the scenic beauty of America's inland resort areas, one of which was Delaware Water Gap, Pennsylvania.

The Settlement of Delaware Water Gap

In 1793, when Antoine Dutot arrived in the area with the intention of founding a city, the vicinity just north of the geological formation known as the Delaware Water Gap had been the site of human habitation for thousands of years. Known as the Minisink by the Lenni-Lenapes, it is estimated that the area was first inhabited by the Paleo-Indians as early as 10,000 to 12,000 B.C. When the first white men reached the region in 1614, they encountered the Minsi tribe of the Wolf Clan of the Lenni-Lenape Nation (the Lenni-Lenape were commonly referred to as the Delaware Indians because they ranged from the headwaters of the Delaware River to the shores of the Delaware Bay).

The Minisink was first explored by Europeans in the early seventeenth century by three travelers from New Amsterdam who entered the area from the Hudson River. One theory, recently contested by historians, is that the Dutch then mined copper from the mines on the eastern side of the river and built a road connecting the mines to Esopus (today Kingston, New York) on the Hudson. The first settler on the west bank of the Delaware River in the Minisink was Nicholas Depui who, in 1727, moved his family from the Hudson Valley to present day Shawnee.

Due to the difficulty of travel through the Gap (the mountains reached right down to the river leaving no room for a road or path), settlers in the Minisink knew little or nothing of settlements to the south. In 1730, Thomas Penn, son of William, sent Nicholas Scull on an expedition from Philadelphia to the Minisink to investigate rumors of settlements there. As a result of Scull's visit, Depui was required to repurchase land from William Allen (who had obtained it from Penn) that he had previously bought from the Indians. After Scull's sojourn, settlers from south of the mountains began to travel into the area. (Northern-bound settlers reached the area via Wind Gap.) It was not until the end of the eighteenth century, however, that the flow from the south eclipsed that of the north.

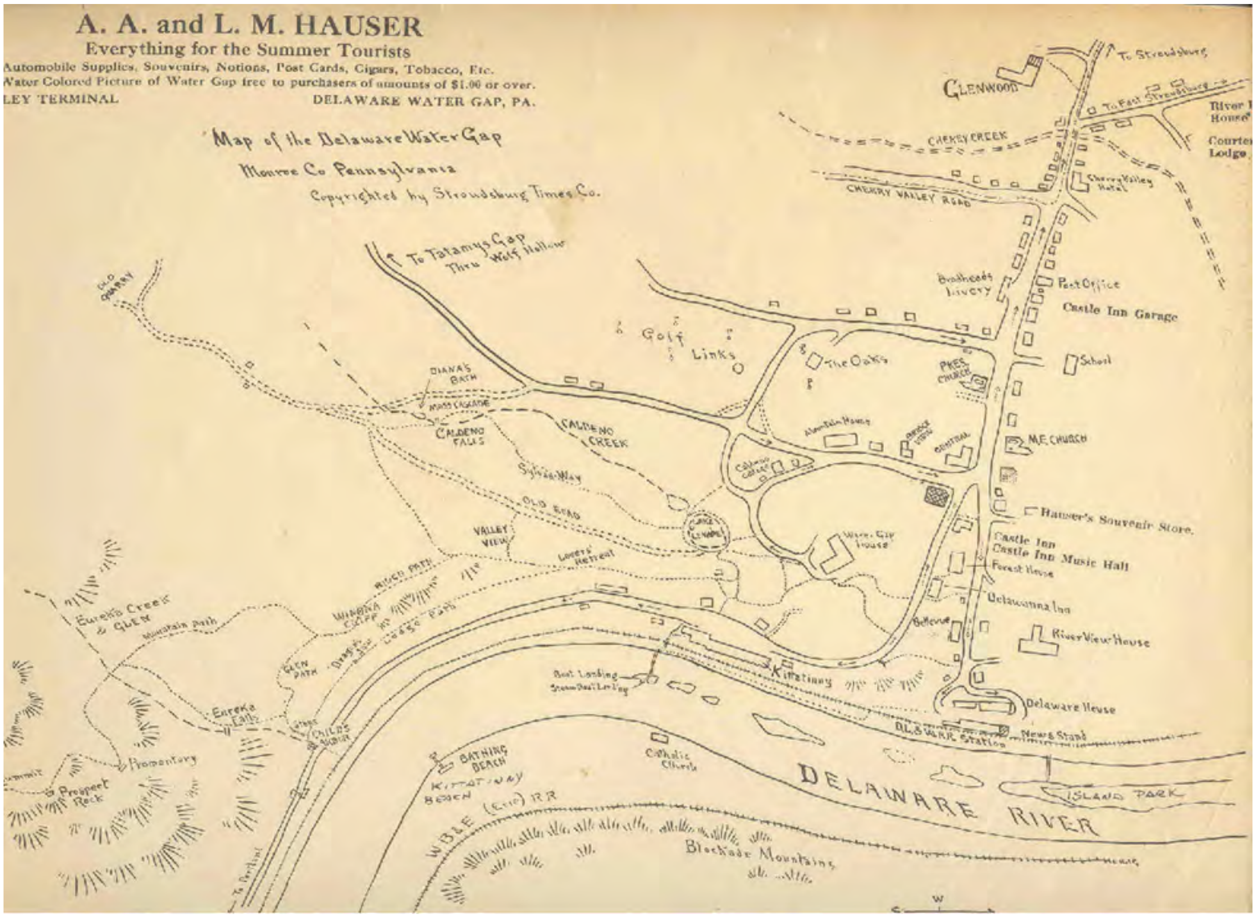
Dutotsburg

A settler from present-day Albany, Daniel Brodhead, moved his family to the area in 1737. Settling in present-day East Stroudsburg, Brodhead lent his name to the new town of Dansbury. The Indian wars of mid-eighteenth century led to a thinning of settlers as many moved away to avoid hostilities. By the time another settler, Jacob Stroud, returned to the area after the Revolutionary War, the Indian threat had been eliminated. Stroud was able to acquired several abandoned farms at very little cost. By 1806, he owned so much land that the area in which he lived began to be called Stroudsburg.

Delaware Water Gap remained unsettled long after settlements nearby had grown. In 1793, Antoine Dutot, a French plantation owner in Santa Domingo, fled the slave uprising there and headed toward Philadelphia. Upon arriving in the Quaker city, Dutot was advised to travel up the Delaware River to the Gap, where he purchased a large tract of land and began to lay out an inland city. He erected a dozen or more wooden buildings, designated a triangular piece of ground for a market, and named the new town after himself. Dutotsburg never became the bustling city its founder had envisioned, however. People moving into the tiny borough built their own houses and Dutot's structures fell into disrepair. Eventually Dutotsburg became known as the borough of Delaware Water Gap, probably in order to benefit from the inherent advertising benefits associated with the well-known geological formation.

Early Growth of the Resorts

This map was given (or possibly sold) at Hauser’s Trolley Terminal & Souvenir Store. It shows where all the hotels and guest houses were located.



The natural beauty of the Delaware Water Gap proved to be an attraction to people traveling through the area. As early as 1820, visitors began staying in the small town where they roomed with local families in order to enjoy the scenery. Conscious of the possibilities, Dutot began constructing a small hotel overlooking the Delaware River in 1829. By 1832, however, he had run out of money and sold the incomplete building to Samuel Snyder. Snyder enlarged and completed the hotel which he named the Kittatinny. The new structure could accommodate twenty-five people and was filled the first season it opened. William A. Brodhead rented the Kittatinny from 1841 to 1851, when he bought it and increased its capacity to sixty. Over the next fifteen years the Kittatinny's size was increased on four separate occasions, first under William Brodhead, and, after 1857, under its new manager, Luke W. Brodhead. By 1860, the hotel could accommodate two hundred and fifty guests.

The success of the Kittatinny led to the establishment of other hotels. In addition, families opened their homes to visitors as a means of augmenting their income. At least one private home gradually grew into a full-fledged resort (the River Farm). By the Civil War, Delaware Water Gap's popularity as a resort area was becoming well-known throughout the northeastern United States. The strained economy of the war years led to a decline in the budding resort industry, but the reconstruction period found city dwellers once again traveling to the Gap. By 1867, the Brainerd, the Lenape, the Glenwood, the River Farm, and the Arlington, had joined the Kittatinny in offering accommodations to visitors. On June 20th, 1872, a new hotel that rivaled the Kittatinny in size and splendor, the Water Gap House, opened its doors.

Water Gap's Popularity

"Delaware Water Gap was the second largest inland resort town in the United States after the Civil War (ranking behind Saratoga Springs, N.Y.), and its clientele were the upper classes of Philadelphia and New York." So says one writer about the area. Although such rankings are hard to quantify, it is clear that the Gap enjoyed a national reputation for its resorts and drew prominent financiers, politicians, and society people from the time of the Civil War until World War I. Even a United States President visited the town (Theodore Roosevelt visited the Water Gap House on August 2, 1910). A publisher of world famous guide books in the nineteenth century included Delaware

Water Gap among the fifteen scenic marvels of the United States. In 1906, an advertising pamphlet estimated that over one-half million people visited the Gap annually.

Unlike today's vacationer who may stay at a hotel for only one night or perhaps a week, Victorian Americans would often spend an entire season at their favorite resort—no doubt as a means of escaping the insufferable summer heat in the city. It was the custom among those families who could afford it to pack mom and the kids off to a hotel in the country for the entire summer where the father would join them on weekends. Summer visitors returned to the same resort year after year, calling it their second home.

What did the Gap have that attracted city visitors? According to Luke W. Brodhead, one of the managers of the Kittatinny and author of a book about the history and legends of the Gap:

> *The principal sources of amusement and recreation are the rambles over miles of mountain paths with vistas of great beauty opening at frequent intervals; carriage drives in many directions over a picturesque and interesting country; steamboat and rowboat service, and good bass fishing on the river in season and trout fishing in the adjacent streams."*

“Perhaps the featuring asset of the Gap, aside from its beautiful gorge, through which flows the placid Delaware, is its health-giving atmosphere, which permeates everywhere and which in itself has given the region much of its charm and popularity." This claim was made by an author extolling the beauty of the area in a book published in 1897. Whether the "atmosphere" in the region is any more healthful than anywhere else is, of course, open to debate. Nevertheless, that theme was played repeatedly in advertisements of the late nineteenth and early twentieth centuries. "The atmosphere is pure and dry, always cool evenings, and even at mid-day seldom so warm as to be uncomfortable. The whole region is free from mosquitoes or malaria." (This from an 1895 book.) As early as 1866, the local newspaper, The Jeffersonian Republican, ran a story reporting that the hotels and boarding houses were full; thus city people were escaping the danger of cholera, it said. In 1873, Doctor F. Wilson Hurd decided that Monroe County would be an ideal spot for his Wesley Water Cure. The Water Cure of Experiment Mills (later the Water Gap Sanitarium) was located just off the current Marshall's Creek exit of Rt. 80, and was instrumental in increasing the influx of visitors to the area.

For the last quarter of the nineteenth century the Gap's popularity earned it repeated mention in The New York Times. During the summer season, four to five articles a month appeared in that paper written by a correspondent in the town.

In order for families to take advantage of Delaware Water Gap as a vacation spot, good transportation was needed to insure that the patriarch could travel back to the city for the week's labor. In the late nineteenth and early twentieth centuries, good transportation (inland) meant railroads.

Transportation to the Gap

Roads

As we have seen, the natural barrier of the Blue Mountains led to early settlement of the area by people moving south from the Hudson River valley instead of north from Philadelphia. Prior to 1800, when Abram B. Giles constructed a wagon road through it, the Delaware Water Gap was not considered a practical passage north or south. Only rough Indian trails wound round the base of the mountains on both sides of the river. (A main Indian trail, upon which a road was later built by colonists, wound through what is now called the Wind Gap as it passed over the mountains.) Shortly after Giles completed his road, a visitor traveled the route and described it as a:

> *wagon road leading between the mountain's edge & the river & which all the labour of the inhabitants have been ineffectual to make more than about 8 feet wide or to clear from excessive roughness as it leads over one rough hillock to another the whole distance.*

Around 1799, in anticipation of the completion of the road, Benjamin Bonham constructed a small inn along it—the first in a town later to become famous for its hotels.

Antoine Dutot built a road in 1798 from his saw mill, below where the Kittatinny once stood, to the site of his planned city. A few years later he obtained a charter for a toll-road and extended his existing road to the River Farm where it connected with one running from Shawnee to Tatamy Gap. Although he set up a toll-gate along the way, he had trouble collecting tolls. In 1823, his road was superseded by one built by the state.

In order to meet the needs of the growing county, roads were widen and improved, and stagecoach lines began to operate. By 1846, a passenger and mail stagecoach stopped in Stroudsburg on the way to Milford from Easton three times a week. By that time, the road through the Gap was sufficiently improved to carry stagecoach travel.

In the early nineteenth century, Henry Drinker, owner of large tracts of land in northeastern Pennsylvania, dreamed of a rail line between the coal fields of Lackawanna County and the Delaware Water Gap. Drinker hoped to connect his line with one into New York, thus improving the marketability of the anthracite coal that had been discovered in the valley. It was not until March 11, 1853, however, that the Delaware, Lackawanna and Western Railroad was formed from the consolidation of two smaller lines. On January 21, 1856, the first train ran from Scranton to the Delaware River five miles below the Gap. It could go no further because the Warren Railroad in New Jersey was not yet open. By May 13 of that year, though, trains could travel from Great Bend (north of Scranton) to New York (actually the route terminated at Elizabethport, New Jersey, opposite the northwest tip of Staten Island). The Southern Division of the Delaware, Lackawanna and Western Railroad was officially opened on May 27, 1856. A train leaving New York at 7:30 in the morning arrived in Delaware Water Gap at 1:15 that afternoon, a trip of almost six hours.

With the intention of gaining access to a terminal closer to Manhattan, the D.L.& W. signed a lease with the Morris & Essex Railroad on December 10, 1868. The lease provided that the D.L.& W. would take over the Morris and Essex on December 31, 1868; thus Hoboken, right across the Hudson from New York City, became the D.L.& W.'s New York station. A ferry ran from the Hoboken terminal to the foot of Christopher Street, directly across the river in Manhattan, and to the foot of Barclay Street which is further downtown. The changes cut over an hour from the trip to the Water Gap.

Railroads

A common ingredient in the success of the towns of Delaware Water Gap, Atlantic City, and Coney Island as resorts was the existence of railroads. The introduction of rail service to these areas resulted in their increased popularity (in fact, Atlantic City did not exist until a rail line was built to the New Jersey shore).

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In 1900, William Truesdale, president of the D.L.& W., perceived that a new route was needed across New Jersey to forestall competitors from gaining the upper hand in passenger traffic. During 1906 and 1907, three studies were conducted to examine the feasibility of shortening the trip from New York to the Gap. It was decided to build a new route from Lake

Hopatcong to Slateford, Pennsylvania. The following account, published in a history of the D.L.& W., illustrates the enormity of the new line (commonly called the New Jersey Cut-Off):

> *The country to be crossed was anything but level. Valleys and roads ran north and south; the railroad ran east and west. There were to be no grade crossings. The new route would require 28.5 miles of new track, two large viaducts, and a fill three miles long and from 75 to 140 feet high. West of the Pequest fill, as it was named, were six miles of continuous cuts and fills. There were thirteen fills, most of which were about fifty feet high, and with fifteen cuts with the big Cut west of Johnsonburg being a maximum of one hundred feet deep and a mile long.*

Truesdale staked the future of his railroad on the success of the new line. Finished on December 24, 1911, at a cost of $11,065,511.43, the new route was a fast and smooth downhill run of twenty-eight miles. It cut eleven miles and twenty-seven minutes off the trip from New York.

In 1895, it cost $2.55 for a ticket from New York to the Gap. Ten years later, it cost twenty cents less. By 1933, the price was up to $2.82. With faster trains and more efficient scheduling, the time it took the train to reach Water Gap from Barclay Street gradually decreased. In 1959, it took just under three hours. Passenger service on the D.L.& W. ended on January 5, 1970.

Another railroad company, the New York, Susquehanna & Western, provided passenger service to the area. Starting on October 24, 1882, the N.Y.,S.& W. ran from Weehawken, New Jersey and stopped in North Water Gap (Minisink Hills), and in Stroudsburg (near the present V.F.W.). The line crossed the Delaware just north of the Route 80 toll bridge (its stone supports can still be seen in the river). N.Y.,S.& W. service to the Poconos ended in 1940.

Passenger service from Philadelphia to the Gap was available on the Belvidere-Delaware Railroad (Trenton to Belvidere). Sometime around 1850, the Belvidere-Delaware extended its track to Manuka Chunk where it connected with the Warren Railroad. Passenger service was provided until October 4, 1947. (The line had earlier been absorbed by the Pennsylvania Railroad.)

Trolleys

On July 10, 1907, The Mountain View Line, connecting Delaware Water Gap with existing trolley lines in Stroudsburg, began operations. During the school year, the trolley served as a school bus, charging students fifteen cents each way.

Meanwhile, trackage was being laid south of the Blue Mountain by the Lehigh Valley Traction Company that would eventually reach the Water Gap resorts. In connection with that company, on August 28, 1905, the Bangor and Portland Traction Company entered Portland from the west, having underpassed the Delaware, Lackawanna and Delaware tracks after a three year conflict. Railroad companies were reluctant to allow trolleys, their competitors, to cross rail lines. The plan was to continue the line into Stroudsburg, but the Lehigh and New England Railroad Company refused permission for trolley tracks to be laid across their rails, and the extension to the resorts was abandoned. Tourists from Philadelphia could travel north on the trolley to Nazareth where they had to change cars. From Nazareth they traveled on the Slate Belt Electric Railway Company's cars to Bangor where they switched cars again to those of the Bangor and Portland Traction Company. At Portland, passengers could ride a bus into Water Gap, or they could take the D.L.& W. The first "Delaware Water Gap Limited" left Chestnut Hill at 9:30 on the morning of July 17, 1908, and reached the Gap six hours and forty minutes later.

Wanting to gain access to the resorts at Water Gap for their "Liberty Bell" route, the Lehigh Valley Traction Company invested $50,000 in the Water Gap and Portland Street Railway Company. On February 21, 1911, portions of the mountain at the narrowest part of the Gap were dynamited to permit space for the tracks. By October, trolleys were running between Stroudsburg and Portland on the newly created Stroudsburg, Water Gap and Portland Railway Company. Open, screen-sided double truck cars painted lemon-yellow were in service in the summer and enclosed cars were used the rest of the year.

On April 1, 1910, the Lehigh Valley Traction Company announced an arrangement with the Philadelphia and Western Railway Company to use part of its line. The use of this track with its terminal at the 69th Street Station in Upper Darby was part of a larger upgrading of the entire rail system. By 1912, passengers could make the entire trip from Upper Darby to Portland without changing cars. Passengers dined during scheduled dinner stops at hotels in either Allentown, Rittersville, Bethlehem, or Nazareth. Alterations made to the cars on the Water Gap route for the comfort of passengers on the long ride included black leather seats with arm rests; baggage racks; carpeted floors; iced drinking water facilities; a

uniformed "tour guide" who pointed out points of interest along the way; and a flashy, newly painted Liberty Bell Limited sign. At Portland, where the Lehigh and New England still refused a right-of-way to the trolley, passengers had to pick up their bags, get off one trolley and walk across the L.N.& E. tracks, and then board another trolley for the ride into Delaware Water Gap.

Direct service to Portland was short-lived. Before the 1913 vacation season opened, continuous service on the Water Gap route was canceled. Passengers had to change cars in Allentown.

In addition to the Liberty Bell Route, the Delaware Valley Route of the Philadelphia and Easton Transit company ran a trolley from Philadelphia to the Gap between 1908 to 1915. The journey took six hours and cost $2.40 round-trip. North of Easton the line was called the Blue Mountain Route and continued in service until November 25, 1926. From Bangor to Portland the route shared L.V.T. Company's tracks.

In 1917, the Stroudsburg, Water Gap and Portland Railway Company became the Stroudsburg Traction Company. The growing popularity of the automobile, however, rang the death-knell of the trolleys. On March 20, 1926, the Bangor-Portland was abandoned and the right-of-way was sold to Northhampton County for construction of a new highway between Portland and Mount Bethel. In November of the same year, the lease of the right-of-way between Portland and Water Gap, which was owned by the D.L.& W., was canceled thus ending service between the two towns. Stroudsburg Traction Company ceased operations in 1928 after trying unsuccessfully to compete with growing bus lines. The last trolley in Stroudsburg ran on September 8. In commemoration several hundred people turned out to witness the end of an era. A local band played "The Old Grey Mare Ain't What She Used To Be."

The Mountain Echo

For a time, beginning in 1879, Delaware Water Gap had its own newspaper. Called The Mountain Echo, the small, seasonal paper focused on activities at the hotels and on local places of interest. The editor was local photographer Jesse A. Graves. One of the services dutifully carried out by the periodical was the listing of all the guests staying at the various resorts.

The Hotels

A 1909 guide to summer resorts in the area had this to say about Delaware Water Gap:

> *Its quota of hotels is second to none in the Unites States. They compare favorably with those in any other section of the country in size and attractiveness and are comparable only to the very finest in the matter or cuisine.*

It is difficult to accurately determine how many hotels operated in the Gap. A search in surviving pamphlets and newspapers for advertisements reveal evidence of only the larger establishments. In addition, as some hotels changed owners, they also changed names, further clouding the issue. Nevertheless, it is estimated that the town of 400 permanent residents could accommodate over 2500 people. Long-time Water Gap resident Casey Drake remembers that, as a boy, the town was so crowded in the summer that it was often difficult to walk down the street.

The two largest and perhaps best known of the hotels were the Kittatinny and the Water Gap House (see photos above). The Kittatinny was located at the present site of the overlook along Rt. 611 just south of the borough. Part of its foundation still stands beneath the spot from which visitors look out at the Delaware River and the Rt. 80 bridge. The same view was enjoyed by guests of the Kittatinny as they stood on the hotel's large veranda. In 1874, the Brodhead brothers increased the hotel's capacity to 275. Then, in 1892, the building was razed to make room for a larger, more elegant New Kittatinny. Able to accommodate 500 guests, the hotel boasted, in addition to spectacular views and cool breezes, the following:

> *Electric lights, elevators, steam heat, running mountain spring water in rooms [and a mountain stream running under the kitchen—which can still be seen from the Rt. 80 bridge], private baths, etc. Noted for its cuisine and service, and the hotel's farm gives to the table products par Excellence."..Bell phone 92; telegraph office in hotel, orchestra, social diversions.*

A 1908 advertisement lists G. Frank Cope as proprietor. Similarly, one from 1917 lists John Purdy Cope as owner.

The Water Gap House was located above the Kittatinny on Sunset Hill (so named because when one stands facing east on the hill one can see the shadows on the mountain across the Delaware slowly rise as the sun sets in the West). Opened by Luke W. Brodhead on June 20, 1872, the Water Gap House had first and second story piazzas twelve to fifteen feet wide and 650 feet long looking out over one of the finest views in the area. In keeping with the mores of the times, Brodhead built the hotel with no bar.

In 1908, the Water Gap House was completely rebuilt at a cost of over $100,000. John Purdy Cope, its new owner, advertised its attractions in the June 14, 1908 edition of The New York Times :

> *Capacity, 300. A MOUNTAIN PARADISE; highest altitude, coolest location, always a breeze, no humidity . . . Commanding views for 30 miles in every direction of the grandest scenery east of the Rockies. Hotel is surrounded by its magnificent park of Old Shades, Rhododendron, Wild Flowers, Rare Plants, and Fine Lawns. . . . entertaining refined, high-class patronage. Running mountain spring water and stationery stands in all rooms. Fifty private tile bats, also public baths. . . . Telephones and telegraphs. Solariums and balconies on all floors. Steam heat, open log fireplaces. Electric lights. Hydraulic elevator. Most modern sanitary arrangements. . . . Hotel supplied from own greenhouse and farm with early vegetables and poultry. Milk from our own dairy of registered cows. Every outdoor sport and indoor amusement. Orchestra and frequent social functions. Private riding academy with high-class saddle horses and instructors; nine-hole golf links; garage and livery—all within the grounds. Coaches meet all trains.*

The Glenwood House opened its doors to summer visitors in 1862 after serving for a while as a boy's academy. In 1897, it was catering to 200 guests, was opened from May to November, and could boast private balconies on the second floor. A 1909 advertisement claimed a capacity of 400. The Glenwood also supplied its tables with fresh fruits and vegetables from its own farm. Of the old resort-hotels, the Glenwood is the only one still operating as a resort today. (The Central House, now the Deer Head Inn, still functions as a rooming house and its bar enjoys a reputation as something of a jazz mecca.)

The Castle Inn opened for business in 1909, and was the last of the great hotels built in the Gap. When it opened it had 112 guest rooms, a ball room, recreation rooms, its own power plant, and its own freezing plant.

The Bellevue was known by two other names over the years. First it was the Juniper Grove House, and later it was called the Arlington. As the Bellevue, it could sleep 150 guests and claimed to be the popular hotel for young people. A big selling point for this and some of the other hotels was their proximity to the train station.

The hotel located closest to the station was the Delaware House, which was situated just across the street. Open all year, the Delaware House could accommodate 50 people and offered, in addition to the normal activities such as fishing, boating, and bathing, also bowling, pool, and billiards.

The Riverview, also located near the station, had a capacity of 250. The Mountain House could hold eighty guests, and the Forest House could hold 100.

These are just some of the hotels located in the Gap. Many hotels, while not located in Delaware Water Gap, nevertheless maintained an address in town in hopes of benefiting from the Gap's popularity. The Karamac, for instance, was located across the river in New Jersey, and yet advertised its Delaware Water Gap address.

The End of an Era

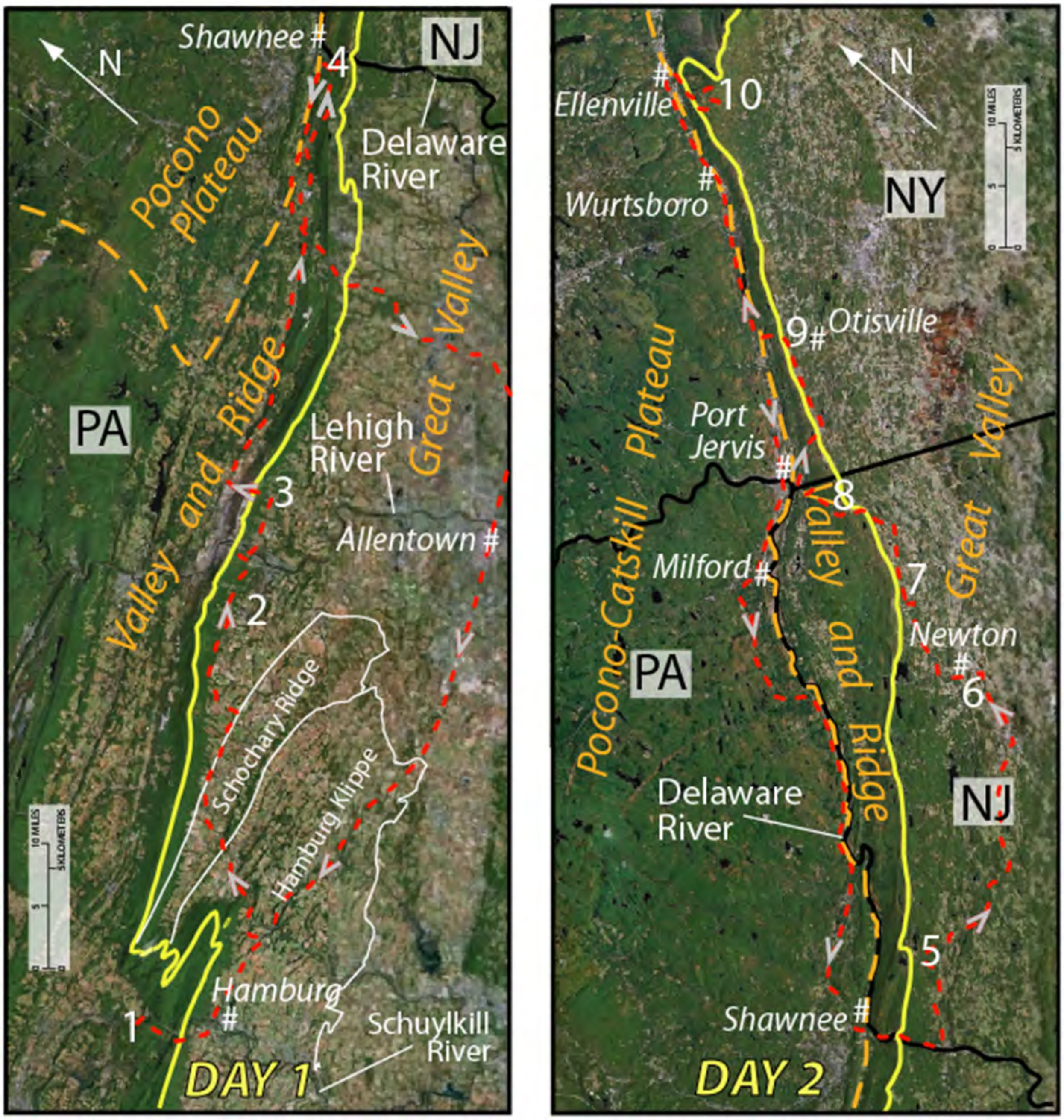
At five o'clock in the afternoon of Thursday, November 11, 1915, workmen, helping to close the Water Gap House for the winter, discovered a fire which had broken out in one of the guest rooms of the hotel. An alarm was sounded and several fire companies responded; but their efforts were in vain. Though a light rain was falling at the time, the entire structure was leveled in only a matter of hours. The loss was estimated at between $150,000 and $200,000. Four days after the fire, it was announced that a new hotel, as large as the Water Gap House, would be built on the same site. The planned hotel was to be fire-proof and, hopefully, would be open for some of the 1916 season. The hotel was never built.

Cope experienced another disaster in 1931, when the Kittatinny burned to the ground. He and his family were awakened at four o'clock on the morning of October 30, by a passing motorist who had seen flames coming from the Kittatinny. By six o'clock, the entire structure was engulfed—a loss of between $500,000 and $750,000.

Why was neither hotel rebuilt? Over the years the Poconos have continued to be a major resort region. Delaware Water Gap, however, has steadily declined as a resort community. Part of the answer for the Gap's decline as a resort lay with changing transportation trends; there was a clear symbiotic relationship between the resort and transportation industries in the town and surrounding area. The large hotels were in an ideal location to benefit from the easy access that the rail lines and trolleys provided. The hotels also furnished the varied transportation companies with a "draw" or need for transportation which the various companies were eager to fulfill. As the business of travel matured into the automobile oriented industry of today, however, the demand for the large hotels located on rail lines diminished. The popularity of the automobile after World War I, in part, changed the way people took vacations. No longer tied to the rail system for transportation, a whole new concept of vacationing developed. In 1909, a story in The *New York Times* anticipated this trend when it reported that a weekend outing with the entire family, stopping for a night's lodging at some comfortable but not too expensive hotel, was superseding the summer-long separation of the father from his family.

The automobile was only part of the answer though. Tough economic times of the 1930's erected a hurdle that, in combination with other factors mentioned, proved too high for Water Gap's resorts to overcome. When the resort industry began to expand after World War II, Delaware Water Gap seemed, for the most part, content to let the resurgence pass the town by. Many of the small boarding houses were converted into private residences. Most of the old hotels were either destroyed by fire, were closed, or continued to operate as best they could under changed conditions. Water Gap's heyday as a resort had come to an end.

Postcards courtesy Lucy Kosmerl.



Map of the 77th Annual Field Conference of Pennsylvania Geologists travel route (red dashed line) showing locations of the ten stops, physiographic provinces, rocks of Shochary Ridge and the Hamburg klippe, and the Taconic unconformity (yellow line) (constructed from Google Maps). Note the rapid decrease in width of the Valley and Ridge east of the Lehigh River.

ROAD LOG AND STOP DESCRIPTIONS

DAY 1—PENNSYLVANIA

Mileage		
Int.	**Cum.**	**Description**
0.0	0.0	Leave from circle in front of Shawnee Inn. The Inn and golf course are located on postglacial stream terraces that reach a maximum elevation of 330 ft (101 m), about 35 ft (11 m) above the mean annual elevation of the Delaware River. An Early Archaic occupation site excavated on Shawnee Island (Stewart, 1991) was dated at 9330 + 545 yr B.P. (Uga-5488).
0.3	0.3	Turn left onto River Road. The road passes over a variety of Silurian and Devonian rocks that are covered in many places by thin, late Wisconsinan till. The rocks were laid down in a variety of depositional environments, including sub-tidal marine, tidal flats, and beaches. They are complexly folded and have different tectonic characteristics than rocks above and below (Figure 1).
0.1	0.4	Limestone of the Shawnee Island Member of the Coeymans Formation on right (measured section 14-b of Epstein, A.G., and others, 1967). The Stormville Member capping the top of the Coeymans Formation is seen in the private driveway to the right (Figure 2).
0.3	0.7	Fossiliferous New Scotland Formation in slope to right.
0.1	0.8	Traffic light at Buttermilk Falls Road. Continue straight.
0.7	1.5	Minimart on left, and Smithfield School on right sit on a late Wisconsinan

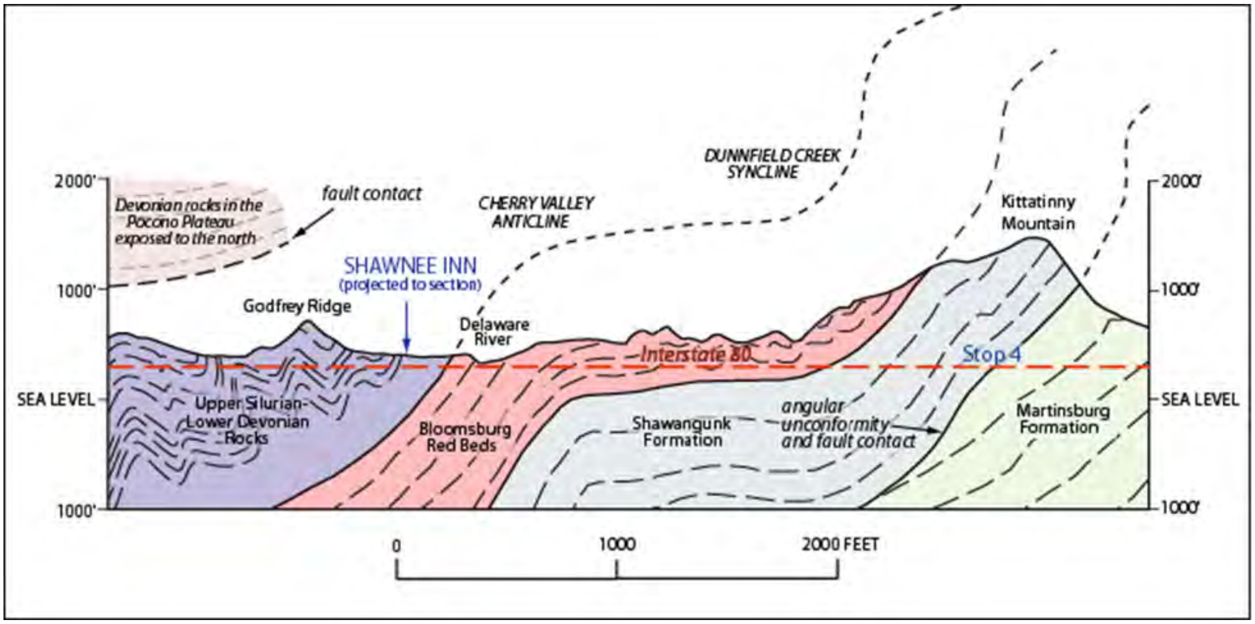
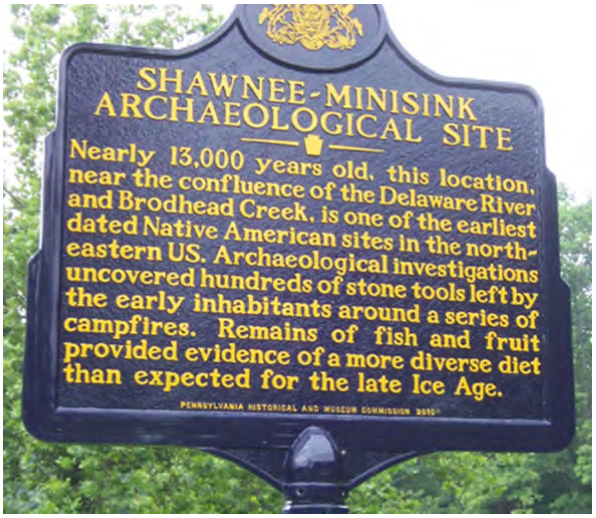


Figure 1. Cross section through Delaware Water Gap showing structural differences between packages of rocks. The position of Shawnee Inn is projected to the section. Vertical exaggeration: 2X. Location of Stop 4, Point of Gap Overlook, is indicated. Note the undulations in the Bloomsburg Red Beds that will be see at mileage 143.1.

		outwash terrace. The terrace lies at an elevation of 400 ft (122 m), about 100 ft (31 m) above the Delaware. Based on its position near the mouth of Marshalls Creek, it was probably laid down by a meltwater stream flowing down the Marshalls Creek valley.
0.1	1.6	Gap View Road on right. 0.3 mi (0.5 km) to the north is the location of an extinct sand and gravel pit in which deltaic deposits were exposed (Figure 3).
0.4	2.0	Village of Minisink Hills. Follow curve to left. Exposures of Coeymans Formation through Esopus Formation along abandoned railroad grade to right. On the crest of the hill northeast of the railroad grade is an imposing ledge of cherty Ridgeley Sandstone (the Indian Chair) from which Amerinds extracted a good-quality flint (Phillip La Porte, personal communication, 2001). Postglacial stream terraces of Brodhead Creek on right. Late Wisconsinan outwash terraces form the higher ground on the left.



0.2	2.2	Historical Marker on left: The Shawnee-Minisink Paleoindian site (McNett and others, 1985) is located on a postglacial stream terrace about 20 ft (3 m) above the Delaware. Work here in the 1970s revealed a very rich and diverse, stratified cultural assemblage of Woodland, Archaic, and Paleoindian components. Radiocarbon dating of organic material collected from a hearth about 9 ft (3 m) deep yielded a date of 10,590 + 300 yr B.P. The hearth is located in cultural zone containing Paleoindian components (clovis point, scrapers, hammerstones). Glacial ice left this area about (15,000 years ago). Question: Were the native Americans (Lenapi/Delaware Indians) here at the time of glacial retreat? There are several references that indicate that the word Minisink suggests a legendary memory of floods that possibly resulted from the retreat and melting of the Wisconsinan glacier. Brodhead (1870) noted that The Indian name of Minisink—meaning the water is gone—given by the aboriginals to the level country north of the Gap, and extending up the river many miles (kilometers), would seem to indicate some tradition confirming the theory of a lake at some remote period of time (Brodhead, 1870 p. 2); and She (Princess Winona of the Lenni Lenape tribe, about 1670) spoke of the old tradition of this beautiful valley having once been a deep sea of water, and the bursting asunder of the mountains at the will of the Great Spirit, to uncover for her the home of her people the vale of the Minisink; the mighty chasm in the mountains, and the twin giants overlooking the vast extent of country to the rising sun, as far as the eye can reach (Brodhead, 1870, p. 27).
0.2	2.4	Cross Brodhead Creek.

Figure 2. Stormville Member of the Coeymans Formation at mileage 0.4. Parallel to cross-bedded conglomeratic arenaceous limestone with quartz pebbles as much as 0.5 in (1.3 cm) long. Abundant brachiopods (*Gypidula coeymanensis*; pencil) and crinoid columnals indicate a high-energy marine environment, such as an offshore bar.

Figure 3. Coarse topset beds overlying finer foreset beds in sand and gravel (removed by pit operations in 1967) along Gap View Road 0.33 mi (0.53 km) north of River Road. Foreset beds dip due west, probably fed by streams that deposited an esker immediately to the east. See Epstein (1969, fig. 5).

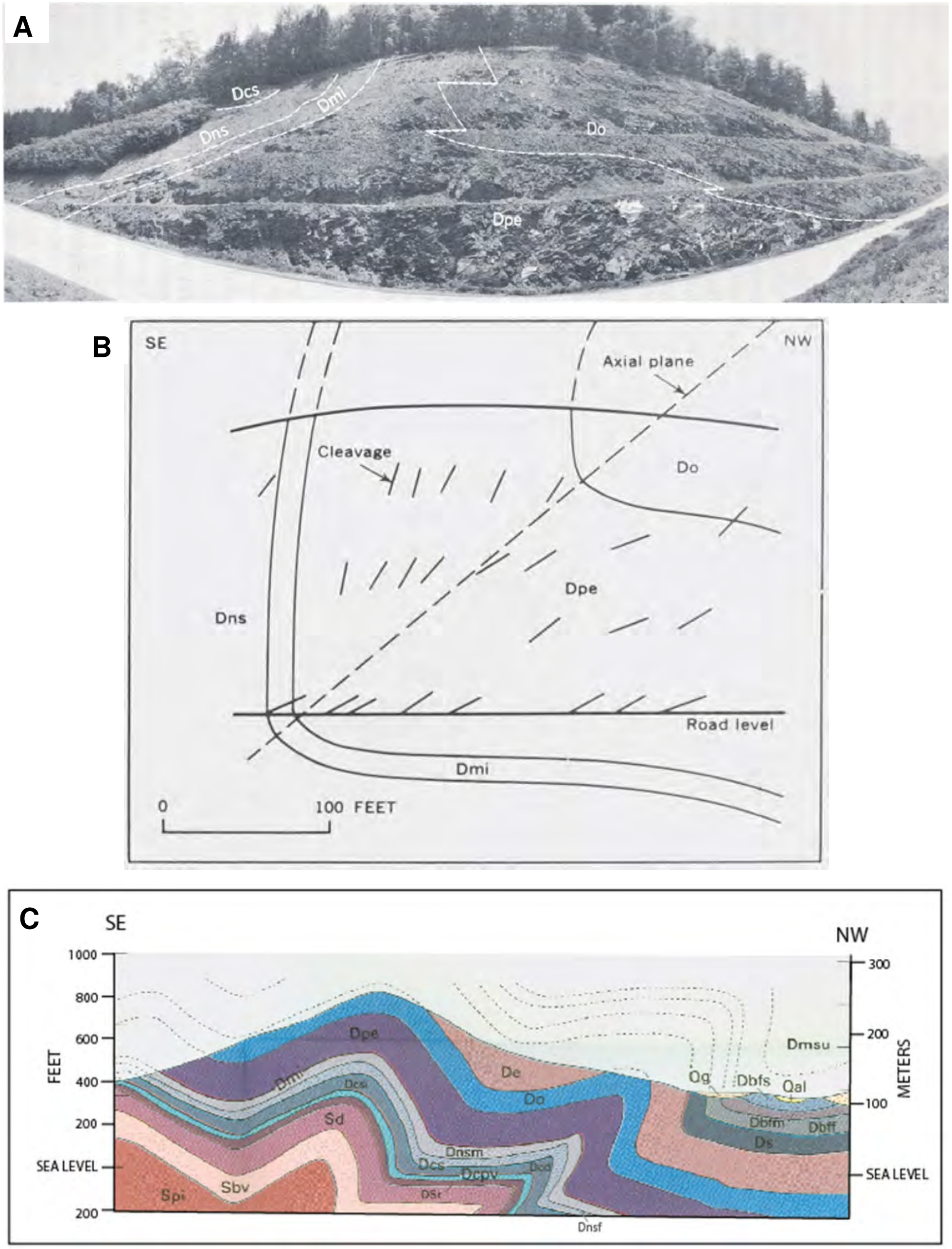


Figure 4. A—Overturned syncline exposed along I-80. Dcs, Stormville Member of the Coeymans Formation; Dns Flatbrookville and Maskenozha Members of the New Scotland Formation; Dmi, Minisink Limestone; Dpe, Port Ewen Shale; Do, Oriskany Formation. Dashed lines are bedding traces. Overturning seems greater because of foreshortening in photo. From Epstein and others (1967, fig. 11); B—Geologic section showing divergent fanning of cleavage in the Port Ewen Shale along I-80. Do, Oriskany Group; Dpe, Port Ewen Shale; Dns, New Scptland Formation; Dmi, Minisink Limestone. From Epstein and Epstein (1969). This fold is part of a complex fold train in Godfrey Ridge; C—Geologic section through Godfrey Ridge at mileage 3.1. Dbfa, Foxtown Member of the Buttermilk Falls Limestone of Epstein (1984), now identified as the Edgecliff Member of the Onondaga Limestone of New York (Ver Straeten, 2001). De, Esopus Formation; Do, Oriskany Group; Dpe, Port Ewen Shale; Dmi. Minisink Limestone; Dnsm, Maskenozha Member of New Scotland Forma-tion; Dnsf, Flatbrookville Member of New Scotland Formation; Des, Stormville Member of Coeymans Formation; Dcsi, Shawnee Island Member of Coeymans Formation; Dcpv, Peters Valley Member of Coeymans Formation; Oed, Depue Limestone Member of Coeymans Forma-tion; Sr, Rondout Formation; Sd, Decker Formation; Sbv, Bossardville Limestone; Spi, Poxono Island Formation.

0.1	2.5	Cross Norfolk Southern (originally, Delaware, Lackawanna & Western) Railroad.
0.2	2.7	Pass under I-80.
0.1	2.8	Traffic light. Turn right onto ramp to I-80 West.
0.3	3.1	Overturned syncline in Lower Devonian rocks on left (Figure D1). Well-developed cleavage fans the fold (Figure D2). This fold is part of a train of complex folds throughout Godfrey Ridge (Figure D3).
0.4	3.5	Cross Brodhead Creek. Note the flat-lying Oriskany Sandstone bluff above the creek. Rumor has it that the Lenape Indians used this fort to shoot arrows down on enemies below.
0.2	3.7	Continue straight at exit 309.
0.2	3.9	Onondaga Limestone on left.
0.9	4.8	Continue straight at Exit 308
0.7	5.5	Cross Brodhead Creek again.
0.2	5.7	Continue straight at Exit 307
1.1	6.8	Onondaga Limestone (Seneca Member) on left
0.6	7.4	Continue straight at Exit 305
0.2	7.6	Exit 304. Bear right onto PA 33S/US 209.
0.9	8.5	Road passes through ridge of stratified drift. During late Wisconsinan deglaciation, proglacial lakes formed in the ice-dammed, northeast-draining valley. Several ice-contact deltas mark ice retreat (Epstein, 1969).
0.8	9.3	Traffic light. Continue straight.
1.0	10.3	Topset and foreset beds in a glacial delta exposed in sandpit to left.
1.4	11.7	Exposure of Marcellus Shale on right. The Marcellus in this area is a medium dark-gray to grayish-black, laminated to poorly bedded, shale and silty shale. It lies more than 4,000 ft (1,219 m) above the Martinsburg Formation. Cleavage is present, but not as well-developed as in the Martinsburg. Folding here is not as profound as in the rocks below. Bedding parting, which is nearly flat, is prominent. Cleavage dips about 38o to the southeast (Figure 5). Pencil cleavage is well developed, formed by splitting along bedding, cleavage, and joints. This property makes it valuable as road fill. The Marcellus was deposited in an anoxic

Figure 5. Marcellus outcrop at mileage 11.7. Cleavage dips moderately to the southwest; bedding is flat; steeper joints interrupt the outcrop. Note "pencil" cleavage in scree in lower left. Small brachipodod on flat bedding surface at bottom of exposure.

(oxygen-starved) marine basin. Because of the reducing environment it is sparingly fossiliferous and contains a depauperate brachiopod fauna, few in numbers and variety. Whereas the Marcellus is a very active gas play in the Alleghany Plateau in northern Pennsylvania, the Marcellus here has reached temperatures too hot to pass gas.

0.9 12.6 Snydersville exit. Continue straight.

0.8 13.4 Pass through road cut in the Schoharie Formation in Godfrey Ridge.

0.2 13.6 Eureka Stone quarry in Schoharie Formation on left. Eureka-Pocono Sandpit in ice-contact delta to right. Over time the pit has exposed excellent examples of deltaic sedimentary structures (Figure 6). This delta marks the first major retreat

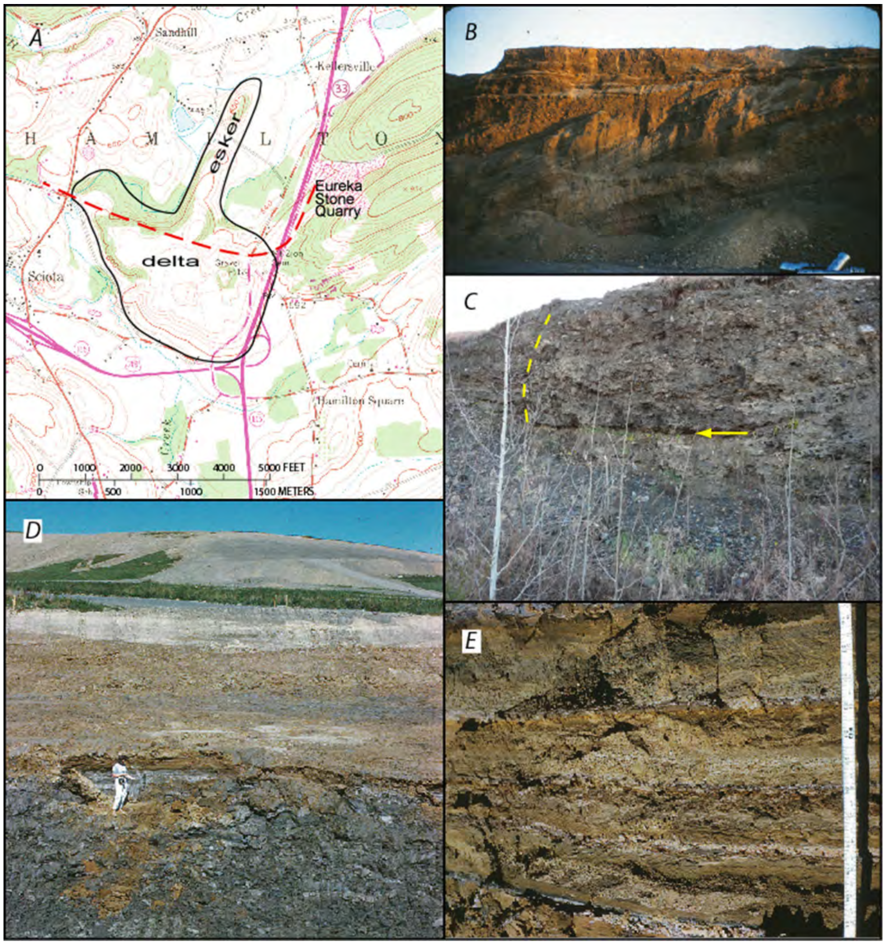


Figure 6. Map and transitory exposures in the glacial delta at Sciota, PA. A—Map showing lobate delta and feeding esker. Dashed red line suggests position of ice front when the delta was deposited. Note kettle hole depressions. From US Geological Survey 7.5-minute quadrangle, 1960 edition, photo-revised 1970; B—Topset and foreset beds during pit operations in 1966. Foresets dip to the south; C—Collapse gravel at the kettle hole near "G" in "Gravel Pit" in A, exposed in 2009. Merges into poorly stratified gravel and sand to the left. These sediments overlie compact gravelly till (at arrow) with abundant clasts derived from the underlying Marcellus shale; D—Frontal foreset slope of the delta with varves exposed at the base during construction of the PA 33 overpass in 1962; E—Varves of clay, silt, and fine sand exposed in base of slope in D.

		position of the Wisconsinan glacier from its terminus at Saylorsburg, 2 mi (3 km) to the south (Epstein and Epstein, 1969).
0.4	14.0	Cemetery in stratified sand and gravel to right. Note the lobate southern front of the delta. The foreset slope of the delta merges into flats underlain by varved clay, silt, and sand (see Figure 6).
2.9	16.9	Exposures in Cherry Ridge to right. There are significant facies changes in Lower and Middle Devonian-age rocks from Godfrey Ridge 3 mi (5 km) to the north (Epstein, 1990). The Esopus and Schoharie Formations become thinner; while the upper part of the Buttermilk Falls Limestone (Onondaga) becomes sandy and becomes the Palmerton Sandstone. More than 200 ft (61 m) of the lower part of the Buttermilk Falls has been leached to a varied-colored clay, which has been exploited previously for whitener in cement (Figure 7).
0.2	17.1	Exit to Saylorsburg. Continue straight.
0.4	17.5	Glacial till in Wisconsinan terminal moraine.
0.3	17.8	Start of scattered exposures of Bloomsburg Red Beds beneath pre-Wisconsinan till.
0.7	18.5	Curve in highway follows form of the upright Wind Gap anticline (Epstein, 1990) in the Bloomsburg Red Beds.
0.7	19.2	Bloomsburg Red Beds outcrop on left.
0.7	19.9	Continue straight past exit to town of Wind Gap. The floor of Wind Gap is at 980 ft (274 m) altitude, about 700 ft (213 m) higher than the bottom of Delaware Water Gap, 13 mi (21 km) to the northeast. A tributary of the Delaware probably robbed the Wind Gap River in the geologic past leaving its gap high and dry (Epstein, 1966).
0.2	20.1	Near-vertical sandstone, conglomerate, and shale in the Minsi Member of the

Figure 7. Early-Middle Devonian rocks exposed in 1962 during construction of PA 33. The rocks are overturned and dip 30-55° southeast. The Schoharie and Esopus Formations (Dse) thin from about 280 feet in Godfrey Ridge to about 150 ft (46 m) in Cherry Ridge. The Palmerton Sandstone (Dp) is absent in Godfrey Ridge and attains 66 ft (20 m) in thickness in Cherry Ridge. The rocks have been affected by deep pre-Wisconsinan weathering, especially the 263 ft (80 m) of Buttermilk Falls Limestone (Dbf) which have been mined locally for whitener in cement (Epstein and Hosterman, 1969). The Buttermilk Falls is presently totally overgrown. Red 1996 Mustang convertible for scale—I shouldn't have sold it!.

		Shawangunk Formation exposed on right.
1.3	21.4	Slate dump in Pen Argyl Member of the Martisburg Formation on right. Bedrock is poorly exposed in this area, being covered by pre-Wisconsinan (Illinoian?) drift.
0.5	21.9	Continue straight past exit to PA512 (Wind Gap/Bath). Surrounding low hills are held up by graywackes in the Ramseyburg Member of the Martinsburg Formation.
4.0	25.9	Continue straight past exit to Belfast.
1.4	27.3	Break in slope in hill to right marks the contact between the slate of the Bushkill Member of the Martinsburg Formation from the less resistant calcareous shale and shaley limestone of the Jacksonburg Limestone. The contact between the two is well exposed along Bushkill Creek, 800 ft (244 m) to the west. Here, dolomite beds in the lower Bushkill form mullions due to shortening along cleavage (Figure 8).
0.1	27.4	Cross Bushkill Creek. For the next 27 mi (43 km) we will be travelling on Cambrian and Ordovician carbonate rocks in the Great Valley section of the Ridge and Valley Province.
0.2	27.6	Continue straight past exit to Stockertown.
0.4	28.0	Hercules Cement quarry and plant to right. The Jacksonburg Limestone is quarried for cement rock. It immediately overlies the Epler Formation of the Beekmantown Group (Epstein 1990).
0.3	28.3	PA33 crosses Brodhead Creek, site of extensive sinkhole collapse due to sinkhole collapse in the Epler Formation, which disrupted traffic along PA 33 in 2001 (Figure 9).
0.7	29.0	Scattered sinkholes along both sides of highway in the Epler Formation.
1.9	30.9	Continue straight past PA248 exit to Wilson.
1.2	32.1	Continue straight past Hecktown exit.

Figure 8. Silicoeus dolomite mullions, as much as 4 ft (1.2 m) long, in basal Martinsburg on Bushkill Creek, north of Stockertown, PA. Shortening approaches 100%.

Figure 9. Sinkholes in Bushkill Creek, tilted concrete pier, and sagging roadway of PA 33 in 2001. See Kochanov (p. 139 of this guidebook) for details.

WARMER SEE PAGE A-3 HIGH 45 LOW 32

IN Sports BANNER SEASON FOR NCC WOMEN. /C-1

IN Local SPARKS FLYING OVER EXPANSION AT PPL PLANT. /B-1

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Specter sending in an army to fix sinkholes

By RYAN HESS
The Express-Times

Federal, state and local officials on Monday renewed the fight against sinkholes around the banks of the Bushkill Creek.

For the second time in six months, Northampton County Executive Glen Reibman on Monday issued a disaster declaration for the sinkhole-plagued niche of the county where Stockertown, Palmer Township and Tatamy meet.

Resident organizer Linda Judicello said one of State Sen. Lisa Boscola's legislative aides visited the creek, surveying new sinkholes that opened last week, and State Rep. Rich Grucela's office was busy making calls Monday morning to lobby for help from Harrisburg.

And from the nation's Capitol, U.S. Senator Arlen Specter an-

Please see HOLES /A-2

Boscola wants to enlist PennDOT

The Army Corps of Engineers needs help to fix sinkholes.

By RYAN HESS
The Express-Times

PALMER TWP. — State Sen. Lisa Boscola on Friday proposed a new answer to the 2-month-old question of who will take responsibility for helping the Army Corps of Engineers fix a series of sinkholes along the Bushkill Creek.

Ridge urges action on sinkholes

Governor has asked PennDOT to work on sinkholes plaguing Bushkill Creek.

By RYAN HESS
The Express-Times

Gov. Tom Ridge has agreed to step in and get state officials involved in the sinkhole problem plaguing the area where Stockertown, Tatamy and Palmer Township meet, state officials confirmed Friday.

Ridge has verbally asked the Pennsylvania Department of Transportation to do emergency work on the sinkholes under the Bushkill Street Bridge, officials said.

The governor's action follows a weeks-long letter-writing blitz by local residents and officials urging Ridge to step in. Most of those letters have been forwarded to PennDOT.

"It's not an official directive," ... Charles, a spokesperson in the governor's press office, said Friday. ... Ridge has asked the Department of Transportation to ... letters and fix ...

der the bridge to determine what is lying beneath the surface. Giant holes in the area have exposed a water line and sucked portions of the creek underground.

"We're going to be sure we know what's down there before we design a bridge," he said.

Members of the Brookwood Group, the grass-roots task force trying to fix the sinkhole-plagued neighborhood near the bridge and the banks of the Bushkill Creek, have accused PennDOT of allowing the sinkhole problem to grow by not taking action.

The Army Corps of Engineers is expected to repair the ... of the ... Creek this summer ... force hopes ... the brid...

THE DETAILS

◆ PennDOT design engineer Don Lerch said Friday afternoon that he hopes the federal Highway Administration will authorize the use of $550,000 in Lehigh Valley Transportation Improvement Program funds.

Sinkholes set to gobble sewer line

By RYAN HESS
The Express-Times

NAZARETH — Sinkholes along the Schoeneck Creek are threatening the sewer line that serves Upper Nazareth Township, Nazareth Borough Municipal Authority officials said Wednesday.

Authority Director Pat Mandes said she may soon need to authorize emergency work to move a 15-inch sewer line that runs next to the creek and railroad tracks north of Tatamy Road in a Seiple field.

The pipe carries between 150,000 and 400,000 gallons of sewage a day from Upper Nazareth and a part of the borough to the sewage treatment plant south of Tatamy Road, she said.

When the corn came down in the fall, a number of new sinkholes were found along the railroad tracks in the field that has seen sinkhole activity ... half a decade.

Mandes said she and authority engineer Donald Keller hiked out to the site last week and found holes that have grown to the edges of the sewer line.

"We're OK at this point, but we're not going to be OK for long ..." she said. "It's going to collapse within a month or two."

The board authorized Keller to collect estimates for the cost of moving the sewer line and performing test borings to make sure a new location would be stable, but a number of natural elements present a problem.

Mandes said the authority's easement in the field offers about 10 feet of space for the line to be moved away from the holes.

This set of sinkholes is less than a mile from the batch that has plagued a Palmer Township neighborhood, where 10-foot wide sinkholes have opened overnight.

"There certainly is the possibility

Please see SEWER /B-6

THE DETAILS

◆ This set of sinkholes is less than a mile from the batch that has plagued a Palmer Township neighborhood where 10-foot wide sinkholes have opened overnight.

0.8	32.9	Bear right onto US22W towards Bethlehem/Allentown.
0.8	33.7	Merge onto US22W.
1.8	35.5	Outcrops of Rickenbach Dolomite on right (Aaron and Drake, 1997).
0.3	35.8	Continue straight past Exit to PA191/Nazareth Pike.
2.6	38.4	Continue straight past PA512/center Street.
1.6	40.0	Continue straight past exit to Schoenersville Road.
0.6	40.6	Continue straight past exit to PA378S.
0.5	41.1	Continue straight past PA987Airport Road.
0.4	41.5	Continue straight past PA987S/Airport Road, unless going to Ollies.
1.5	43.0	Road cuts in Richenback Dolomite (Drake, 1996).
0.5	43.5	Cross Lehigh River.
0.2	43.7	Continue straight past Fullerton Avenue exit.
0.6	44.3	Continue straight past McArthur Rd/7th Street exit.
1.0	45.3	Continue straight past 15th Street exit.
1.8	47.1	Continue straight past Cedar Crest exit.
1.7	48.8	Continue straight past exit to US 309/Quakertown.
0.8	49.6	Continue straight past exit to PA Turnpike.
0.4	50.0	Continue straight past Kuhnsville exit.
0.8	50.8	Merge onto I-78W.

1.3	52.1	Continue straight past PA100, exit 49A and B.
1.2	53.3	Hills straight ahead and to the right underlain by the Martinsburg Formation.
1.7	55.0	Upgrade in I-78 marks contact between the Martinsburg Formation and the Epler Formation of the Beekmantown Group. Sherwood (1964) noted that the Jacksonburg Limestone was missing between the two units and interpreted the structure here and nearby as a series of isocloinal recumbent folds with characteristic slaty cleavage that were formed by gravity tectonics during an early period of deformation that are overprinted by smaller open folds and crenulation cleavage. He did not assign an age to the earlier folding, but noted recumbent folds in Silurian and Devonian rocks north of Blue Mountain. Drake (1987) mapped the contact as a folded thrust fault that bounds an overturned recumbent synform in the Epler Formation which is separated from a recumbent overturned limb in the Martinsburg Formation. The Martinsburg is shown as a series of NNE-trending overturned folds that cut across the older synform.
0.7	55.7	Approximate contact between the Martinsburg Formation and Weisenberg Member of the Windsor Township Formation of the Hamburg klippe sequence (Drake, 1987).
1.3	57.0	Continue straight past exit to PA863.
1.0	58.0	Windsor Township Formation outcrops on right (Lash, 1985).
1.0	59.0	Windsor Township Formation outcrops.
0.8	59.8	Graywackes in the Windsor Township Formation.
2.1	61.9	Continue straight past PA737 exit.
1.0	62.9	Windsor Township Formation outcrops on right.
2.9	65.8	Small outcrop on I-78 to right and larger outcrop on Old US 22 to the south in the Windsor Township Formation comprise rippled calcisiltite and shale with an early Early Ordovician conodont assemblage (Figure10).
1.2	67.0	Continue straight past the PA145 Lenhartsville exit.
2.6	69.6	Exposures of greywacke on right in the Windsor Township Formation (Lash (1987a).
2.3	71.9	Continue straight past Exit 30 to Hamburg.
0.7	72.6	Cross Schuylkill River.
0.1	72.7	Take exit 29B to right onto PA 61.
0.3	73.0	Cabela's on left.
0.7	73.7	Traffic light. Continue straight. Graywacke in the Windsor Township Formation

Figure 10. Ripple-bedded calcisiltite (light lenses) and calcareous shale, 0.9 mi (1.4 km) east of Lenhatrstville, PA, along old US 22. These are in slide blocks in the Hamburg klippe (Epstein and others, 1972). They contain North Atlantic Province conodonts of early Early Ordovician age (lower Arenigian) (Bergstrom and others, 1972).

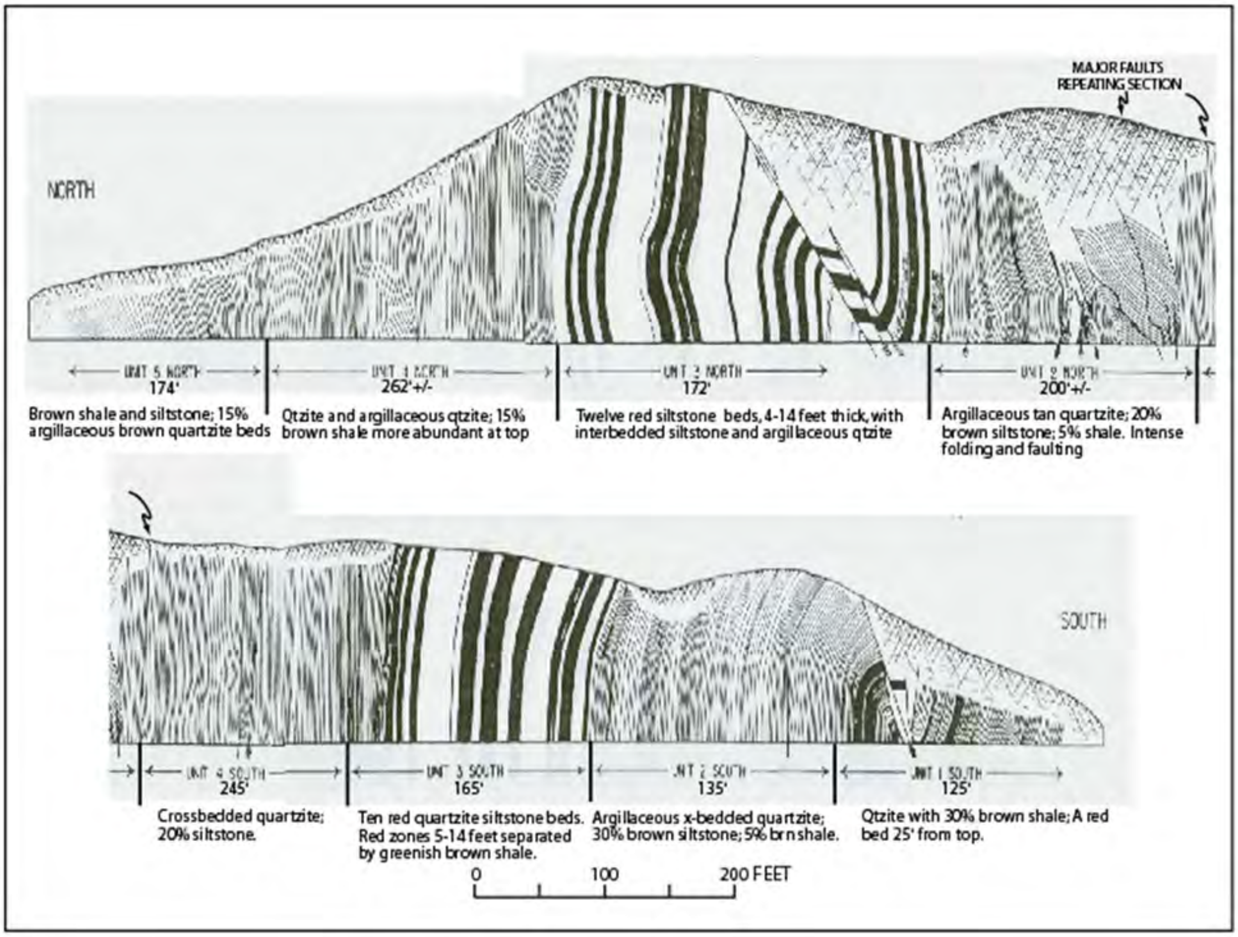

Figure 11. Section of the Clinton Formation along PA 61 just north of the Schuylkill River. Modified from Burtner and others (1958). Section is 2X original.

		on right.
0.8	74.5	Cross Schuylkill River. The river flows on the Tuscarora Sandstone here which is exposed in railroad cuts on both sides of the river.
0.2	74.7	Two-thousand-foot-long outcrop in the Clinton Formation on right, comprising near vertical, faulted and crumpled, interbedded siltstone, quartzite, and red beds (Figure 11), described in detail by Burtner and others (1958).
0.3	75.0	Turn LEFT onto Broad Street in Port Clinton.
0.2	75.2	Cross Little Schuylkill River and park in lot to left.
		STOP 1: SCHUYLKILL GAP
		See detailed stop description on p. 217.
		Leave Parking lot and return to PA61.
0.2	75.4	Turn right (south) on PA 61.
0.5	75.9	Cross Schuylkill River.
0.8	76.7	Traffic light. Continue straight.
0.2	76.9	Traffic light. Continue straight.

0.3 77.2 Traffic light. Continue straight. Do not turn right onto I-78/US22W.

0.3 77.5 Turn right onto I-78/US22E.

0.6 78.1 Cross Schuylkill River.

0.3 78.4 Continue straight past Exit 30/Hamburg.

0.4 78.8 Outcrop of Windsor Township Formation on right.

5.0 83.8 Turn right at Exit 35 onto PA143/Lenhartsville.

0.2 84.0 Stop sign. Turn left. We will be passing through exposures within the Windsor Township Formation in the Hamburg klippe for the next 4.8 mi (7.7 km), including thick greywacke and red claystone.

Figure 12. Slickensided overturned greywacke interbedded with shale with two cleavages. These are shown as strain-slip and fracture cleavages with an implied Alleghanian age of deformation (Lash, 1987a).

0.5 84.5 Graywacke on left.

0.3 84.8 Zettlemoyers Bridge over Maiden Creek on Long Road to right. Overturned greywacke and shale of the Windsor Township Formation with two cleavage and slickensides along Mountain road to the left (Figure 12). Beds immediately to the north dip south and are upright in the northern limb of the overturned syncline.

Spitzenberg, a 500-foot-high hill 1 mi (1.6 km) to the northeast (Figure 13), consists of about 150 ft (46 m) of gently dipping red and green, partly cross-bedded sandstone and carbonate-clast conglomerate unconformably overlying steeply dipping rocks of the Windsor Township Formation (Lash, 1985). Whitcomb and Engle (1934) named the Spitzenberg Conglomerate and believed

Figure 13. Spitzenberg hill, 2 mi (3 km) northeast of Lenhartsville, PA. The top is capped by 150 ft (46 m) of red and green, horizontally bedded to cross bedded sandstone and polymictic conglomerate with limestone clasts as much as 10 in (25 cm) long.

Figure 14. Location map and view of the Blue Rocks boulder field. Intersection of Long/Mountain Road and PA 143 is at mileage 9.6.

it was an erosional remnant of Triassic age. A late Ordovician to Early Silurian age was preferred by Stephens (1969) and Platt and others (1972) because a similar sequence of rock, however without the limestone conglomerate, underlies the Tuscarora Sandstone in Sharps Mountain 2.5 mi (4 km) to the west (Lash, 1985, 1987a). Lash (in Lash and others, 1984) expounded the sedimentology of the Spitzenberg rocks.

The road to the left (Blue Rocks Road) leads to the 2,000-foot long Blue Rocks boulder field (Figure 14), 1 mi (1.6 km) to the northwest,whose origin has been discussed by Potter, 1968. We will not be visiting the boulder field. The map gives directions for post-field trip visitation.

0.5	85.3	Overturned graywacke and shale of the Windsor Township Formation with abundant load casts on left.
0.2	85.5	Enter Albany Township.
0.2	85.7	Spitzenburg (pointed mountain) straight ahead (see Figure 13) .
0.5	86.2	Inverted red and gray shale grading up into greywacke of the Windsor Township Formation on left.
0.5	86.7	Little Roundtop Road to right leads to Spitzenburg.
0.3	87.0	Resistant Tuscarora conglomerate and sandstone caps nose of syncline at the Pinnacle.
0.3	87.3	Long exposure of greywacke
0.1	87.4	Interbedded red claystone and greywacke.
0.3	87.7	Excellent exposures of wildflysch, consisting of boudinaged sandstones and shales with scaly cleavage. Site of Stop 4 of the 49th Annual Field Conference of Pennsylvania Geologists (Lash and others, 1984). These broken formations were characterized by boudinaged and lozenge-shaped/isolated sandstone pods in a sheared shale with scaly cleavage. They developed at the frontal edge of the Greenwich slice in a convergent margin setting. (Lash, 1987b; Codegone and others, 2012).
0.2	87.9	Hawk Mountain Road to left. A visit to the Hawk Mountain Sanctuary is most rewarding (**http://www.hawkmountain.org/**). Continue straight.

0.4	88.3	PA737. Kempton with the WK&S Railroad (Hawk Mountain Line) displays vintage locomotives and offers local train rides by men with their big toys. Continue straight on Pa143, entering the Slatedale quadrangle
0.5	88.8	The Kistler Valley Fault separates rocks of the Windsor Township Formation from those of the Shochary Ridge sequence (Epstein and Lyttle, 1993), which holds up Shochary Ridge, rising to nearly 700 ft (213 m) above the valley floors to our right. The New Tripoli Formation forms the lower part of the sequence, consisting 4,000 ft (1,219 m) of fossiliferous, calcareous greywacke interbedded with thick slate. The overlying Shochary Sandstone, ranges to more than 4,000 ft (1,219 m) thick, comprising thin- to thick-bedded calcareous greywacke and interbedded slate. These two units form the singular Shochary syncline, a deep overturned syncline bounded by faults and with no complementary anticline. For the next 5.8 mi (9.3 km) we will be traversing rocks that make up Shochary Ridge,
0.5	89.3	Shochary sandstone on left.
0.7	90.0	More sandstone. Trough of the Shochary syncline.
1.0	91.0	Village of Wannamakers
0.4	91.4	Leaser Road on left leads to Leaser Lake
0.8	92.2	Village of Jacksonville.
0.2	92.4	Pleasure Ct leads to Leaser Lake on left.
0.3	92.7	Ontelaunee Rd leads to Leaser Lake on left.
0.4	93.1	Hills to right are in the north limb of the Shochary syncline.
0.3	93.4	Village of Lynnport.
1.2	94.6	Buried contact between the Martinsburg Formation and New Tripoli Formation along the Eckville fault.
0.1	94.7	Slate dump in Pen Argyl Member of the Martinsburg Formation. We will visit the Member at the next stop.
1.4	96.1	Turn left onto Mosserville Road.
0.4	96.5	Several abandoned slate quarries and dumps in the Pen Argyl Member of the Martinsburg Formation for the next 2,000 ft (610 m) on left in a series of short wavelength folds (Figure 15).
0.5	97.0	Stop sign. Continue straight.
0.6	97.6	Poor exposures of greywacke in the Ramsyeburg Member

Figure 15. Abandoned slate quarry in the Pen Argyl Member of the Martinsburg Formation along the Mosserville Road. Bedding dips gently to the left (southwest) and cleavage dips more steeply in the same direction. Behre (1933, p. 347)

		of the Martinsburg Formation on right. About 1 mi (1.6 km) to the west, these graywackes become rarer in a series of folds and the Ramseyburg is no longer mappable (Epstein and Lyttle, 1993, p. 7).
0.4	98.0	Stop sign. Juntction with US 309. Continue straight. Road becomes Mountain road.
0.2	98.2	Ground covered with veneer of pre-Illinoian till making mapping of bedrock difficult.
1.9	100.1	Irregular topography atop Blue Mountain to left due to a series of northwest dipping thrust faults cutting overturned beds in the Shawangunk Formation and Bloomsburg Red Beds. (Epstein and others, 1974).
2.7	102.8	Turn right on Brown Street, leading to Slatedale.
0.8	103.6	Turn right into parking area of Penn Big Slate Company Manhatten Quarry (Figure 16). Note the large slate dump ahead and to the left (Figure 17).

Figure 16. Sign outside the Penn Big Bed Slate Company quarry.

Figure 17. Slate dump east of the Penn Big Bed slate quarry, a typical mound of waste slate common throughout northeast Pennsylvania, some of which exceed 200 feet in height.

STOP 2: PENN BIG BED SLATE COMPANY QUARRY (MANHATTAN MINE)

See detailed stop description on page 237.

Leave parking lot of Penn Big Bed Slate Quarry, turning left onto Brown Street.

0.8	104.4	Stop sign. Turn right on PA143/Mountain Road.
0.9	105.3	Cross over northeast Extension of the Pennsylvania Turnpike. Lehigh Tunnel through Blue Mountain to left. See discussion for Stop 3.
1.9	107.2	Talus covered slope in Lehigh Gap straight ahead.
0.3	107.5	Stop sign at junction with PA873. Bear leftish towards PA248, crossing the Lehigh River.
0.2	107.7	Lehigh River. Note fencing and other fetaures used to stabilize the slope.

0.1	107.8	Traffic light. Turn right onto 248E.
0.1	107.9	Traffic light. Continue straight on PA248E.
0.1	108.0	Gravel road to stop 3 on left. Continue straight for 0.7 mi (1.1 km) to turn-around point.
0.7	108.7	Turn left at Gulf Station and re-trace route along PA248.
0.8	109.5	Carefully turn right after blinking light onto gravel road.
0.1	109.6	Park in parking area and settle down with LUNCH. After eating, burping, and farting, proceed northward towards the Martinsburg-Shawangunk contact.
		STOP 3 AND LUNCH: LEHIGH GAP.
		See detailed stop description on page 248.
		Leave Parking area at Stop 3.
0.1	109.7	Carefully turn left onto PA243E.
0.2	109.9	Turn left on Timberline Road.
2.7	112.6	Stop sign. Turn left on PA946 towards Danielsville.
1.1	113.7	Traffic light. Turn left on Blue Mountain Drive and ascend Blue Mountain.
0.8	114.5	Coarse-pebble conglomerate in the Weiders Member of the Shawnagunk Formation is overturned 50o to the southeast (Figure 18).
0.6	115.1	Devil's Potato Patch on right, a boulder field.
0.2	115.3	Cross Appalachian Trail.
0.1	115.4	Blue Mountain Ski slope to right.
0.2	115.6	Sand pits in Chestnut ridge in middle ground to left are in weathered Palmerton and Oriskany Sandstones.
0.3	115.9	Bloomsburg Red Beds on right in southeast limb of recumbent fold that has been rotated past the horizontal (Figure 18).
0.9	116.8	Blue Mountain Lodge on right. Entering village of Little Gap.
0.3	117.1	Bear left on Lower Smith Gap Road towards Palmerton.
0.2	117.3	Turn right on Covered Bridge Road. Buses may have to detour to the left around the bridge.

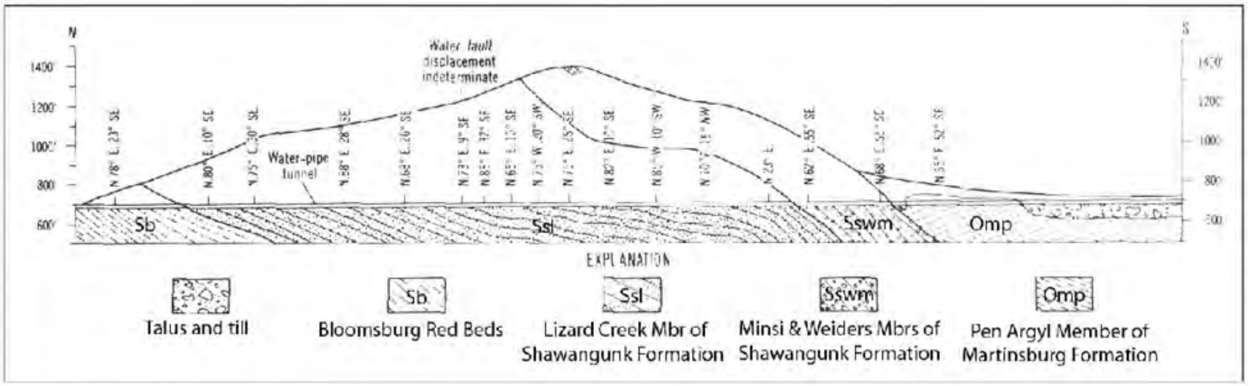

Figure 18. Cross section through Blue Mountain at Little Gap along water tunnel for the city of Bethlehem, PA., from Epstein and others (1974, fig. 142). Dips plotted are corrected to tunnel direction. Actual dips and strikes are recorded above section. All dips are overturned to southeast except northwest dips which are in beds that have been rotated more than 180°. Modified from unpublished data by B.L. Miller, 1940.

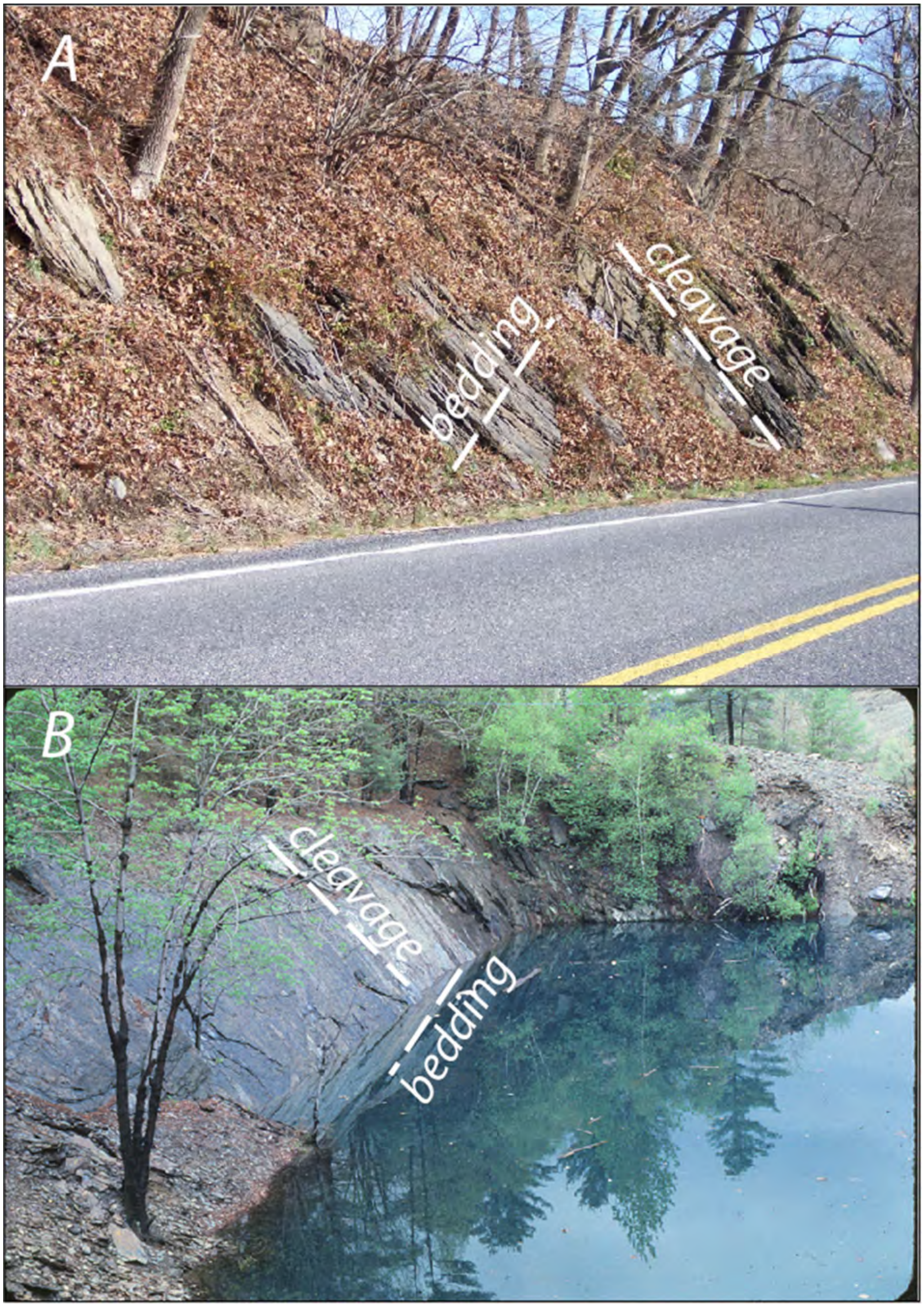

Figure 19. A—Well-developed slaty cleavage in the Mahantango Formation exposed in a series of road cuts about one mile east of Little Gap, PA; B—Bray Quarry No.1 (Behre, 1933, p. 125), a slate quarry in the Mahantango Formation just north of the village of Aquashicola, PA, 3 mil (5 km) west of Little Gap. The prominent cleavage dips 65° southeast; bedding dips 69° northwest. Behre (1933) noted that slate production ceased about 1915. This observation supports the conclusion that the regional slaty cleavage, prominent in the Martinsburg Formation, passes through all rocks at least into those of Middle Devonian age. Picture taken in 1981.

0.5	117.8	Cross Aquashicola Creek through covered bridge.
0.1	117.9	Village of Little Gap. Turn right on Little Gap Road.
0.3	118.2	Mahantango Formation on left. For the next 0.6 mi (1 km) uniform siltstones have pronounced slaty cleavage that dips 40-50^{o} southeast towards the road. Beds dip 40-80^{o} to the northwest on the south limb of the Weir Mountain syncline (Stop 3, Figure 5). The cleavage in these Devonian rocks are as well developed as those in the Martinsburg Formation and has allowed quarrying for slate nearby (Figure 19).
0.1	118.3	Cleavage in the Mahantango Formation on left.
0.3	118.6	Mahantango outcrop on left.
0.6	119.2	Mahantango outcrop on left. Little Gap Road becomes Kunkletown Road as we pass eastward from Carbon County into Monroe County.
2.1	121.3	Continue straight towards Kunkletown, do not turn left on Silver Spring Blvd..
0.9	122.2	Village of Kunkletown. Continue straight.
0.2	122.4	Continue straight on Kunkletown road. Do not turn left on Fiddletown Road.
3.0	125.4	Sand and clay pits on Chestnut Ridge to right (Epstein and Sevon, 1978). Deep weathering of the Palmerton Sandstone of Devonian age has removed much of its cement, making for an easily excavated sand resource. Weathering of Lower and Middle Devonian shaley limestones, such as the Buttermilk Falls (now Onondaga) and New Scotland, has produced clay as much as 300 ft (91 m) deep that is used as a whitener in cement (Epstein and Hosterman, 1969.
0.2	125.6	Hill in middle ground to right underlain by the Nis Hollow Sandstone Member of the Mahantango Formation (Epstein and Sevon, 1978).
1.7	127.3	Shale chip gravel derived from the Marcellus Shale in slope to left.
0.7	128.0	Shale borrow pit to left.
0.6	128.6	Stop sign. Continue straight on Kunkletown Road.
1.5	130.1	Stop sign. Saylorsburg. Turn right onto Old Pa115.
0.5	130.6	Turn left on Cherry Valley Road (County 2004) towards PA33.
0.3	130.9	PA33 is a quick alternate route to Stop 4, Delaware Water Gap. We will continue straight on Cherry Valley road.
0.1	131.0	Many abandoned clay pits in Chestnut Ridge to right (geologic discussion given in Figure 7).
0.4	131.4	Camel Back Mountain in distance to left.
0.2	131.6	County 949/South Easton Belmont Pike to left. Continue straight on Cherry Valley Road.
0.5	132.1	Scenic/geologic view left (Figure 20).
1.6	133.7	Village of Bossardsville.
0.2	133.9	Hanson aggregate quarry on right. Excellent exposures in complexly folded Upper Silurian rocks (Poxono Island Formation, Bossardville Limestone, and Decker Formation) were examined by the 32nd Field Conference of Pennsylvania Geologists (Epstein and Epstein, 1967) and again later (Epstein and Epstein, 1969, Figure 21).

Figure 20. View looking northwest of Cherry Valley Road. The short-dashed white line is at the upper level of the topset plain of the glacial delta near Sciota, PA, described at mileage 13.6 and Figure 6. Glacial lake clays and outwash in flat fields lie in front of the delta. Camelback Mountain is held up by flat-lying Upper Devonian roack. Godfrey Ridge comprises complexly folded late Silurian to lower Middle Devonian rocks. Middle Devonian shales and siltstones make up the hills between Camelback and Godfrey.

0.5 134.4 View of Cherry Valley to northeast Figure 22).

1.0 135.4 Flat floor of Cherry Valley to right underlain by Wisconsinan glacial lake beds.

We are in the middle of the Cherry Valley National Wildlife Refuge, lying in Monroe and Northampton Counties, Pennsylvania, southwest of and adjacent to the Delaware Water Gap National Recreation Area.

Figure 21. Folds and faults in the Bossardville Limestone in the Hanson quarry.

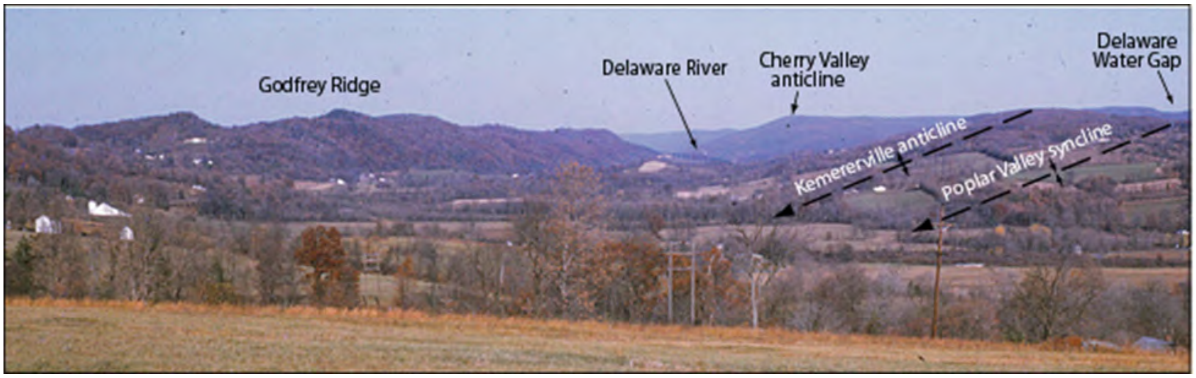

Figure 22. View to northeast from Cherry Ridge. The southwest-plunging Kemmererville anticline is nicely defined by the rounded hill in the Bloomsburg Red Beds. The bumps on Godfrey Ridge reflect complex folds in a variety of Upper Silurian through Middle Devonian rocks. The flat floor in the middle ground is underlain by Wisconsinan lake beds (Epstein, 1969).

		It was approved by the Fish and Wildlife Service on December, 2008, and was established to preserve the habitat for many rare and endangered plants and animals, including the bog turtle The refuge includes two caves where White Nose Syndrome in bats is a concern. About 20 mi (32 km) of the Appalachian Trail lie atop Kittatinny Mountain in the refuge.
0.1	135.5	Laminated intertidal Bossardville Limestone outcrop on right.
1.1	136.6	Bear right at Y in road heading toward Delaware Water Gap.
0.3	136.9	Deep mudcracks in Rondout Dolomite to left (Figure 23).
0.3	137.2	Kiln on left. The Bossardville Limestone is presently crushed for aggregate, but was burnt for agricultural lime many years ago.
0.1	137.3	Coeymans Limestone outcrop on left.
1.8	139.1	Stop sign; junction with PA191. Turn left toward Delaware water Gap.
0.2	139.3	Turn right on Cherry Valley Road toward Delaware Water Gap.
0.7	140.0	Stratified sand and gravel in covered slope to left.
0.5	140.5	Turn left onto detour from Cherry Valley Road (as of July, 2012). The road was closed ahead because of a landslide in stratified drift that developed along the steep river-cut slope in stratified drift (Figure 25).
0.6	141.1	Stop sign. Turn right on Fenner/Greenbrier Road.
0.2	141.3	Stop sign. Turn left rejoining Cherry Valley Road at the duck pond.
0.3	141.6	Hummocky stratified drift underlies golf course to right.
0.4	142.0	Stop sign. Continue straight. Enter Village of Delaware Water Gap.
0.2	142.2	Stop sign. Beware heavy traffic! Continue straight.
0.2	142.4	Stop sign. Turn right on PA611S.
0.2	142.6	Northwest dipping Shawangunk Formation on right.
0.2	142.8	Crest of Cherry Valley anticline (see Figure 1).
0.1	142.9	Resort Point overlook on left. This was the site of the Kittatinny House, one of the largest of many vacation hotels visited during the mid 1800s – early 1900s. It was destroyed by fire in 1931, and was never rebuilt. Opening of the Poconos to the north with abundant new resorts and higher/cooler climate spelled the end of the Delaware Water Gap resort era. See Wilson in this guidebook, p. __. Time permitting, we may return to this locality as STOP 4a.
0.2	143.1	Passing through a series of undulations in the Bloomsburg Red Beds (see Figure 1). Note southeast-dipping cleavage.
0.7	143.8	Contact between Bloomsburg Red Beds and the Tammany member of the Shawangunk Formation dipping xxo NW.
0.7	144.5	Turn right into Point of Gap parking lot. Discussion will be at the kiosk on the small hill. **STOP 4: DELAWARE WATER GAP.** See detailed stop description on page 272.
		Turn left onto PA 611N leaving parking lot to return to Shawnee Inn.
1.6	146.1	Resort Point Overlook; possible Stop 4A. See detailed description on p. 292.

Figure 23. Mudcracks more than two feet deep in the Whiteport Member of the Rondout Formation. Many laminated Silurian rocks in Pennsylvania are mudcracked. Their polygons are extended in the *b* tectonic direction. Slaty cleavage may be preferentially concentrated in these mud-crack columns along the *bc* plane, accentuating the apparent depth of the columns (Figure 24).

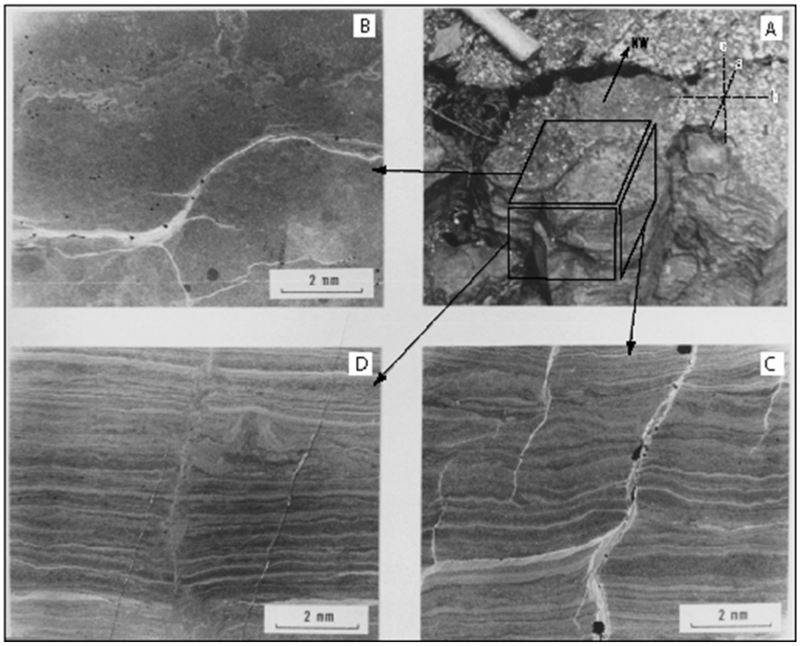

Figure 24. Deformed mud-crack polygons in laminated dolomite (A) that have been shortened in a northwest direction with a l/w ratio averaging 1.8/1. The coordinate axes are: A, direction of tectonic transport; B, direction of fold axes; C, perpendicular to *ab* plane. B, C, and D are negative prints of acetate peels showing the pronounced development of cleavage along the columns that are subparallel to *b* (B, *ab* plane; C, *ac* plane) and lack of cleavage development in the *bc* plane, D.

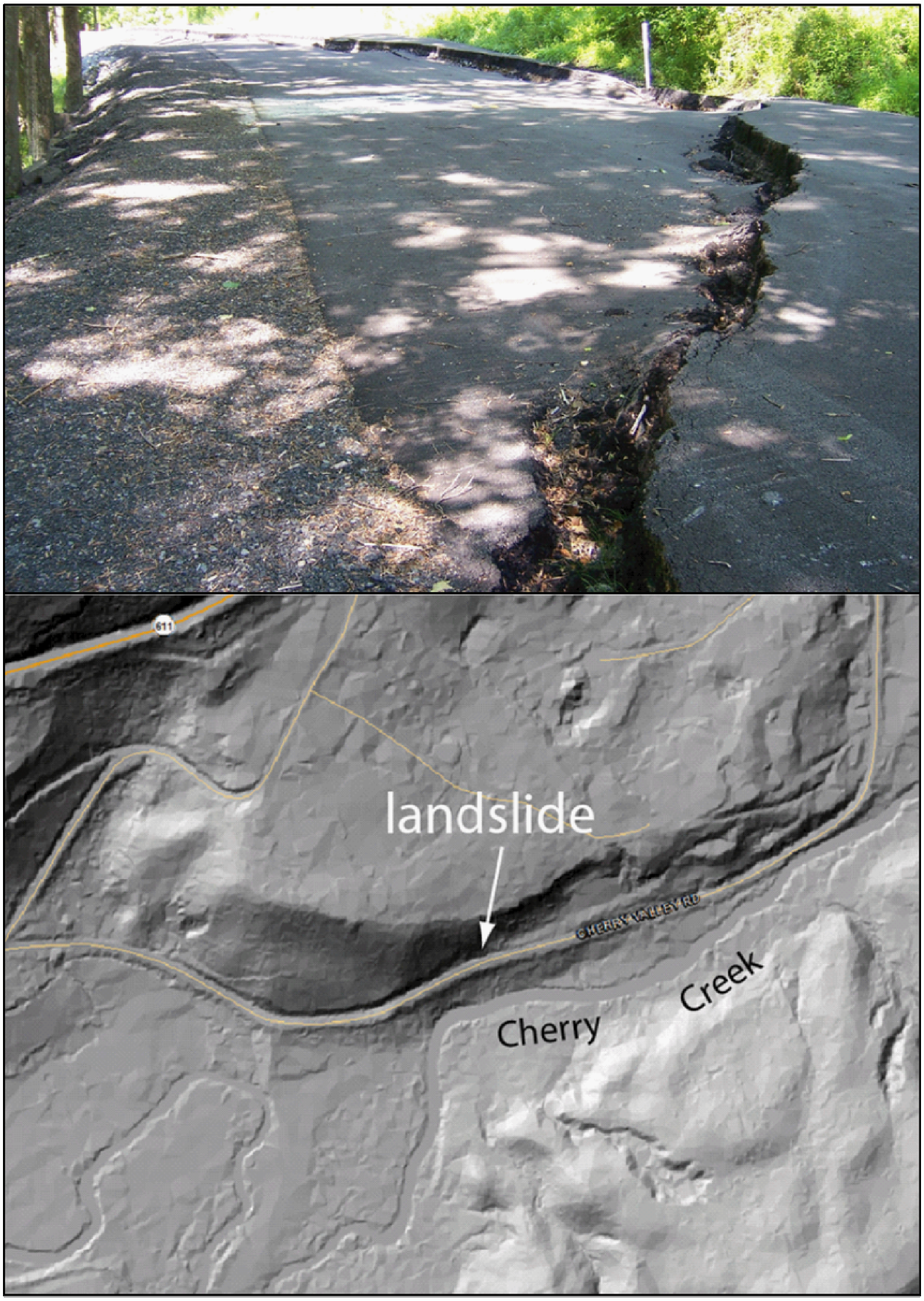

Figure 25. Landslide in freshly-laid blacktop at crest of ice-contact stratified drift north of and along the steep bank of Cherry Creek to the left (top) and lidar image showing the steep cut bank along Cherry Creek at the site of the slide (http://www.pasda.psu.edu/). Previous landsliding is evident along this stretch of the road. The slide occurred in September, 2011.

0.6	146.7	Traffic light in Village of Delaware Water Gap. Turn right onto Broad Street.
0.1	146.8	Diner on right, a favorite meeting place for geologists and other societal members of ill-repute.
0.3	147.1	Traffic light. Turn right onto River road.
0.3	147.4	Cross Brodhead Creek.
0.4	147.8	Stop sign at Village of Minisink Hills. Continue to right.
1.1	148.9	Traffic light at Buttermilk Falls Road. Continue straight.
0.5	149.4	Turn right into Shawnee Inn.
0.4	149.8	Unload at front of Inn.
		End of Day one trip. Have a beer or two.

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DAY 2--NEW JERSEY AND NEW YORK

Mileage		
Int.	**Cum.**	**Description**
0.0	0.0	Leave from circle in front of Shawnee Inn. The Inn and golf course are located on postglacial stream terraces that reach an elevation of 330 ft 101 m), about 35 ft (11 m) above the mean annual elevation of the Delaware River. An Early Archaic occupation site on Shawnee Island (Stewart, 1991) was dated at 9330 ± 545 yr B.P. Turn left onto River road. The road passes over a sequence of Silurian shale, limestone and dolomite that is covered in many places by thin, late Wisconsinan till.
0.7	0.7	Traffic light at Buttermilk Falls Road. Continue straight.
0.5	1.2	Minimart on left, and Smithfield School on right sit on a late Wisconsinan outwash terrace. The terrace lies at an elevation of 400 ft (122 m), about 100 ft (31 m) above the Delaware. Based on its position near the mouth of Marshalls Creek, it was probably laid down by a meltwater stream flowing down the Marshalls Creek valley; the outwash forming an outwash fan that coalesced with the valley train in Delaware Valley.
0.6	1.8	Village of Minisink Hills. Sits on outwash terrace, 100 ft (31 m) above Delaware River. Follow curve to left.
0.2	2.0	Historical Marker on left: Shawnee-Minisink Archeological Site. About 1,500 ft (457 m) eastward (left side) is the Shawnee-Minisink Paleoindian site Island (McNett and others, 1977). It is located on postglacial stream terrace similar in elevation to the terrace at Shawnee on the Delaware. Work here in the 1970s revealed a very rich and diverse, stratified cultural assemblage of Woodland, Archaic, and Paleoindian components. Radiocarbon dating of organic material collected from a hearth about 9 ft (3 m) deep yielded a radiocarbon date of 10,590 +/- 300 (W-2994). The hearth is located in cultural zone containing Paleoindian components (clovis point, scrapers, hammerstones).
0.2	2.2	Cross Brodhead Creek. Famous fly fishing stream during the latter part of the 19th and early 20th centuries that rivaled the more famous Catskill streams. Buffalo Bill, Annie Oakley, Grover Cleveland, Benjamin Harrison, and Theodore Roosevelt were some of the more notable persons that fished these waters (Ingram, 1998). Flooding along the Brodhead in August, 1955 (Hurricanes Connie and Diane) claimed over a hundred lives including 37 campers, many of them children, whom were staying at Camp Davis on the banks of Brodhead Creek near the village of Analomink, about 6 mi (10 km) to the northwest from this position. The following is an excerpt from the Morning Call, an Allentown-based newspaper about that tragic event (reprinted in an article by Frank Whelan of the Morning Call, October 13th, 2004). *Forty-six people, children and their mothers were spending five weeks of vacation at the religious camp. Among them were Jennie Johnson of Jersey City, N.J., and her three children. She was interviewed by The Morning Call* on

Aug. 22, 1955, and said that around 6:30 p.m. on Aug. 18 she and her children were watching the creek. We watched the stream rushing past and remarked how pretty it looked. There wasn't anything to worry about, at least we didn't think so then, she said.

They were sitting in the bungalow a half-hour later when the building began to shake. Johnson remembered that it sounded as if a dam had broken. She and her children fled the shaking building for the big, solid home of camp supervisors, the Rev. and Mrs. Leon Davis. There they joined the rest of the campers. The Davises, who had left earlier to go into town, were not there. Their return had been blocked by the rising water. Although the three-story house seemed safe, water quickly began to rise. As it reached each floor, the screaming campers fled to the next. Finally they were forced to seek refuge in the attic. The campers were watching the water climb the attic stairs after them when the building shuddered and collapsed.

Johnson told The Morning Call she was hit on her head by a board and passed out. When she came to, she found herself floating. Johnson grabbed one board and then another to try to stay afloat. Eventually she drifted onto a debris pile, praying until 7 a.m., when she was rescued. She found her 19-year-old daughter, but her two sons, ages 14 and 10, had died. When the final count was made, only nine of the 46 campers who had been at Camp Davis survived.

0.3	2.5	Traffic light. Turn left on Broad Street toward I-80E.
0.2	2.7	Turn right on ramp to I-80E.
0.5	3.2	Merge onto I-80E
0.1	3.3	Bloomsburg Red Beds with fish scales on right.
0.2	3.5	Northwest-dipping sandstone and conglomerate of the Shawangunk on right in the northwest limb of the Cherry Valley anticline (Epstein, 1973).
0.2	3.7	Crest of Cherry Valley anticline.
0.1	3.8	Cross Delaware River. Glacially scoured and river-washed surface of Bloomsburg Red Beds to left. The elevation of the bedrock floor beneath the Delaware River and thick glacial-valley fill is shown in Figure 1.
0.3	4.1	Series of undulations in Bloomsburg Red Beds on left.
0.4	4.5	Late Wisconsinan outwash fan to right, laid down at the mouth of Dunnfield Creek.
0.7	5.2	Downstream entrance to Delaware Water Gap (Figure 2). Note bend in dip of Shawangunk on cliff across the river in Pennsylvania. Epstein (1966) suggested that this flexure played a part in the location of the Delaware Water Gap.
0.1	5.3	When this road crews cut this roadway some old timer named Epstein happened to be present and noted some trace fossils and mudcracks on the underside of a shale bed within the Minsi Member of the Shawangunk Formation (Epstein and Epstein, 1969, fig. 8D). The Taconic unconformity separating Shawangunk above from Martinsburg Formation below was not exposed during roadway construction.; thick talus consisting of Shawangunk boulders on left conceal the contact. It was seen by Beerbower (1956) who reported a one degree divergence in dip and three degree in strike.

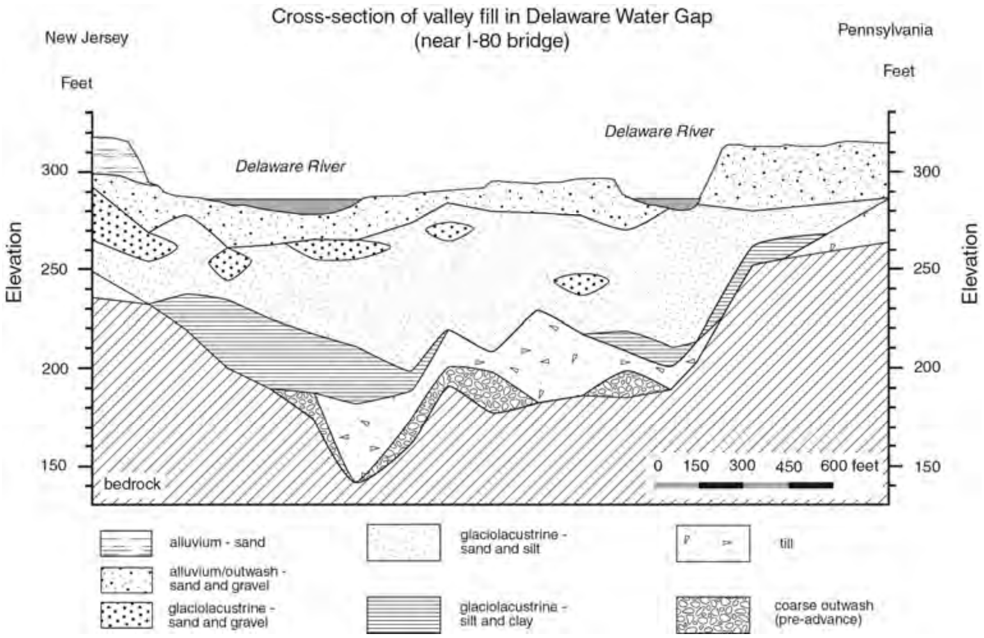

Figure 1. Interpretive cross-section of Delaware Water Gap near I-80 Bridge showing depth to rock and valley-fill stratigraphy. Thick deposits of Late Wisconsinan silt and clay, and sand presumed to be glaciolacustrine, lie in the subsurface throughout the Delaware River valley from Belvidere, NJ, to Port Jervis, NY. These materials were laid down in small proglacial lakes formed during deglaciation when slightly older outwash downvalley and in some places end moraine dammed the valley. Based on depth to rock throughout the valley and the elevation of the river channel where it flows over rock at Marble Mountain Gap (Witte and Stanford, 1995), there has been as much as 150 ft (46 m)of scour over the last two glaciations. Section based on detailed geologic logs and blow counts on file at New Jersey Geological Survey.

Figure 2. Aerial view of the Delaware Water Gap looking downstream. I-80 bridge in foreground. The meandering course of the Delaware River is congruent with plunging folds in the Shawangunk Conglomerate and Bloomsburg Red Beds. Photo by R.W. Witte, 2006.

0.3	5.6	Camp Weygadt to the right is the proposed new visitor’s center for DEWA. A nearby slate quarry was opened in 1820 by Mr. Schofield. It later came to be owned by the Delaware Water Gap Slate Company and a slate factory was added. A 1860 industrial census showed that the company produced 2000 squares of roofing slates, and about 725 boxes of school slates (Clemensen, 1996; Epstein; 1974). To support the slate industry a company town called Browning was built in 1870. Operations ceased in 1904 because the remaining slate was of poor quality. The thick-bedded slate here resembles the slates of the Penn Argyl Member, but they are interbedded with graywackes of the Ramseyburg Member. The Pen Argyl forms the host rock of most eastern Pennsylvania slate quarries. It is unconformably overlapped by the Shawangunk Formation west of Delaware Water Gap (Epstein, 1973).
1.0	6.6	Traveling on postglacial stream terrace, high outwash terrace on left.
0.7	7.3	Cross Stony Brook.
2.4	9.7	Turn right at exit 4C to NJ94N toward Blairstown.
0.1	9.8	Allentown Dolomite on left. Here we are traversing an Allentown cored anticlinal structure that plunges to the southwest just across the Delaware River and west of Portland, PA.
0.1	9.9	Continue north on NJ89.
0.3	10.2	Allentown Dolomite on right. We will be traveling up the Paulinskill Valley, which is underlain by Cambrian and Ordovician carbonate rocks, such as the Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone. The valley is flanked by hills held up by slates and graywackes of the Martinsburg Formation, fault-bounded contact with the carbonates on the east valley wall and gradational contact with the Jacksonburg Limestone on the west side of the valley.
0.4	10.6	Intersection with Stark Road (village of Warrington). Ice-contact deltas in the lower part of Paulins Kill valley delineate three ice-retreat positions (Ridge, 1983). These deposits lie as much as 100 ft (30 m) above the Paulins Kill, and they form the bulk of meltwater deposits in Paulins Kill valley. These deltas were laid down in small proglacial lakes held in the south-draining valley by older outwash deposits downvalley and possibly by ice in the Delaware Valley. This stepward style of deglaciation can be traced throughout the Paulins Kill valley. Based on the morphosequence concept (Koteff and Pessl, (1981); Ridge (1983) and Witte (1988) have delineated 14 ice-retreatal positions in the valley. The meltwater? terrace deposits that cover parts of the valley floor were formed by meltwater emanating from these up valley positions. The broad meltwater terraces in the vicinity of Vail and Walnut Valley (mileage = 14.1) lie well below the ice-contact deltas. Their lower positions in the valley reflect a lowering of local base level as older outwash down valley became further incised by meltwater draining from younger retreat positions upvalley.
1.0	11.6	Pass through railroad tunnel (Conrail, formerly Delaware-Lackawanna & Western R.R.; built in 1909).
0.8	12.4	Road to Mt. Pleasant on left. Pass through village of Hainesburg. A nearly

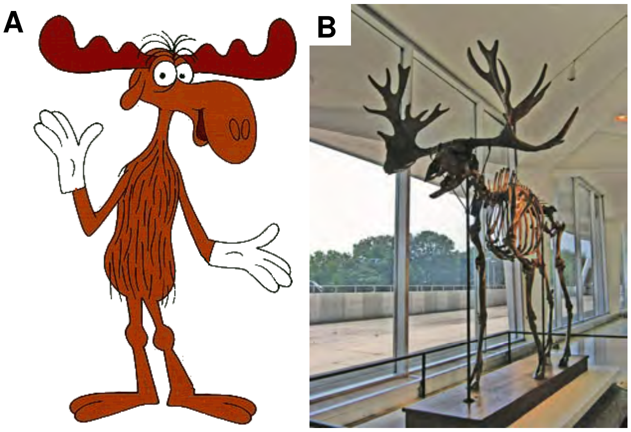

Figure 3. A—Artist's rendition of *Cervacles scotti* that was found in 1885 at Mt. Hermon, about four mi (6 km) southeast of Hainesville, New Jersey; Right—Reconstruction of the skeleton in the New Jersey State Museum.

		complete skeleton of *Cervacles scotti* Lydecker (Figure 3) was recovered from a bog just southwest of the village.
0.2	12.6	Pass over Yards Creek. For next 1.5 mi (2 km) cross over large ice-contact delta that was laid down in small proglacial lake held in by older outwash downvalley.
0.1	12.7	Cemetery on left in late Wisconsinan outwash (ice-contact delta).
3.2	15.9	Enter Blairstown Township.
1.7	17.6	Turn left onto Walnut Valley Road towards Yards Creek.
0.1	17.7	Beekmantown Group, upper part dipping northwest on west roadside. Just above this outcrop and around the bend lies the Jacksonburg Limestone which is covered by thin till. The Beekmantown unconformity lies at the Beekmantown-Jacksonburg contact. It marks the peripheral bulge migration from present day east to west caused by thrust sheet loading from the approaching Taconic island arc complex. Most of the large erratics are the Shawangunk Formation (whitish quartz-pebble conglomerate), with lesser red sandstone boulders of the Bloomsburg Red Beds.
0.8	18.5	Pass Frog Pond Road on left.
0.1	18.6	Cross over Yards Creek. Ramseyburg Member of the Martinsburg Formation exposed in creek bed to the right. Here the Ramseyburg has a well developed southeast dipping cleavage.
0.4	19.0	Many till stones beneath power lines to right. Common in areas of thick till.
0.5	19.5	Cliffs of Shawangunk Formation to the left.
2.4	21.9	Continue straight across intersection with Mt Vernon Road to guard house at Yards Creek Generating Station (117 WalnutValley Road). Check in and continue to parking area.
0.2	22.1	Park.

STOP 5: YARDS CREEK PUMPED STORAGE HYDROELECTRIC GENERATING STATION—MARTINSBURG SLATY CLEAVAGE; TACONIC UNCONFORMITY

See detailed stop description on page 294.

Leave parking area at Yards Creek and return to guard gate.

0.2	22.3	Turn left on Mt Vernon road.
0.1	22.4	Cross Yards Creek.
1.0	23.4	Outcrop of Martinsburg on right. Note its well developed, southeast-dipping cleavage. Ravine cut by meltwater on the left.

0.5	23.9	Cross over Stony Brook. Transition to carbonate-floored valley.
0.8	24.7	Stop sign. Turn left on Buchanan Road.
0.4	25.1	Stop sign. Turn left on NJ 94N.
0.4	25.5	Exposure of the dolomite facies of the Beekmantown Group, lower part on north roadside. Behind the supermarket on the left is the type section of the Jacksonburg Limestone. It rests unconformably atop the different units of the Beekmantown Group in New Jersey depending on the amount of previous erosion. The basal Jacksonburg, commonly called the cement lime member by the quarry workers is a shallow water carbonate that is abundantly fossiliferous. As the Taconic foreland basin begins to develop the Jacksonburg shows evidence of deepening water through an increase of argillaceous content. This marks the cement rock member of the Jacksonburg. Cement quarries in eastern Pennsylvania and western most New Jersey excavate and sell this material as it has an almost perfect Portland cement-type chemistry. Thomas Edison opened a quarry in the cement rock member in Stewartsville, New Jersey. The cement rock is only found in this area as farther to the east the fossiliferous cement lime grades directly into the Bushkill Member of the Martinsburg Formation. Regional outcrop patterns suggest that this Jacksonburg depositional pattern is controlled by the original foreland basin morphology. The deeper water Penn Argyl Member of the Martinsburg displays a similar pattern cropping out in eastern Pennsylvania and just across into New Jersey along I-80. Farther to the east the upper member of the Martinsburg, the High Point Member (Drake, 1991) becomes coarser grained and more proximal to its sediment source.
0.2	25.7	Cemetery on right lies in late Wisconsinan ice-contact delta.
0.2	25.9	Cross over Jacksonburg Creek.
0.3	26.2	Outcrop on right of Beekmantown Group crops out on right (southern roadside). This exposure lies on an anticlinal hinge. The carbonate sequence that continues upsection through the woods to the south contains an abundance of chert and supported small Paleoindian workings.
0.3	26.5	Sitting on the southeastern dipping limb of the anticline is an exposure of the Beekmantown Group, lower part. Immediately south lies a southeast dipping thrust fault that traverses almost the entire Paulins Kill carbonate valley.
0.2	26.7	Enter Blairstown. Originally named Smyths Mills after Benjamine Smyth who built a small gristmill around 1760. Renamed Butts Bridge in 1795 and officially changed to Blairstown in 1839. In 1820 the village consisted of a few dwellings, store-post office, tavern, black smith shop, and a few barns (www.blairstown-nj.org/AboutUs.html).
0.4	27.1	Traffic light. Continue straight on NJ 94N towards Newton and cross over Paulins Kill.
0.4	27.5	Outcrop of Martinsburg on right.
1.0	28.5	Series of outcrops of the Ramseyburg Member of the Martinsburg on right for the next 2.5 mi (4 km). We are just into the deep-water foreland basin deposits on the southeast side of the long anticlinal structure. The ribbon slates generally dip to the southeast with a well-developed southeast dipping cleavage. Several small folds occur within the Martinsburg. A southeast dipping thrust fault to the

		north places the Upper Ordovician Martinsburg over the Lower to Middle Ordovician carbonate units
3.8	32.3	Johnsonburg Rd. on right.
1.1	33.4	Leave Warren County and enter scenic Sussex County with cowsies.
0.2	33.6	Yellow Frame Presbyterian Church (Figure 4). Completed in 1786 on the last of three sites used by the local congregation. Yes, the original structure was painted yellow.
1.1	34.7	Thin-bedded Bushkill Member of the Martinsburg Formation on slope to left. Penecontemporaneous slump folds, presumably set in motion by an earthquake, was exposed about 40 years ago in pull-off area, now covered (Figure 5).
0.5	35.2	Outcrop of Martinsburg on right. As we continue along this route the Ramseyburg, a coarser grained turbidite than the Bushkill, can be seen on both sides of the road. Ramseyburg turbidites are characterized as Tbcde, and Tcde pattern while the Bushkill is more commonly a Tde structure.
0.3	35.5	Outcrop of Martinsburg on left.
0.3	35.8	Martinsburg on left.
0.6	36.4	Martinsburg on left.
0.5	36.9	Outcrop of Martinsburg on right.
0.4	37.3	As we continue along NJ 94 we are slowly migrating across the Martinsburg units toward another Cambrian and Ordovician carbonate belt.
0.3	37.6	Traffic light. Junction with County 610 (Phil Hardin Road). Continue straight.

Figure 4. Yellow Frame Presbyterian Church, a pre-revolutionary congregation that first met in 1750 near a place called Log Gaol, now known as Johnsonburg.

Figure 5. Penecontemporaneous slump folds, presumably set off by an earthquake, in laminated beds of the Bushkill Member of the Martinsburg Formation exposed in a clearing about 200 ft (61 m) long in 1974. The interval of folding is about 4 ft (1.2 m) thick; contacts with flat-lying beds above and below are abrupt. The amplitude of some folds is as much as 1 ft (0.3 m). The axes of the folds plunge 29°, N.85°W. Folds appear to verge to the southwest (left), suggesting current flow in that direction, agreeing longitudinal flow patterns in the Martinsburg Basin suggested by McBride (1962).

2.7 40.3 Enter Newton. Originally formed as a township in 1750. The town, a regional transportation hub, was originally built around the Sussex County Court House (Figure 6) which was completed in 1765. In 1780, the courthouse was the site of a raid by James Moody. The event was described as follows by historian Kevin W. Wright of Sussex County:

Figure 6. Sussex County Courthouse, Newton, New Jersey. The original courthouse was completed in 1765 and rebuilt in 1848 after it was largely destroyed by a fire the previous year. Inset photo—Moody's Rock, a Loyalist hangout during the Revolutionary War.

On May 10, 1780, Loyalist Lieutenant James Moody led six men from Staten Island on a daring raid to free eight prisoners held in the Sussex Gaol on various suspicions and charges of loyalty to the British Crown. Hearing a knock in the dead of night, the Sheriff called down from the upper room, asking these shadowy figures their business. Lt. Moody replied that he had captured a notorious Tory, who was one of Moody's men. Though seemingly delighted, the wary jailer refused to open the door. Moody then identified himself and threatened to pull down the building. With loud Indian war hoops, his small troop alarmed the sleeping villagers. Meanwhile, Lieutenant Moody gained entry through a casement and succeeded in releasing the prisoners. Despite a spirited pursuit lasting several days, the militia failed to capture the raiders. (excerpt from (**www.revolutionarywarnewjersey.com/new_jersey_revolutionary_war_sites/towns/newton_nj_revolutionary_war_sites.htm**).

Supposedly, Moody hid out in caves and rock shelters (inset, fig. 6) located a few miles (kilometers) south of town in an area known as the Muckshaws. Geologic mapping in that area has only revealed the presence of very small caves that would hardly be suitable as a hideout for a small group of wanted men.

0.5 40.8 Outcrop of Martinsburg on right.

0.6 41.4 Enter squared circle to right. Stay in left lane as you circulate counter clockwise.

0.2 41.6 Enter Main Street.

0.1 41.7 Keep left towards US 206N.

0.1 41.7 Turn right onto US 206/94N.

0.3	42.0	Note Martinsburg outcrop on left as it plays a part in the next stop. The outcrop displays a well developed cleavage and locally a high concentration of veins cut the Martinsburg. Northwest dipping Jacksonburg Limestone is exposed just one block to the east of our present location
0.4	42.4	Turn left on North Park Drive.
0.1	42.5	Turn left towards Home Depot.
0.2	42.7	Drive into parking lot and park along outcrop on south side. Stop 2.
		STOP 6: NEWTON, NJ HOME DEPOT PARKING LOT
		See detailed stop description on page 302.
		Return to US209/94N, right at traffic light.
0.3	43.0	Traffic light, continue straight.
0.1	43.1	Grand Union Klippe on left.
0.4	43.5	Traffic light, continue straight.
0.6	44.1	Martinsburg outcrop on left.
0.3	44.4	Traffic light, continue straight on US 209 N.
0.5	44.9	Cross over Paulinskill Valley Rail Trail.
0.1	45.0	County Rt. 626 (Halsey – Myrtle Grove Rd.) on left.
0.1	45.1	Ogdensburg-Culvers Gap moraine and ice-contact deltas on left (Figure 7). Recessional moraines in northwestern New Jersey form arcuate, nearly continuous to segmented, cross-valley ridges that mark former, stable, ice-marginal positions of the Laurentide ice sheet. These features are late Wisconsinan age, following looping courses through the Kittatinny and Minisink Valleys. They consist of noncompact, stony, silty-sandy till (diamicton) with minor beds and lenses of water-laid sand, silt, and gravel. This material is distinctly different from the more compact, and less stony ground moraine or till that lies near the moraine. Additionally, stratified drift is not a major constituent, even in places where it crosses river valleys (former glacial lake basins). Their course indicates the margin of the Kittatinny and Minisink Valley lobes was distinctly lobate at both a regional and local scale. Topography varies between ridge-and-swale and knob-and-kettle, with the former more prevalent along the outer morainal margin. The following definition, modified from Flint (1971) describes the character of these features. An end moraine is a ridge?like accumulation of drift built along any part of the margin of an active glacier. Its topography is initially constructional, and its initial form results from (1) amount and vertical distribution of drift in the glacier, (2) rate of ice movement, and (3) rate of ablation. Flint stressed the role of active ice transporting drift to the glacier margin, and the amount of drift in the ice sheet. Presumably, the more active the glacier and the more drift it contains, the larger the end moraine it will make. In addition, syndepositional and postdepositional modification of the moraine through ice shove, collapse due to melting of buried ice, and resedimentation of supramorainal materials chiefly by mass wasting, all act to give the recessional moraines their overall form.

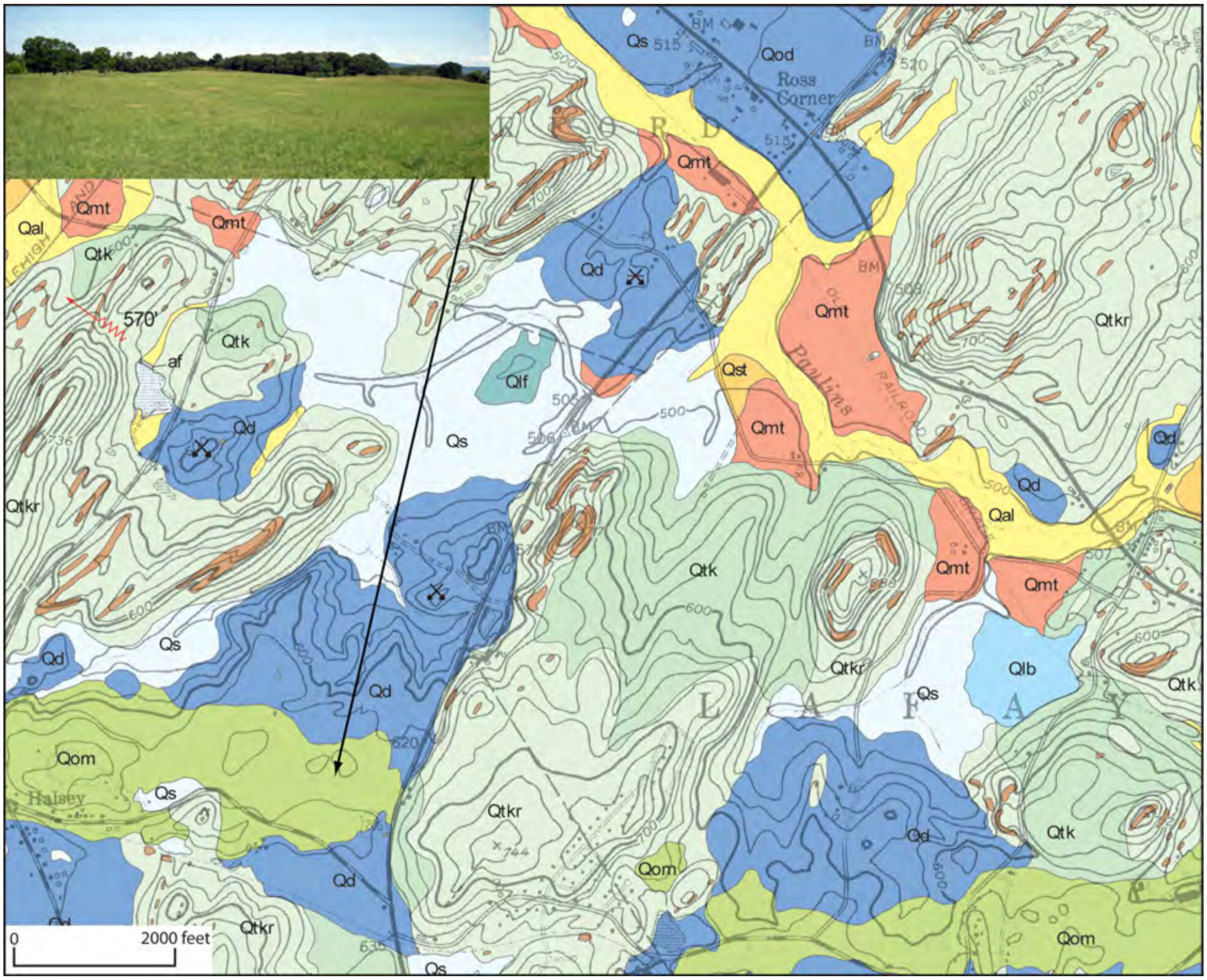

Figure 7. Surficial geologic map of part of the field trip route, Ross Corner, New Jersey. The inset photo shows the low knob and swale topography of the Ogdensburg-Culvers Gap moraine located on the west side of Route 206. List of map units: Qtk – thick till, Qtkr – thin till, Qom – Ogdensburg-Culvers Gap moraine, Qk – kame, Qd – ice-contact delta, Qlb – glacial lake-bottom deposit, Qmt – meltwater terrace deposit, Qst stream-terrace deposit, Qs – swamp and bog deposits, Qal – alluvium. Small, light brown, unlabeled unit are extensive rock outcrop. Map from Witte and Monteverde (2006).

0.4	45.5	Martinsburg on both sides of road.
0.5	46.0	Om on right.
0.4	46.4	Cross small tributary of the Paulins Kill. Discuss lowland north of Qom.
0.5	46.9	Om on right, pencil cleavage.
0.1	47.0	Cross over Paulins Kill.
0.1	47.1	Ross Corners. Traffic light. Ross Corner, intersection of Routes 206, 15, and 565. Turn left on US 206 N toward Branchville. Large outwash plain on right laid down in small unnamed glacial lake in the Paulinskill Valley.
0.2	47.3	Baseball stadium of the minor league New Jersey Cardinals on right.
0.8	48.1	Lehigh and New England Rail Road, glacial Lake Wallkill spillway. Just upvalley from the spillway lies the Augusta Moraine. Similar to the Ogdensburg-Culvers Gap moraine it also defines a major retreat position of the

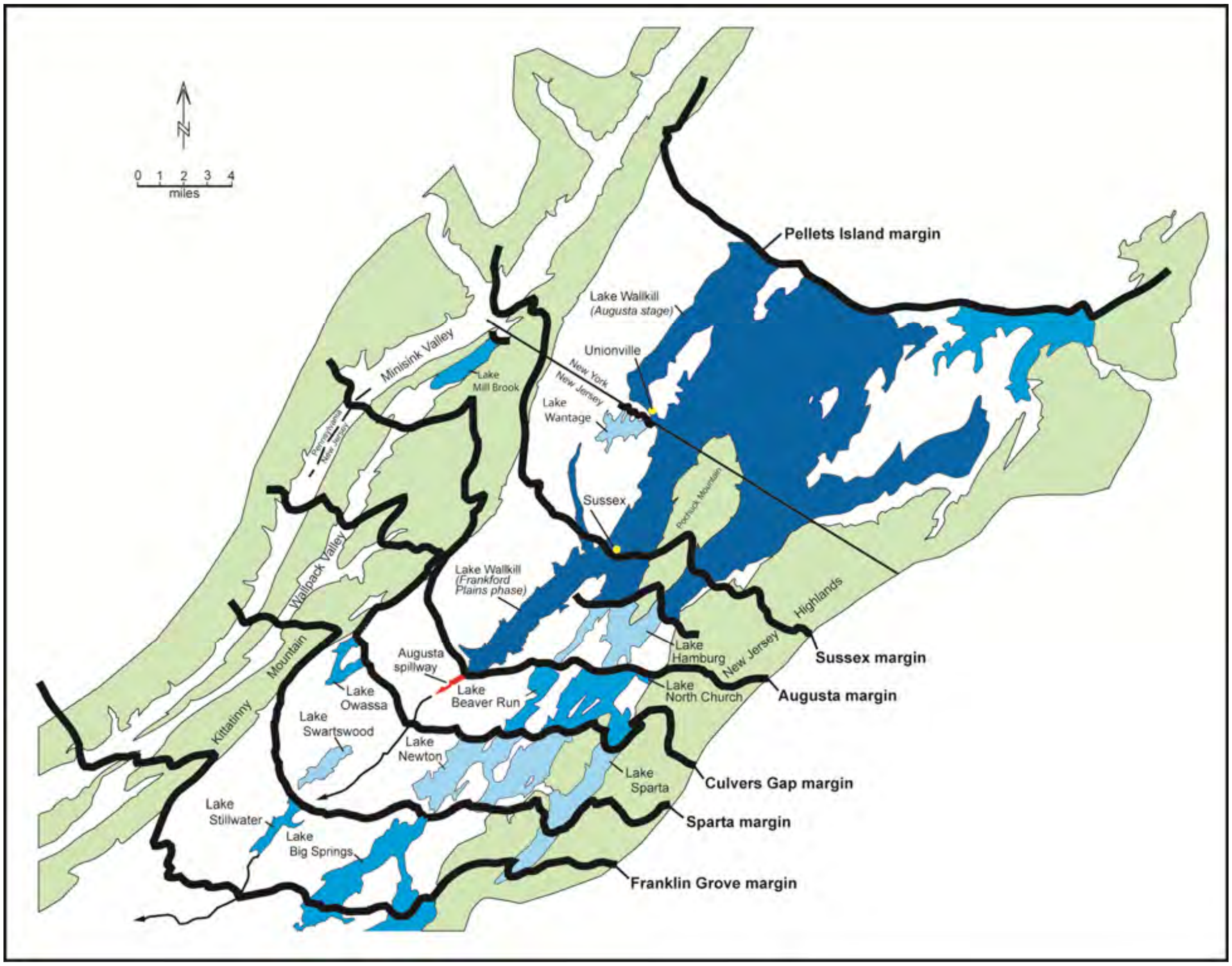

Figure 8. Late Wisconsinan ice-recession margins and glacial lakes in the upper parts of Kittatinny and Wallkill Valleys, New Jersey and New York. Retreat of the Kittatinny Valley ice lobe from the Augusta moraine resulted in the formation of glacial Lake Wallkill in Papakating Creek valley. The lake initially drained south across the moraine into the Paulins Kill valley. As the size of the lake and its drainage basin increased during retreat of the ice lobe, discharge increased and the spillway was lowered by fluvial erosion into an underlying outwash deposit. Eventually, a narrow deep channel was cut through the outwash by the outflowing stream. Erosion of the channel continued until bedrock was reached, and the level of the lake stabilized. Present elevation of this threshold, called the Augusta spillway, is estimated to be 495 ft (151 m) above sea level and the period during which Lake Wallkill utilized this spillway is called the Augusta stage. The period prior to the formation of the stable spillway is called the Frankford Plains phase of glacial Lake Wallkill. Lake Wallkill continued to expand northward into New York up until ice uncovered the northern end of the Skunnemunk Mountains, and a lower outlet was uncovered (365 ft (111 m) above sea level), the lake discharging into the Moodna Creek Valley. Figure modified from Witte (1997).

Kittatinny Valley lobe. The moraine where it crosses Papakating Creek valley overlies stratified sand and gravel, which shows it was deposited after a readvance of the Kittatinny Valley lobe. The extent of the readvance is unknown; however, based on the deglaciation history of Kittatinny Valley (Ridge, 1983; Witte, 1997) the readvance was probably minor. The retreat of the margin of the Kittatinny Valley ice lobe from the Augusta Moraine resulted in the formation of glacial Lake Wallkill in Papakating Creek valley (Figure 8). Initially, the lake's spillway was over morainal deposits of the Augusta Moraine. As the size of the lake and its drainage basin in-creased during retreat of the ice lobe, discharge increased and the spillway was lowered by fluvial erosion into the underlying coarse gravel and sand that lies beneath and south of the moraine. Eventually a narrow deep channel was cut through the sequence by the outflowing stream. Erosion of the channel continued until bedrock was reached, and the level of the lake stabilized. Present elevation of this threshold, called here the Augusta spillway, is estimated to be 495 ft (151 m) above sea level. The period antedating the formation of the stable spillway is called the Frankford Plains phase of glacial Lake Wallkill.

0.1	48.2	Traffic light. Continue straight. Plains Road on right.
1.0	49.2	Traffic light. Continue straight.
0.3	49.5	Traffic light. Turn right onto CR 519 N toward Branchville.
0.2	49.7	Bear left onto Mill Rd. (CR 519).
0.1	49.8	Cross Culvers Creek.
0.3	50.1	Branchville. At stop sign turn sharp right following Wantage Ave. (CR 519 N). Branchville was settled by William H. Beemer in 1690 who built a grist mill along Culvers Creek. Named Branchville in 1821. Back in the day of COGEOMAP, Don claims he would detour many miles (kilometers) out of the way to drive north of Branchville, just to get a glimpse of a bikini-clad, work boots wearing, raven-haired beauty who was operating a commercial, walk behind Gravelly lawn mower. Following extensive peer review, this sighting has never been verified.
0.4	50.5	Cross over Dry Brook. Start of long Martinsburg outcrop.
0.3	50.8	End of exposure.
0.5	51.3	Turn left following CR 519 N (Wantage Rd.).
0.6	51.9	Cross over Dry Brook.
0.7	52.6	Martinsburg on left.
0.3	52.9	Martinsburg on left.
0.1	53.0	Large swamp on right in Dry Brook Valley is largely the result of beaver dams.
0.4	53.4	Cross over Dry Brook again (now would be a good time for an adult beverage).
0.1	53.5	Martinsburg on right.
0.1	53.6	Martinsburg on right.
0.2	53.8	Martinsburg on both sides.
0.4	54.2	Martinsburg on both sides. (Do we really need to see more Martinsburg? Where is that drink?)
0.3	54.5	View of Sunrise Mountain to the left. Second highest point along the Appalachian Trail in New Jersey. Just below and slightly southwest of the mountain is the only known natural exposure of the Taconic Unconformity in New Jersey (Figure 9).

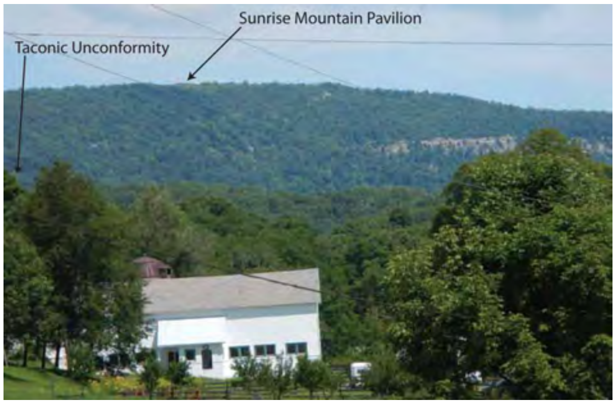

Figure 9. The only known, natural exposure of the Taconic unconformity in New Jersey located about 1 mi (1.6 km) southwest of Sunrise Mountain and 1200 ft (366 m) east of the Appalachian Trail.

		Unfortunately we won’t be going there due to its distance from the road and a mount of bushwacking needed.
0.5	55.0	Turn left onto Crigger Road.
0.9	55.9	Stop sign. Turn right onto Neilson Road.
1.5	57.4	Bog on left. Nothing notable about it. Just need a surficial reference to break up the monotony of “turn right” and “outcrop left”!
0.8	58.2	Syenite on left.
0.4	58.6	Martinsburg Hornfels complex.
0.7	59.3	Park busses on left alongside of road.
0.1	59.4	Trailhead to Stop 7.
		STOP 7: LUSSCROFT FARM AND BEEMERVILLE SYENITE
		See detailed stop description on page 314.
		Continue northeast on Neilson road.
0.3	59.7	Volcanic Hill Road on right. This road leads up to the volcanic diatreme responsible for some of the material observed at the last stop. Diverse xenoliths consisting of Mesoproterozoic gneiss, Cambrian and Ordovician platform carbonates and Martinsburg can all be found within the volcanic material. Several other volcanic diatremes exposures have been mapped in the area (Spink, 1967; Drake and Monteverde, 1992).
0.4	60.1	Stop sign. Turn left on NJ519N.
0.4	60.5	Junction with Sussex County 650. Continue straight on 519N.
1.6	62.1	Stop sign. Turn left on NJ23N/519N.
0.4	62.5	Enter Colesville.
0.9	63.4	Graywacke of the High Point Member of the Martinsburg Formation on left.
0.7	64.1	Martinsburg on right.
1.0	65.1	Bear left on Sussex 23; do not turn right on 519.
0.3	65.4	Martinsburg graywacke on left.
0.4	65.8	Appalachian Trial. Do not drive on it.
0.3	66.1	Turn right into High Point State Park.
0.2	66.3	Entrance booth. Continue straight towards monument. We are riding atop a narrow exposure of the High Point Member of the Martinsburg Formation with Shawangunk Formation to both the east and west. This represents a narrow fold in the Taconic unconformity which plunges to the northeast and unfortunately is not exposed.
0.1	66.4	Shawangunk erratic at split in road.
0.2	66.6	Picnic pavilion on right and outcrop of Martinsburg (High Point Mbr.). The Martinsburg plunges out just before Lake Marcia.
0.3	66.9	Lake Marcia and High Point Monument on right (Figure 10). Supposedly, the lake was named in 1855, after Marcia Smith, fiancee\` of a state geologist. It’s amazing how far an excuse a geologist will use to keep going out into the field. (**http://www.njskylands.com/pkhighpt.htm**).

Figure 10. Highpoint in the Skylands Region of New Jersey, is the highest elevation in the state at 1,803 ft (550 m). The monument rests on coarse clastic rocks the Shawangunk Formation. It was built in 1930 and adds an additional 220 ft 67 m) to the altitude of New Jersey.

0.3	67.2	Shawangunk Formation dips northwestward on left side of road.
0.1	67.3	Park road to Cedar Swamp on left (only known inland occurrence of Atlantic White Cedar). Continue straight uphill toward monument.
0.9	68.2	Park below monument. **STOP 8 AND LUNCH: HIGH POINT STATE PARK** See detailed stop description on page 334.
		Retrace route back to Route 23.
1.5	69.7	Stop sign. Turn right onto Rte 23N.
0.1	69.8	Om on right.
0.3	70.1	Saw Mill Road on left. Borings along gas pipeline about 2.5 mi (4 km) southwest show that the overburden (mostly late Wisconsinan till) is as much as 120 ft (37 m) thick. Many of the glacial landforms in this area are drumlins.
0.3	70.4	Shawangunk outcrop.
0.1	70.5	Steeny Kill Lake on right. The lake is manmade, its earthen dam on the lake's north side, constructed in 1938.
0.6	71.1	Steeny Kill Lake moraine. Small recessional moraine that marks a minor stillstand or readvance of the Minisink Valley lobe.
0.3	71.4	Two till exposures in ravine along Clove Brook, 0.5 mi (0.8 km) to the northwest (Figure 11). Here, exposed at a recent slump, is 10 ft (3 m) of yellowish-brown quartzite-rich till (Shawangunk clasts) overlying more than 30 ft (9 m) of reddish-brown, red sandstone-rich till (Bloomsburg Red Beds clasts). This change in till lithology is consistent with an ice flow shift from southward to nearly westward that occurred during deglaciation (topic discussed at High Point Stop 8).

Figure 11. Brown quartzite-rich till overlying reddish-brown red sandstone rich till exposed along the face of a small slump located along the upper reach of Clove Brook, High Point State Park, New Jersey. The reddish-brown till, largely derived from the Bloomsburg Red Beds, represents a more southerly flow across Kittatinny Mountain. The brown till, largely derived from the Shawangunk Formation, represents a southwesterly to westerly flow. This change in till provenance is consistent other indicators of ice flow (drumlins, striae, erratic dispersal) that show a more regional southerly flow superceded by a southwesterly to westerly flow during deglaciation.

0.5	71.9	Till exposure to right. What variety? Vanilla or chocolate?
0.7	72.6	Bloomsburg Red Beds outcrop on right.
0.3	72.9	Kame consisting largely of cobble-pebble gravel on right. Probably deposited in a small reentrant formed between the glacier's margin and a small valley that drained the higher ground to the east.
0.8	73.7	Clove Road on left, lower part of Mill Brook Valley. The north-draining valley contains many small ice-contact deltas that were deposited in glacial Lake Mill Brook, an ice-dammed lake.
4.2	77.9	Traffic light. Rte 23 becomes CR 15. Enter New York.
0.1	78.0	Merge onto I-84E toward Middletown.
3.7	81.7	Shawangunk-Martinsburg unconformity exposed on right. The angular discordance at the unconformity is five degrees (see Figure 3 on p. 39 of this guidebook).
2.6	84.3	Turn right at Exit 2 to Mountain road.
0.3	84.6	Turn right onto Mountain Road/CR 35.
4.5	89.1	Intersection. Turn slight left onto Mountain road following CR 73.
2.9	92.0	Martinsburg outcrop on left.
0.4	92.4	Martinsburg outcrop on left.
0.3	92.7	Martinsburg outcrop on left.
0.9	93.6	Stop sign. Turn left onto Highland Ave/CR 11. Enter Town of Otisville on Main Street.
0.6	94.2	Stop sign. Turn left on NY 211/State Street.
0.3	94.5	Begin Shawangunk float on right.
0.2	94.7	Shawangunk outcrop on right.
0.5	95.2	Buses pull off along side of road to right just before CR 61. Cross highway and follow abandoned railroad grade to the left (southwest) to Stop 9.
		The abandoned quarry in the hill to the right icontains northwest-dipping thin shales interbedded with typical Shawangunk quartzites and conglomerates (see

Epstein, 1993, fig. 5). These rocks are on line with exposures 1.2 mi (1.9 km) to the southwest to which Swartz and Swartz (1931) applied the name Otisville Shale Member of the Shawangunk Formation. This unit is out to lunch, that is, it is poorly defined, it is unmappable, and was discarded by Epstein (1993). Perhaps after this trip Epstein should be discarded. Clarke (1907) measured the rocks in the quarry and showed that shale makes up less than 3 percent of the section.

STOP 9: OTISVILLE RAILROAD CUT

See detailed stop description on page 354.

NOTE: If we do not go to Stop 10 at this point because of tourist crowding and abundant leaf peepers at the Sams Point Nature Preserve, then do not proceed on CR 61 but follow CR 211 straight ahead for 2.6 mi (4.2 km) and turn left onto US 209 and follow the road log back to Shawnee Resort. Pick up mileage 97.3 at the intersection with US 209N.

		Pull out and immediately turn right onto CR 61.
0.2	95.4	Sandstone and conglomerate of the Shawangunk Formation behind retaining wall.
1.9	97.3	Stop sign. Turn right onto US 209N.
5.4	102.7	Traffic light. Intersection with NY 17. Continue straight on US 209N. Excellent exposures of units within the Shawangunk Formation and Bloomsburg Red Beds, as well as the Silurian-Ordovician unconformity (15° discontinuity) are present to the east along NY 17 (Epstein, 1993).
0.8	103.5	Enter village of Wurtsboro
0.6	104.1	Traffic light. Continue straight on US 209N. Pastrami and corned beef sandwiches at Danny's on right.
2.2	106.3	Wurtsboro airport on right. Believed to be the oldest operating glider airport in the country.
2.0	108.3	Sand and gravel pit in delta to right (Figure 12).
1.1	109.4	Hill to right is in the Phillipsport moraine.
1.8	111.2	Town of Wawarsing, so the sign says. It is not! It is Summitville, which gets its name from the fact that it is the highest point on the old Delaware and Hudson Canal (Heroy, 1974).
2.3	113.5	View of northwest limb of the Ellenville arch to right.

Figure 12. Topset and foreset beds in a glacial delta in a sandpit east of US 209. This is the Phillipsport moraine of Rich (1935), a kame moraine that lay at the Hudson River-Delaware River drainage divide (see Reynolds, 2007).

0.9	114.4	Outcrop of moderately northwest-dipping gray shale, siltstone, and sandstone of the Mount Marion Formation on left (see Appendix 2 of this guidebook, p. 32).
0.8	115.2	Enter Ellenville.
0.8	116.0	Traffic light. Turn right on NY 52E/Center Street.
0.2	116.2	Traffic light. Continue straight on Center Street.
0.2	116.4	Cross Sandburg Creek.
0.2	116.6	Pass Broadhead Street/Berme Road. The Ellenville zinc?lead mine and a rock quarry in the tongue of the Shawangunk are located at the base of the mountain to the left. See Sims and Hotz (1951) and Rutstein (1987, p. 116) for descriptions.
0.2	116.8	Stop sign. Bear right on NY52E and ascend the mountain
0.1	116.9	Cross North Gully, joining NY 52. Exposures of the Ellenville Tongue of the Shawangunk Formation in roadcuts and Wurtsboro Tongue of the Bloomsburg Red Beds (see Epstein, this guidebook, Figure 3 on p. 5) in the creek bed of North Gully to the left.
0.4	117.3	Wurtsboro Tongue of the Bloomsburg Redbeds on left. The road follows this unit for several hundred feet (scores of meters).
0.4	117.7	Outcrops of uppermost Shawangunk , Ellenville Tongue, in flatirons on northwest limb of the Ellenville arch.
0.1	117.8	Cross South Gully.
1.0	118.8	There is a pull-off here where, 0.1 mi (0.16 km) below on the other side of the road, sedimentary structures in the uppermost Shawangunk are exposed (careful of high-speed traffic if you wish to stop here). The following description is from Epstein and Lyttle (1987). The full story is in Epstein (1993). The Ellenville Tongue of the Shawangunk Formation here consists of crossbedded and planar?bedded conglomeratic quartzite and pea?gravel conglomerates, with minor thin, lenticular light?olive?gray shale. Channels are abundant and many beds pinch out along strike. Shale drapes in crossbeds are common. Flattened silty shale balls up to 8 in (20 cm) long are seen on the lower exposed bedding surface. Crossbed trends throughout the immediate area are to the northwest. The sedimentary structures, current trends, and petrographic characteristics suggest a fluvial, braided stream environment of deposition, similar to the interpretation for the Shawangunk in eastern Pennsylvania (Epstein and Epstein, 1972). The beds dip about 45°NW. They are interrupted by a kink fold whose axis trends 18° S56° W., a more easterly trend than the regional strike of the beds. This fold, and scattered others in this part of the Shawangunk Mountains, may represent a later stage of Alleghanian folding than seen to the southwest in New Jersey. If the leaves are off the trees, you may be able to see the linear valleys in the Catskill Mountains to the north. These post-Taconic structures are discussed at Stop 10.
0.2	119.0	Small thrusts in Shawangunk to left. These have a strike similar to the kink axis at Stop 3 and may also be later structures.

0.3	119.3	Ellenville Tongue of the Shawangunk Formation; Launch site for hang gliders straight ahead.
0.3	119.6	Middle shale unit of Shawangunk on left.
0.1	119.7	Back into overlying quartzite unit.
0.2	119.9	Shale unit of Shawangunk to left, nice view at turn off to right. At this turn off you can see the flat?floored valley of Sandburg Creek underlain by glacial lake clays. In the far distance to the north the hills are underlain by sandstones of the Ashokan Formation, and in the far distance to the north are the higher Catskill Mountains underlain by Middle and Upper Devonian rocks of the Catskill Formation. The valleys in the Catskills are aligned along linears that may controlled by structural weakness. Casual observation of some o f the valleys indicate that the rocks become more intensely jointed as the center of the valleys are approached, and exposures are lacking in their centers. In this area we have been able to divide the lower part of the Shawangunk Formation into lower and upper units separated by a middle shale?bearing unit about 100 ft (31 m) thick (see Epstein, this guidebook, Figure 3 on p. 5). The shale unit underlies topographic lows, generally allowing for easy mapping. This unit can be seen at the base of the exposed section here, and consists of more than 80 ft (24 m) of interbedded, laminated, ripple laminated, olive?gray silty shale and moderate?brown and light?olive?gray very fine to medium?grained, crossbedded, lenticular sandstone, slightly conglomeratic in places. Many of the sandstones have harp channeled bases and some are ripple?topped. The shale unit is overlain by several hundred feet (scores of meters) of thin? to medium?bedded, medium?grained, partly conglomeratic, partly feldspathic, crossbedded, channeled quartzite with scattered thin and lenticular olive gray shale. The quartzites appear to be evenly bedded from a distance, but closer scrutiny shows that they are channeled, lenticular, and unevenly bedded.
1.0	120.9	Turn left on road to Cragsmoor and Ice Caves Mountain. Between here and Stop 10, the road will be mostly on glacial till, with a few scattered exposures of the Martinsburg Formation.
1.4	122.3	Village of Cragsmoore. Bear right past the post office onto South Gully Road.
0.1	122.4	Turn right onto Sams Point road.
0.2	122.6	Cragsmoor Fire Dept. on right. Martinsburg exposure on left. This exposure and a few more up the road peeking through their till cover are n the Taconic tectonic zone of broad open folds. Views of continuous cliffs of the Shawangunk Formation in the broad top of the Ellenville arch may be seen at several places along this road.
0.7	123.3	Nice exposure of till on bank to right (if you like till—reminds us of a song about glacial love: Till There Was You!).
0.4	123.7	Enter Sam's Point Preserve and park. Stop 10. Visit the displays in the Conservation Center and hike up the trail to Sam's Point atop the Shawangunk outcrop.

STOP 10: ELLENVILLE ARCH

See detailed stop description on page 362.

		Leave the Nature Preserve, following Sams Point road back to Cragsmoor.
1.2	124.9	Stop sign. Turn left onto South Gully Road.
0.1	125.0	Continue onto Cragsmoore road.
1.5	126.5	Turn right on NY 52W.
1.0	127.5	View of Catskill Mountains in skyline.
3.0	130.5	Enter Ellenville at bottom of mountain. Continue straight on NY 52/Main Street.
0.1	130.6	Turn left following NY 52 onto Center Street.
0.5	131.1	Traffic light. Continue Straight on NY 52/center Street.
0.2	131.3	Traffic light. Continue straight.
0.1	131.4	Traffic light. Turn left onto US 209S/Main Street.
0.4	131.8	Traffic light. Kohl's on left. Continue Straight
1.5	133.3	Traffic light in Wurtsboro. Continue straight toward Port Jervis.
1.5	134.8	Traffic light at NY 17. Continue straight on US 209.
5.4	140.2	Village of Deer Park.
3.2	143.4	Intersection with NY 211. Continue straight on US 209.
0.7	144.1	Neversink River. Delaware and Hudson Canal County Park on right. Possible traffic light while bridge is being repaired.
5.7	149.8	Polished and striated Onondaga Limestone on left.
0.9	150.7	Entering Port Jervis.
0.5	151.2	Continue straight on US 209.
0.4	151.6	Traffic Light. Junction with US6. Turn right following US 209/US 6W.
0.2	151.8	Traffic light. Turn left following US 209/US 6W.
0.4	152.2	Traffic light. Continue straight on US 209.
0.2	152.4	Cross Delaware River in Matamoras, PA.
0.9	153.3	Traffic light.
0.1	153.4	Junction with I-84W. Continue straight on US 209.
0.2	153.6	Traffic light. Continue straight on US 209.
0.4	154.0	Junction with I-84E. Continue straight.
0.3	154.3	Traffic light. Paddlers Point Shopping Center. Continue straight.
0.1	154.4	Traffic light. Continue straight.
0.3	154.7	Traffic light. Continue straight.
0.1	154.8	Traffic light. Continue straight.
0.1	154.9	Traffic light. Continue straight. Note cliff face above I-84 to right. The valley here has been glacially scoured resulting in many hanging valleys and waterfalls.
3.8	158.7	Enter Milford. Tom Quick Inn on left. Jim Quick, Chief Scientist of the USGS Earth Surface Processes Team (what a name!), asked Epstein if he knew of the name Ben Quick from anywhere in Pennsylvania, because he knew he was

related to such a person. So, Jim and Jack visited the Tom Quick Inn, his actual ancestor, and the legend of Indian-slayer Tom Quick, an Indian slayer was recounted. The story can be found in many places, including **http://www.genyourway.com/ss-7.html** (accessed 9/7/2012), here presented:

THOMAS QUICK was born about 1690 in New York. He married Margrieta Dekker December 22, 1713 in New York. They were the parents of at least seven children. The family eventually settled in Milford, Pennsylvania, about 1733 as the first white settlers recorded in the area. Milford is the county seat for Pike County and right on the Delaware River. During the summer of 1983 the town of Milford had a large celebration of this event, commemorating the 250 years since the first settler came to the area.

Although Thomas Quick is recorded as the first settler in the area, there probably were earlier people in the area as a number of settlers were listed as living just across the river in New Jersey as early as 1701. Since a number of Dutch related men were in the area, the Dutch Reformed Church sent their ministers into the area. For this reason the Historical Society does not feel that this Thomas Quick was the first settler and it should not be celebrated as such.

It was said that Indians were abundant in the area as it was on the Delaware River, rich in animals and fish for food and clothing. The Quicks had to live with the Indians for survival and therefore treated the Indians with respect and kindness. They supplied them with food and clothing. They were able to live with the Indians for over 20 years with only minor problems, even as more and more white settlers came to the area.

The legend goes that in 1756 while Thomas Quick and one of his sons and his son-in-law were working by the river, farming or cutting wood for their mill, they were attacked by Indians from a nearby woods. The Quicks, having no *weapons, ran for their lives for the house.*

The elder Quick was heavy and old (about 66 years old). His sons grabbed him by the arms and tried to hurry him along. He begged the boys to abandon him and flee.

One of the sons was wounded by a bullet. The boys at last had to leave their father. The boys escaped by crossing the frozen Delaware River into New Jersey. But they were able to see the Indians kill and scalp the elder Quick and cut a pair of silver buckles from his trousers.

One of his sons, Tom Quick, pledged he would revenge the death of his father. He was about 22 years old at the time. Years later he got the buckle back after killing a number of Indians in cold blood. Legend has it that he killed over 100 Indians. A number of books and articles on the internet have been written about the exploits of this Tom Quick as he became a famous frontiersman and Indian fighter. He lived until 1795, about 61 years old.

Was he history or legend? He became an official legend in 1889 when the town erected the Settler's Monument and transferred his remains there from a grave in Matamoras where he was buried.

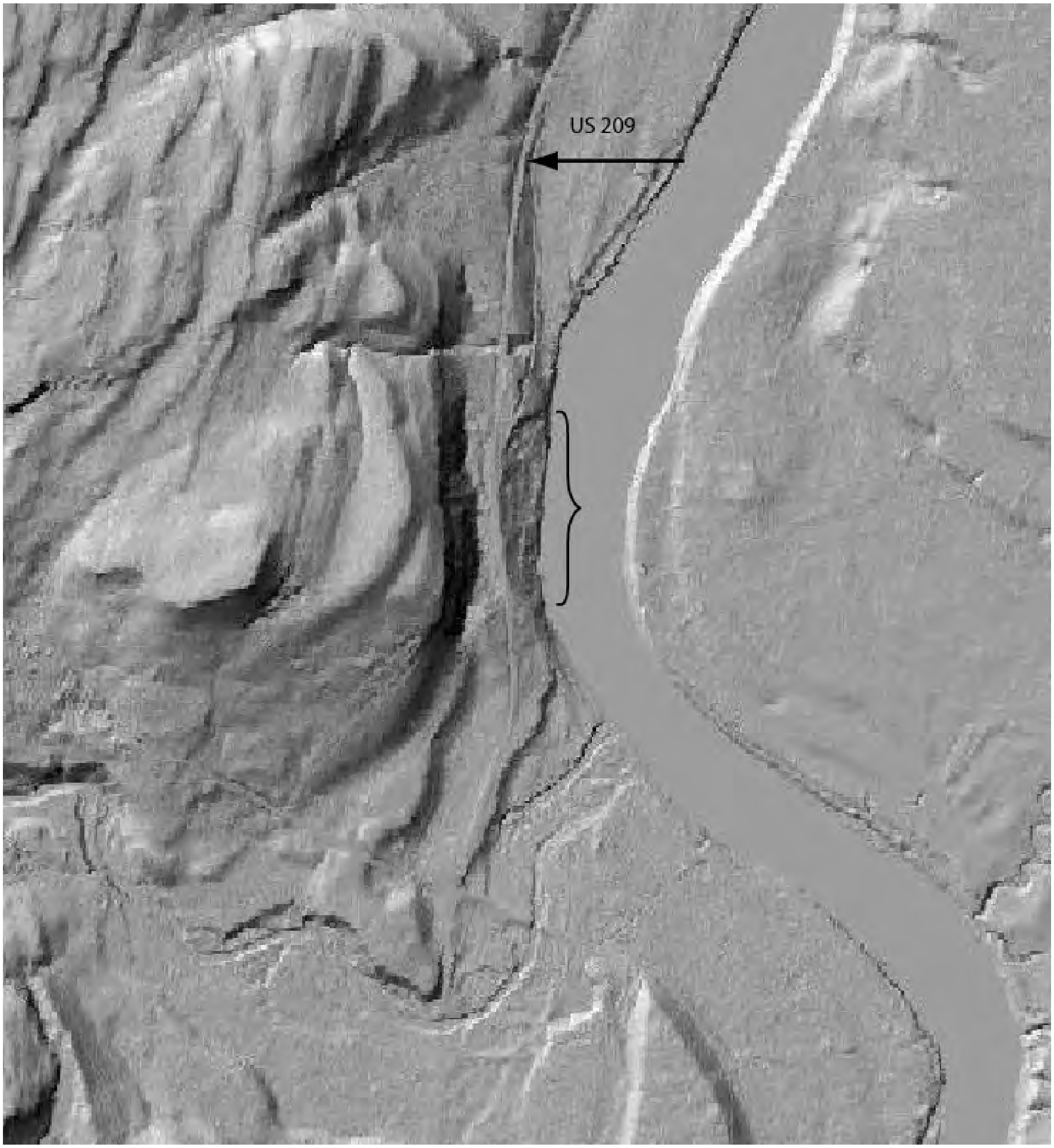

Figure 13. Lidar imagery showing landslide causing slumpage of US209 along the outside bend of the Delaware River. The slump is re-activation of the 1,000 ft- (305 m)-long landslide, affecting 560 ft (171 m) of the highway at the apex of the landslide's head. The road has been shutdown since xxx. The obvious culprit is the over-steepening of the slope in glacial till which was cut along the outside meander of the nearby Delaware River. The northward-striking, westward dipping Devonian rocks are well defined to the left in the image.

In 1997, the Quick's zinc monument on Sarah Street was vandalized with a sledgehammer. It was repaired but has not been redisplayed because of objections by native Americans.

0.5	159.2	Traffic light. Dingmans Ferry. Turn right on US 6 following detour. Normally we would turn left following US209 through Delaware Water Gap National Recreation Area. Flooding and landsliding (Figure 13) during tropical storm Lee in September 2011 resulted in closing the highway necessitating this detour.
0.2	159.4	Turn left on Mill Street and follow CR2001/Milford Road.
7.7	167.1	Turn left on RTE 739/Dingmans Turnpike.
2.5	169.6	Traffic light. Turn right on US209S, entering Delaware Water Gap National Recreation Area.
9.8	179.4	Marcellus on right.
0.9	180.3	Cliffs on right support shales of the Marcellus Formation at the base and Mahantango Formation siltstones above.
1.1	181.4	Cross Bushkill Creek in town of Bushkill.
1.1	182.5	Leaving DEWA.
0.6	183.1	Two quick traffic lights. Continue straight
1.1	184.2	Exposure of fault in basal Marcellus on right (Figure 14; see also Ver Straeten and others, 2001, p. 185).
1.7	185.9	Traffic light. Continue straight.
0.4	186.3	Traffic light. Continue straight.
0.4	186.7	Traffic light. Continue straight.
0.5	187.2	Traffic light. Continue straight.
0.8	188.0	Traffic light. Intersection with Mt. Nebo/Oak Grove Dr. Continue straight.
0.2	188.2	Enter new bypass. The Marshalls Creek Traffic Relief Project was completed and open to the public on June 12, 2012, relieving long lines of stop-and-go traffic at the bottleneck at Marshalls Creek.
0.4	188.6	Traffic light, continue straight. Onondaga Limestone outcrop.
0.2	188.8	Onondaga on left.
0.5	189.3	Large Schoharie outcrop on left.
0.2	189.5	Enter roundabout. Continue left onto US 209S.
0.6	190.1	Roadcut through interbedded shale, limestone, and chert of the Port Ewen Shale-Shriver Chert interval.
0.2	190.3	Roadcut through highly fossiliferous Port Ewen shale.

Figure 14. Two Noo Joisey geologists looking at the shear zone in the basal Martinsburg Formation (Union Springs Member) overlain by cleaved shaly siltstone of the Stoney Hollow Member of the Marcellus. The same shear zone has been seen in several scattered places all the way northeast to New York and around the northern edge of the Catskill Plateau. Has the entire Pocono-Catskill Plateau slid on this decollement? But, that's another story.

0.6	190.9	Deep road cut through the Port Ewen Shale. On the west side of the road is a 32-ft (10–m) long erratic of cherty limestone sitting on the shale (Figure 15).
0.5	191.4	Cut in south-dipping lower Onondaga Limestone, Schoharie Formation, and upper Esopus Formation. Buttermilk Falls on Marshalls Creek, the type locality of the Buttermilk Falls (=Onondaga) Limestone, is about 0.1 mi (0.16 km) to the east of here.
0.3	191.7	Traffic light. Turn left on Buttermilk Falls road.
0.2	191.9	Outcrop of Schoharie on left.
0.5	192.4	Traffic light. Turn left on River Road. Exposure of New Scotland Formation on left.
0.3	192.7	Turn right into Shawnee Inn.
0.2	192.9	Pull into parking lot.

Figure 15. Humongous Onondaga erratic derived from the Edgecliff Member of the Onondaga Limestone, which has supplied scattered large erratics like this one throughout the area. (see White, 1882, p. 46-48).

End of Trip.

Go Home!

Don't bother me anymore.

DAY 2 ROAD LOG REFERENCES

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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.

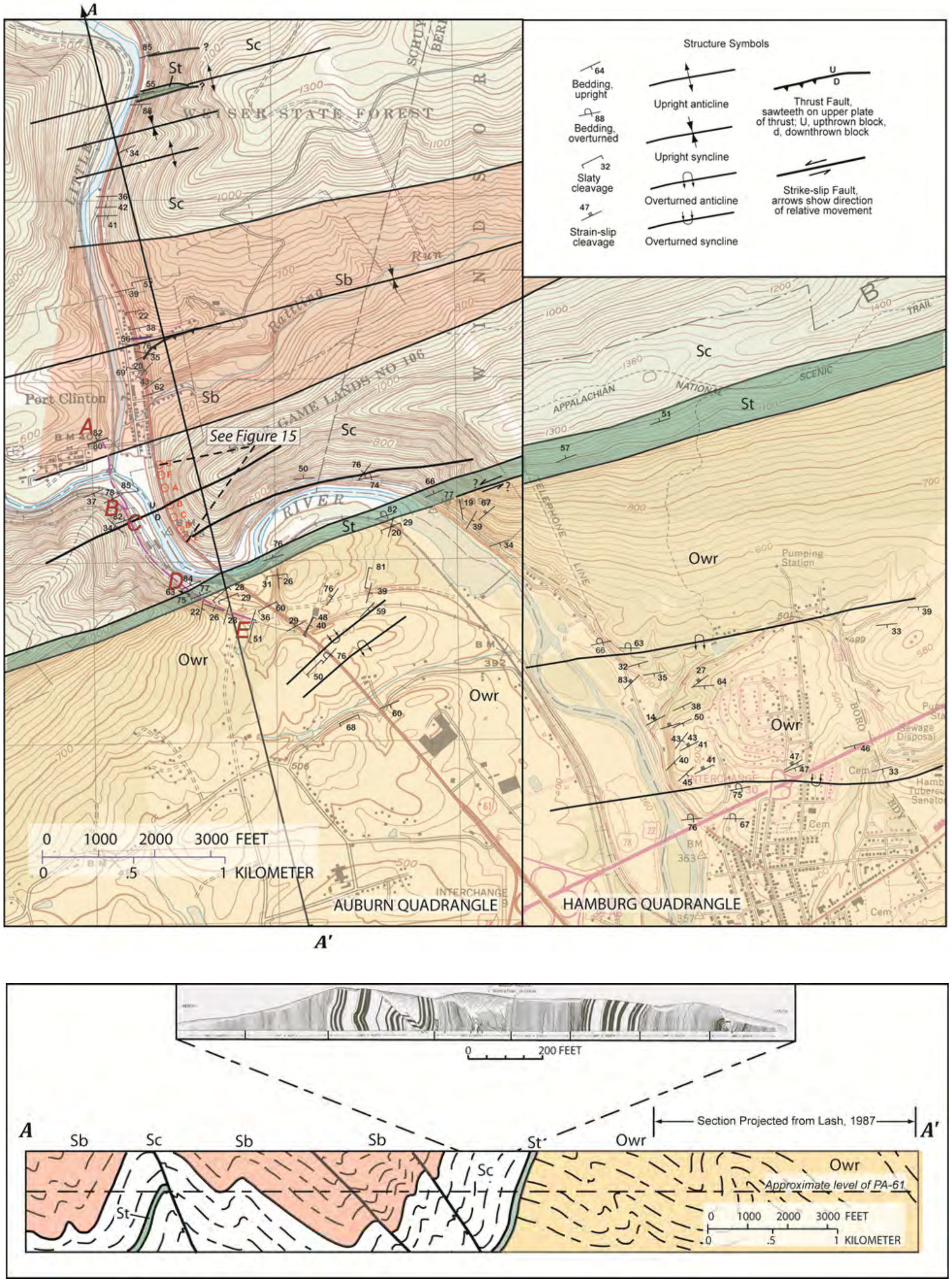

Figure 1. Reconnaissance geologic map and section of the Schuylkill Gap area, based on a traverse along PA-61 and modifications of Stephens (1969; see also Figure 11, Day 1 Road Log). The upper figure in the cross section shows details in the Clinton Formation from Buetner et al. (1958). The southern 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*.

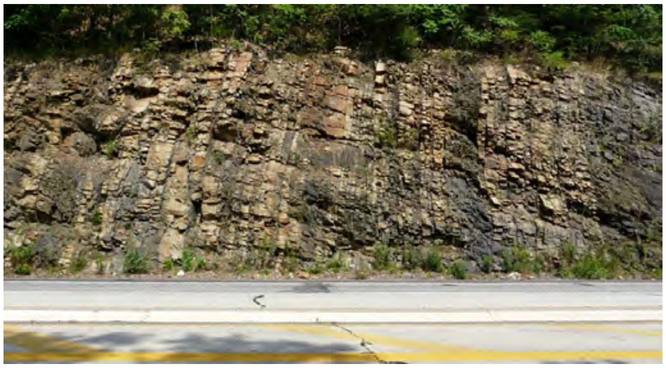

Figure 2. Sandstone and shale in the middle part of the Clinton Formation along PA-61 (mileage 74.7 of the Day 1 Road Log).

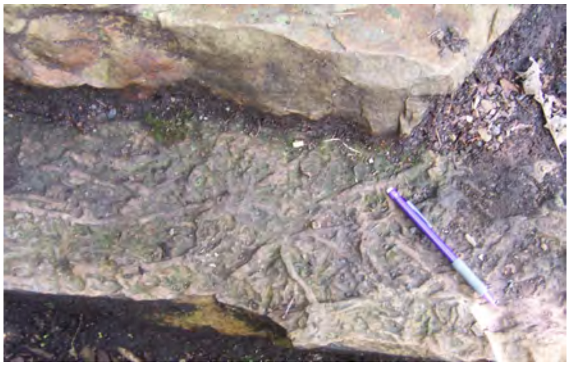

Figure 3. Horizontal burrow, *Arthrophycus* in rock step half-way to the rail trail.

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.

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.

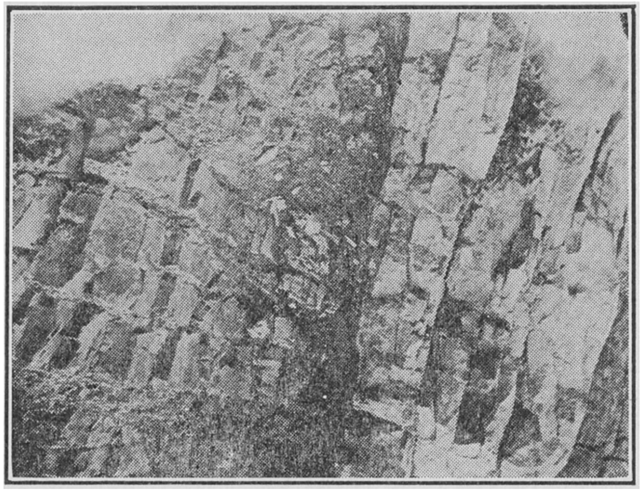

Figure 4. Grabau (1921, p. 293) described this exposure as “Unconformity between Hudson River sandstone (nearly horizontal) and Shawangunk conglomerate, steeply inclined and overturned to the west. Near Port Clinton, Pennsylvania”. There appears to be a zone of possible shearing near the contact.

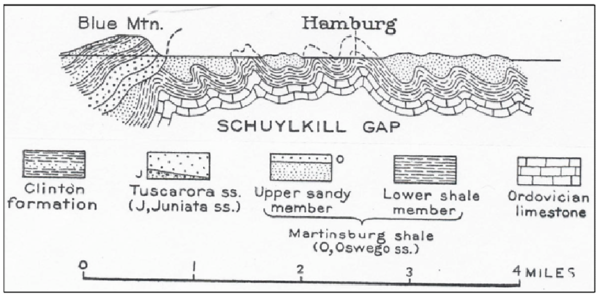

Figure 5. Stose’s (1930, p. 636) cross section through Schuylkill Gap showing the contact between the “upper sandy member” of the “Martinsburg shale” (Windsor Township Formaytipon of this report) at the outcrop level.

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 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*.

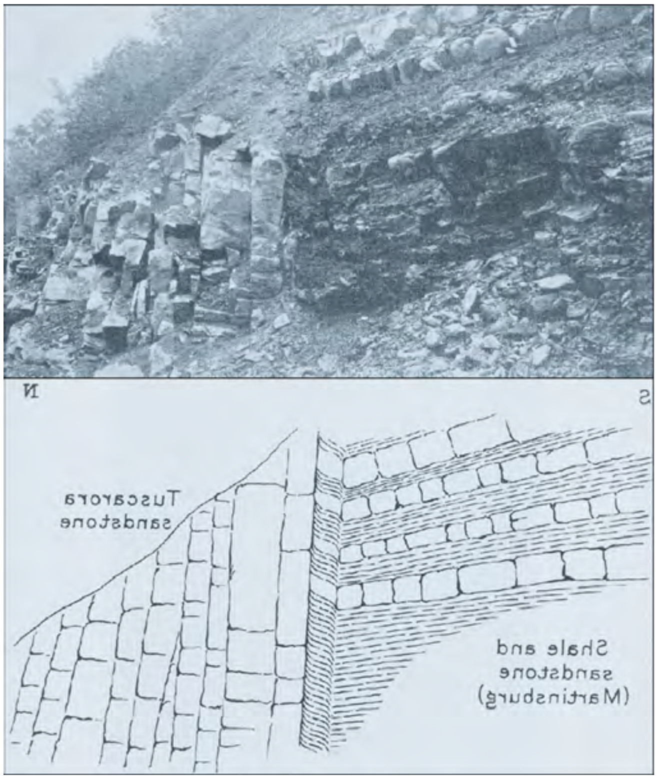

Figure 7. Closeup of the easternmost exposure of the unconformity along the Reading Railroad on the south side of the tracks. Stose (1930, Pl. 10) noted shearing at the contact, but considered it minor.

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".

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.

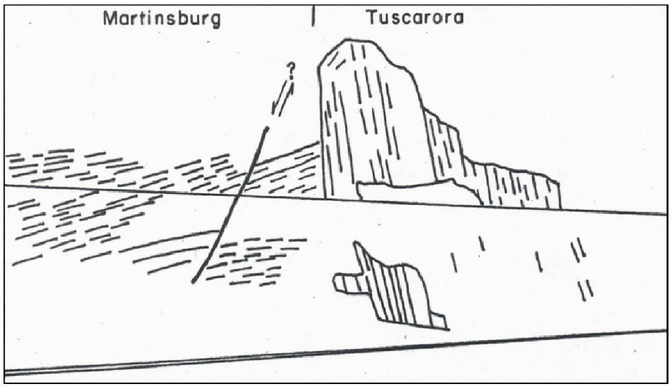

Figure 8. Sketch of the fault in the "Martinsburg" south of the contact with the Tuscarora at our Locality *D*, which Hoskins (1963) argued for predominant faulting accounting for the angular relation between the two formations. Note the similarity to Figure 6.

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.

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°E with a near vertical dip, ranging between 80°NW to 80°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).

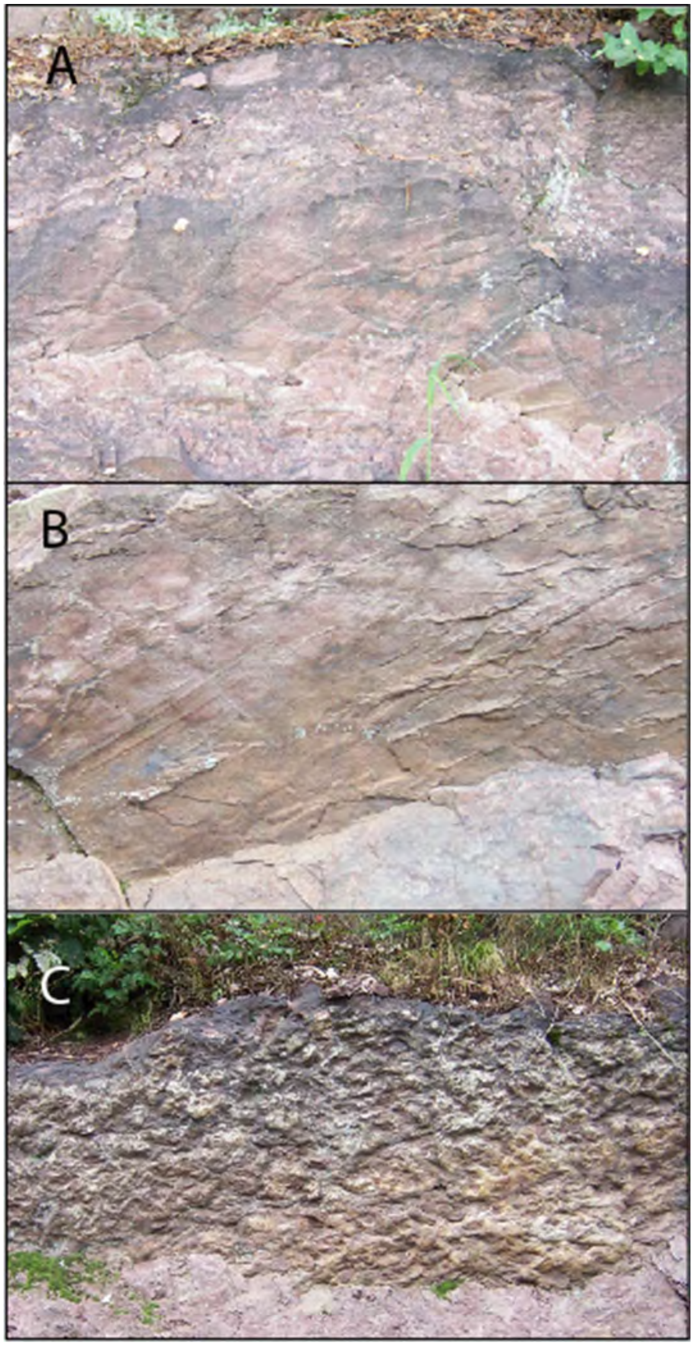

Figure 10. Sedimentary structures in the Bloomsburg Red Beds at Locality 1. A—Faint mudcracks at the base of a sandstone bed; B—linear scour marks, groove casts; C—load casts.

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.

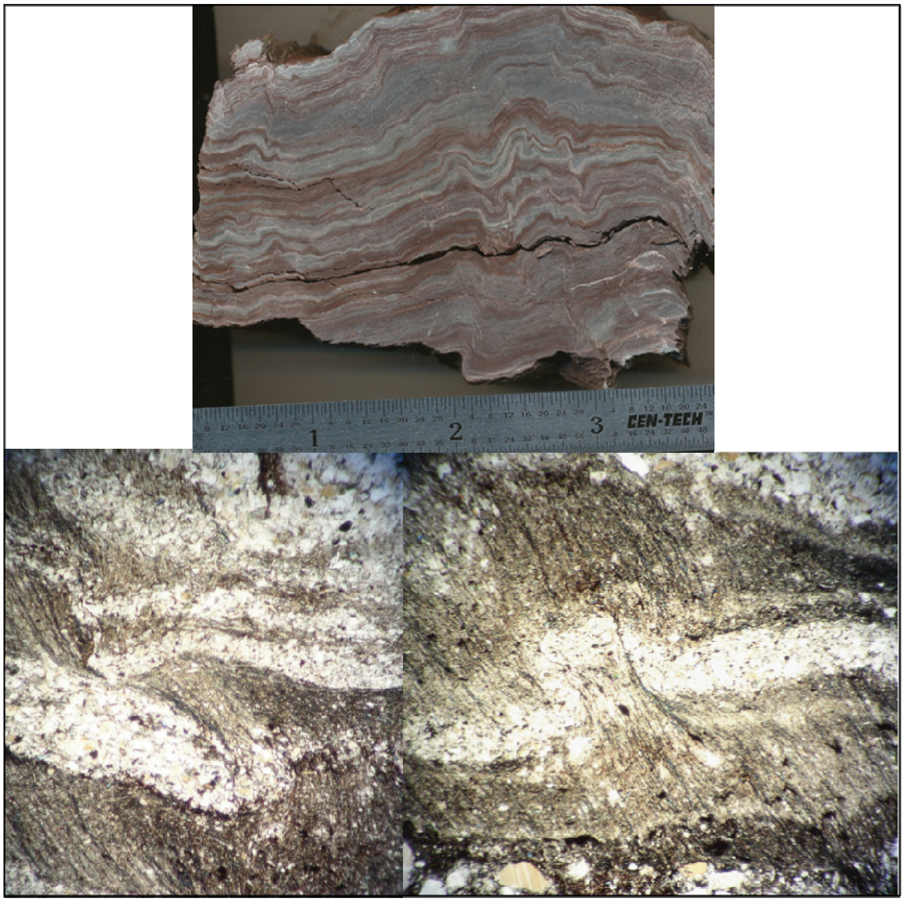

Figure 12. Scan of cut sample and thin-sections of laminated very fine sandstone, siltstone, and shale in the Bloomsburg Red Beds, along the off-ramp on the west side of PA 61 about 200 ft (61 m) north of the junction with PA 895. Crinkling resulted from shortening in the more resistant sandstone and 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° (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°) 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.

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 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.

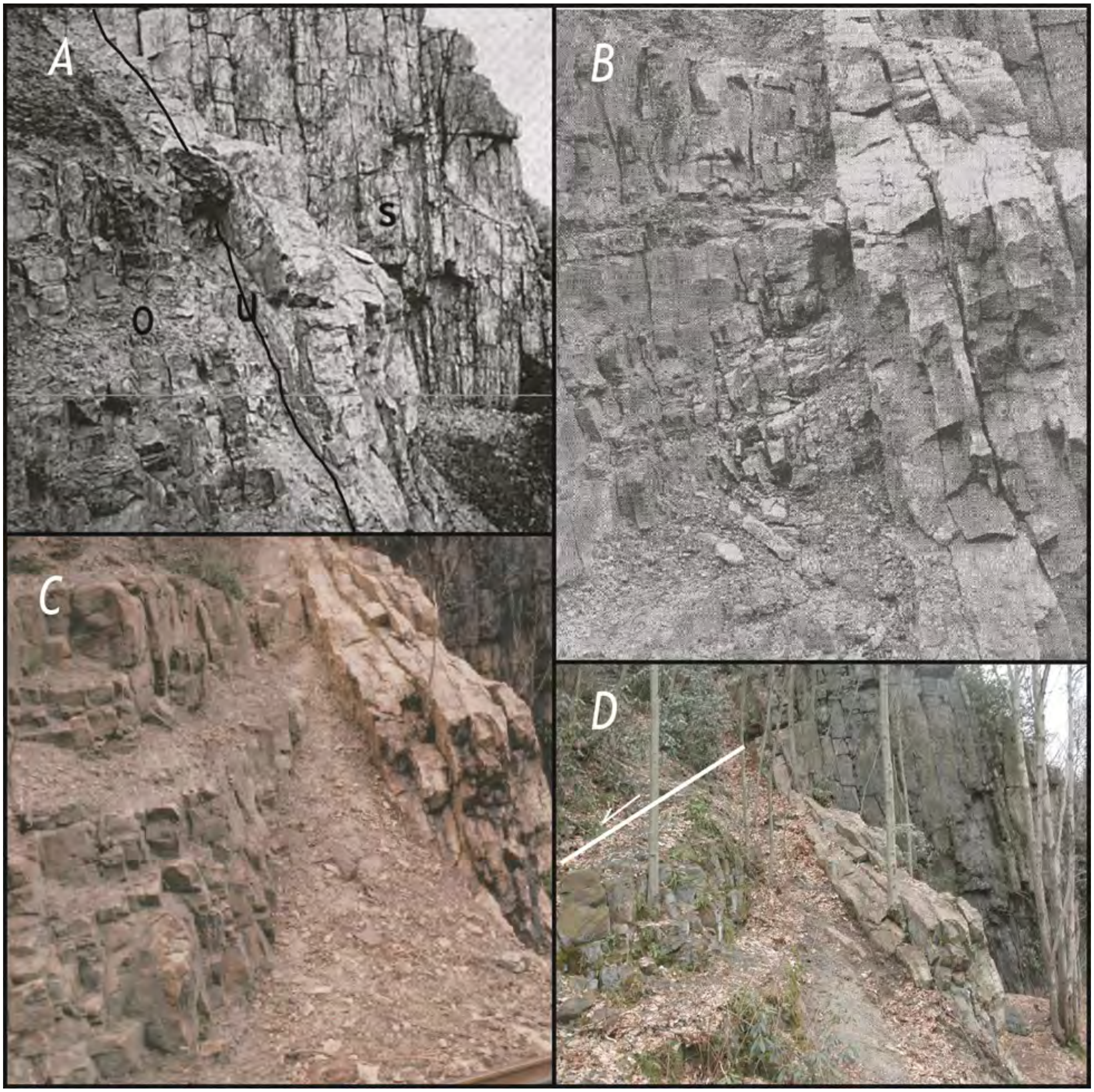

Figure 16. Appearance of the outcrop from pre-1925 to 1982. Your own photograph will take you up to date. A—From Miller, 1922: “Nearly horizontal Ordovician strata (0) separated by an unconformity U) from nearly vertical Silurian strata (S). The originally horizontal Ordovician strata were turned on 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.

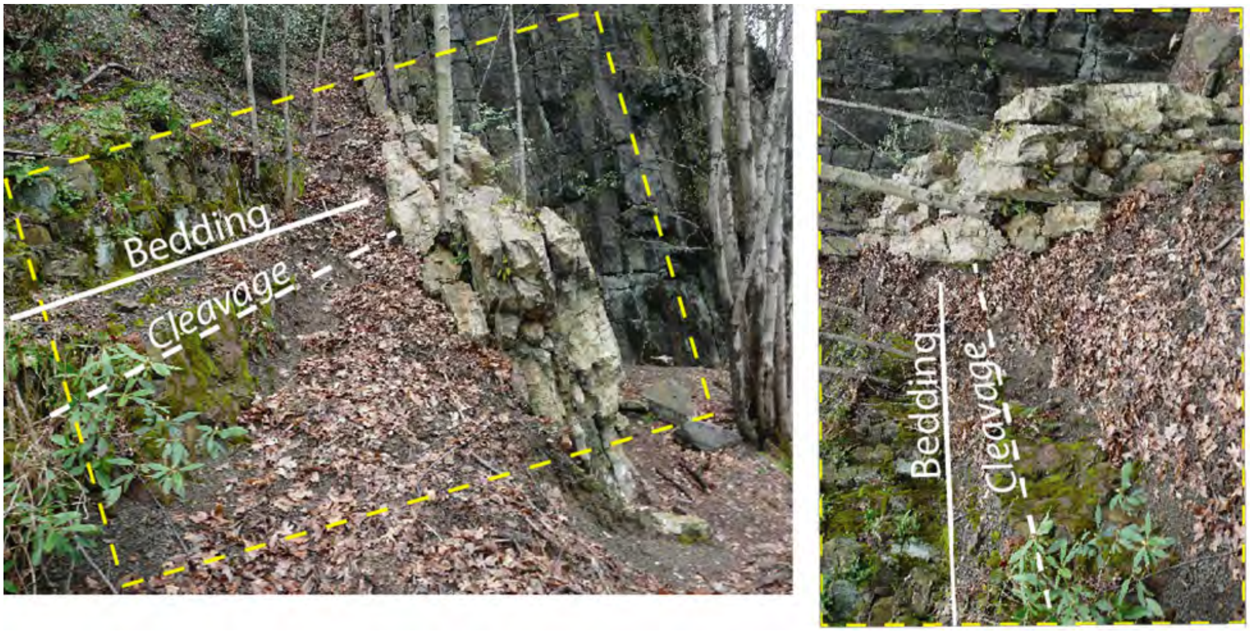

Figure 19. The present-day orientation at the Silurian-Ordovician boundary (left picture) rotated so that the Tuscarora is horizontal (right frame). It's a *PUZZLEMENT!*

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.

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°SE., whereas it is 71°SE in Silurian rocks.

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

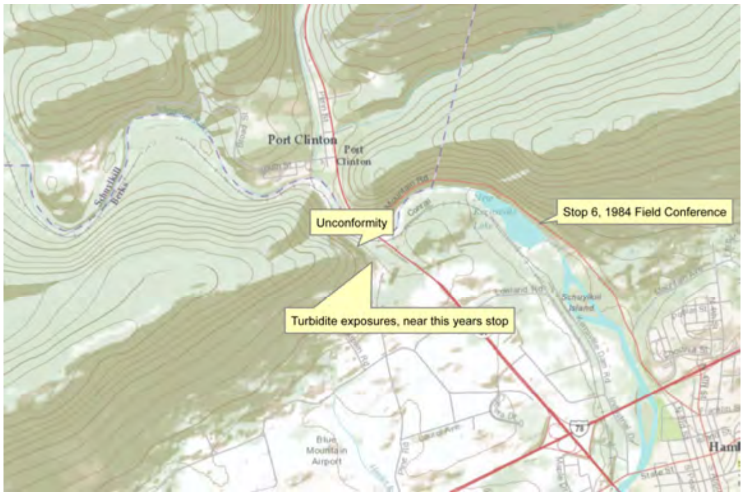

Figure 22: Location map of the Port Clinton area, showing the location of Stop 6 of the 1984 Field Conference, Stop 1 of the 2012 Field conference (the unconformity), and the location of the

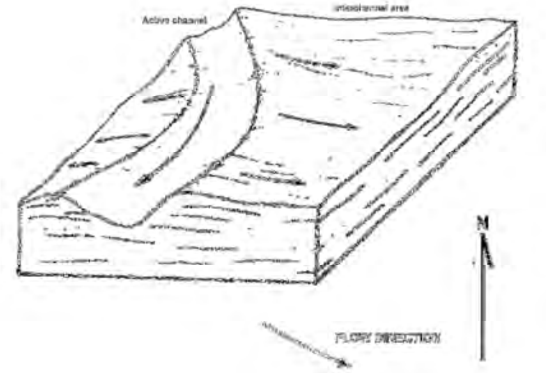

Figure 23: Initial state of sedimentation (modified slightly from Lash et al., 1984, p. 126, fig. 91A).

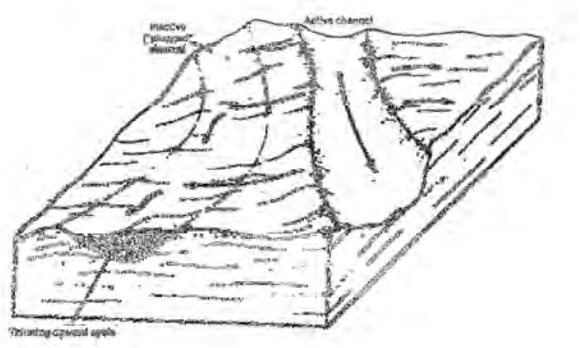

Figure 24: Abandonment of an active channel, resulting in thinning-upward sequences (modified slightly from Lash et al., 1984, p. 126, fig. 91B).

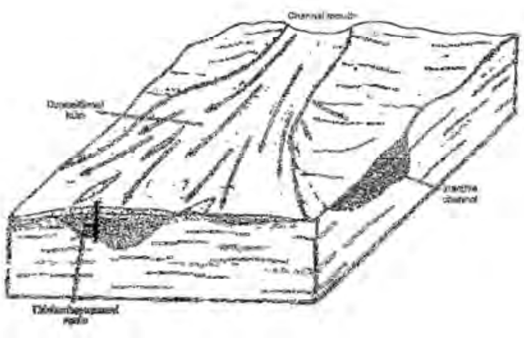

Figure 25: Return to thickening-upward sequence during the sedimentation of a depositional lobe (modified slightly from Lash et al., 1984, p. 126, fig. 91C).

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).

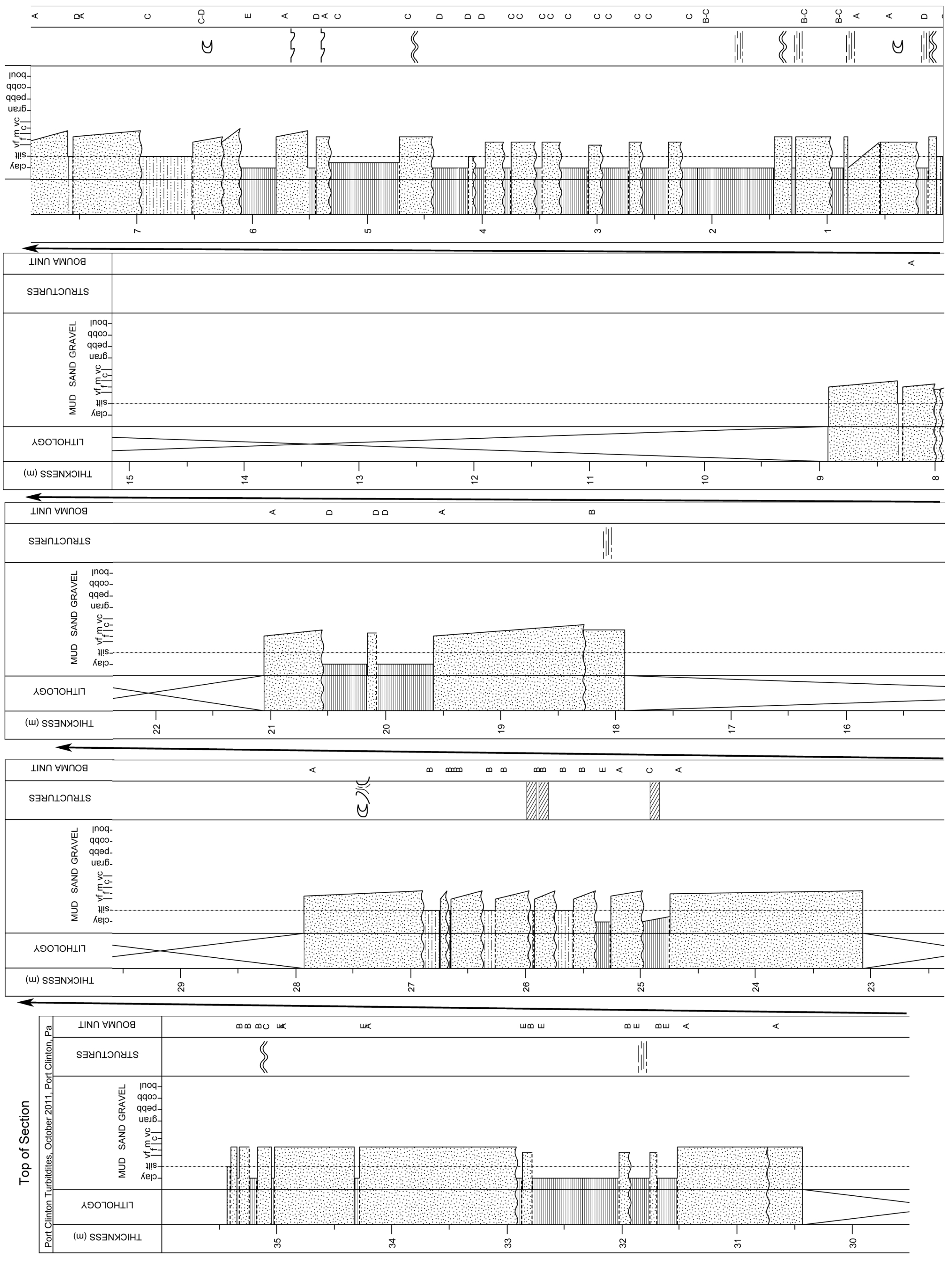

Figure 6: Measured section, south of Stop 1. See Figure 7 for legend.

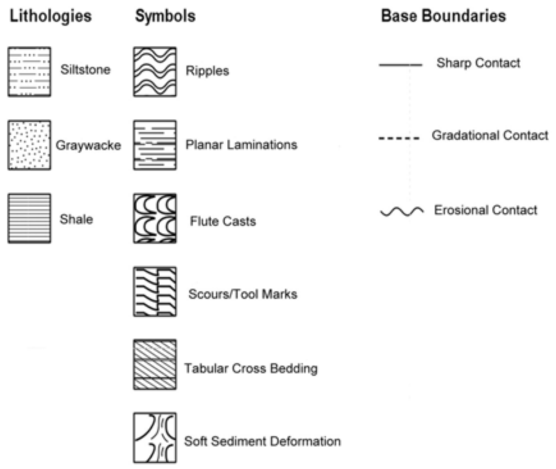

Figure 27: Key of symbols used in the measured section in Figure 6.

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

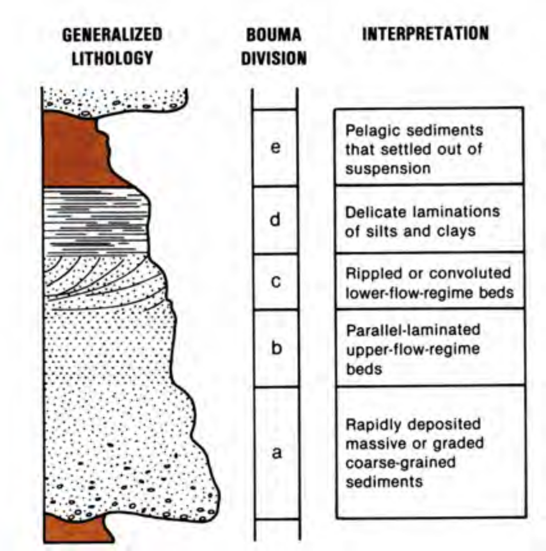

Figure 30: Idealized facies model for a turbidite sequence. From Harper, 1999.

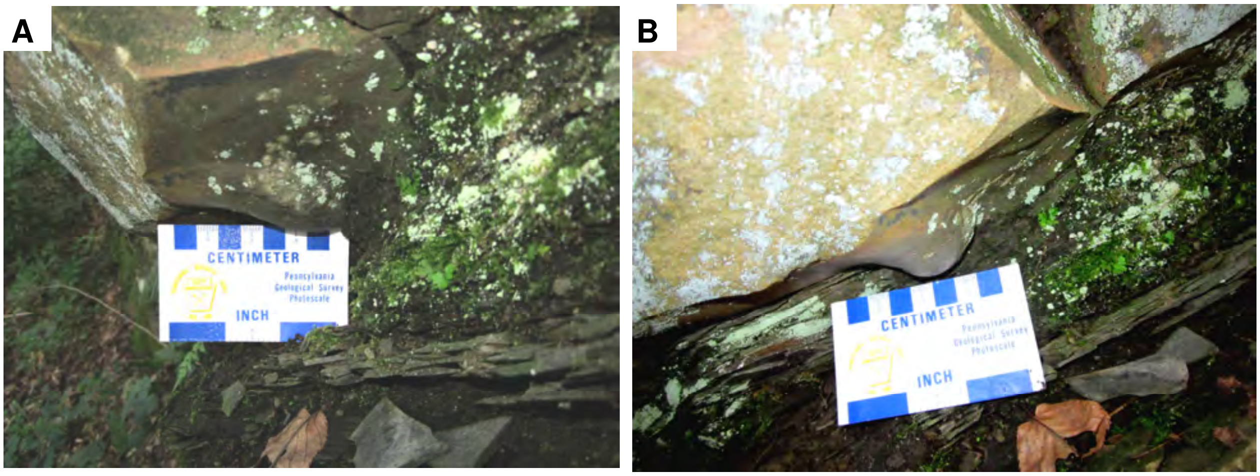

Figure 31: Photographs of flute cast in T_A bed. A – Flow direction is from the right to the left; B – Same as A, but with photo from the front. Flow direction out of the page.

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).

Epstein, J.B., 2012, Stop 2: Penn Big Bed Slate Company Quarry (Manhattan Mine), *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. 237-247.

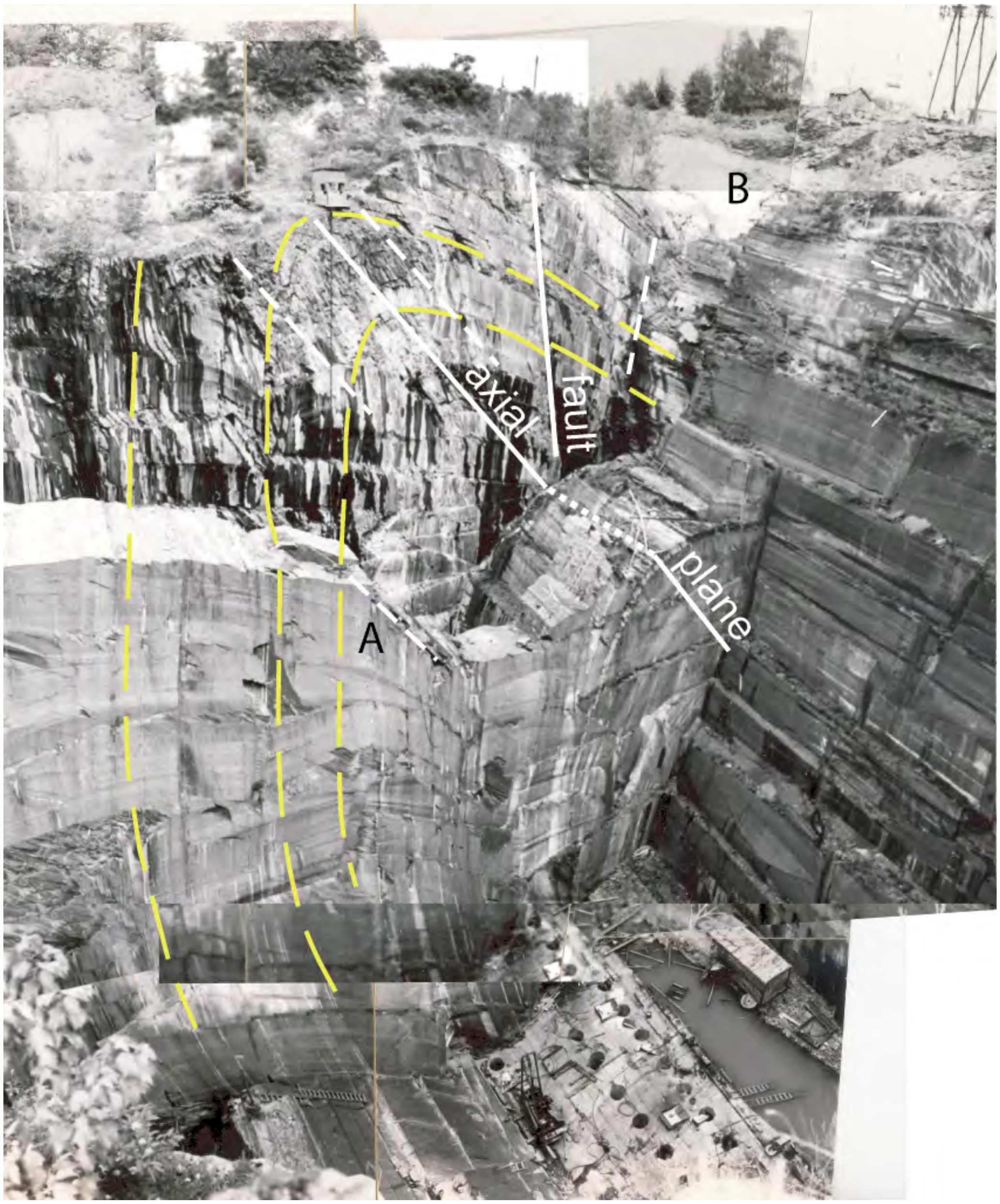

Figure 1. Overturned anticline in the Pen Argyl Member of the Martinsburg Formation in the quarry of the Penn Big Bed Slate Company, 2000 ft (610 m) north of Slatedale, Pa. Picture taken in 1980. View looking eastward. Bedding traces are shown by long-dashed yellow lines. Cleavage (short dashed white 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.

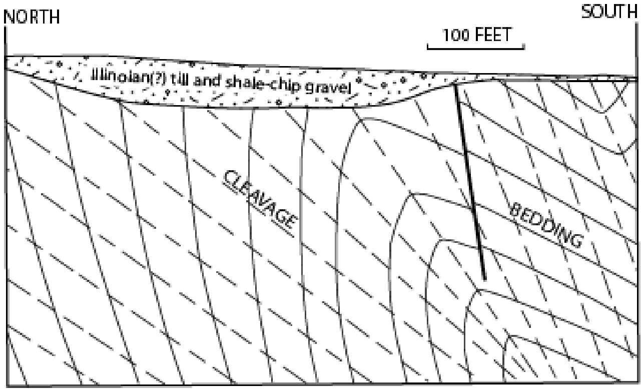

Figure 2 Diagrammatic cross section showing overturned folds, a reverse fault and fanning of cleavage in the Penn Big Bed Slate Company (Manhattan) quarry. Overburden, comprising till and shale residuum, thickens to the north in the quarry area.

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° (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.

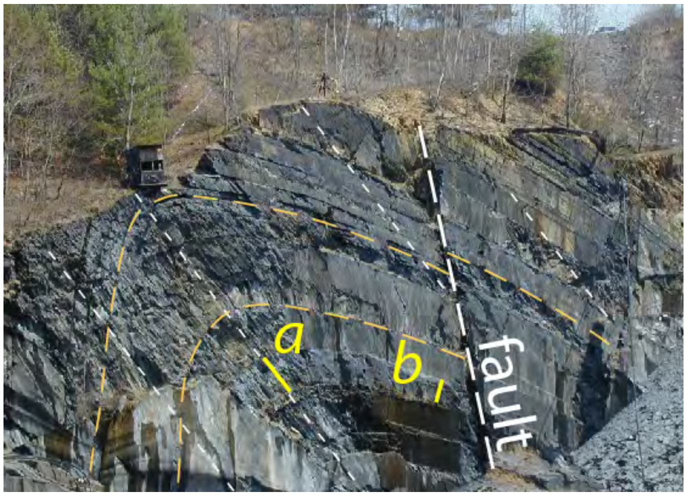

Figure 6. Close-up of anticline hinge area showing the difference in the length of a piece of slate that could be derived from the same bed in the hinge area (a) and on the limbs (b). In this case the length in the hinge is 180 percent greater than in the limb.

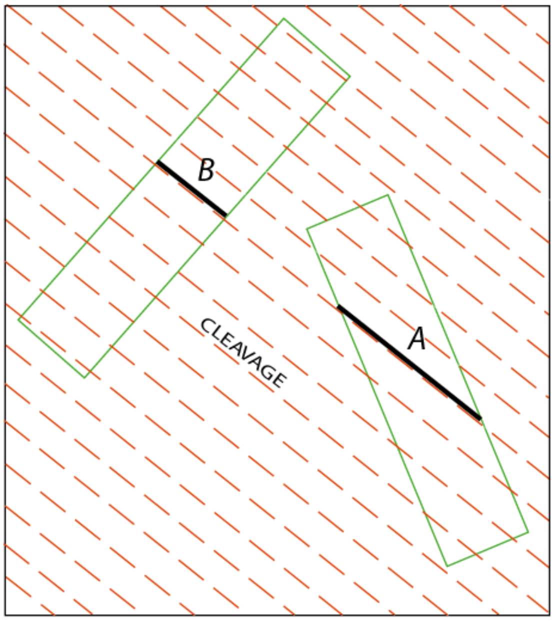

Figure 7. The length of a piece of slate that can be derived from a bed of given thickness (solid rectangle) is determined by the angle between bedding and slaty cleavage. Where bedding is at a low angle to cleavage (*A*) the length of the slate piece is much longer than where bedding is about perpendicular 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°, 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.


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.

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.

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

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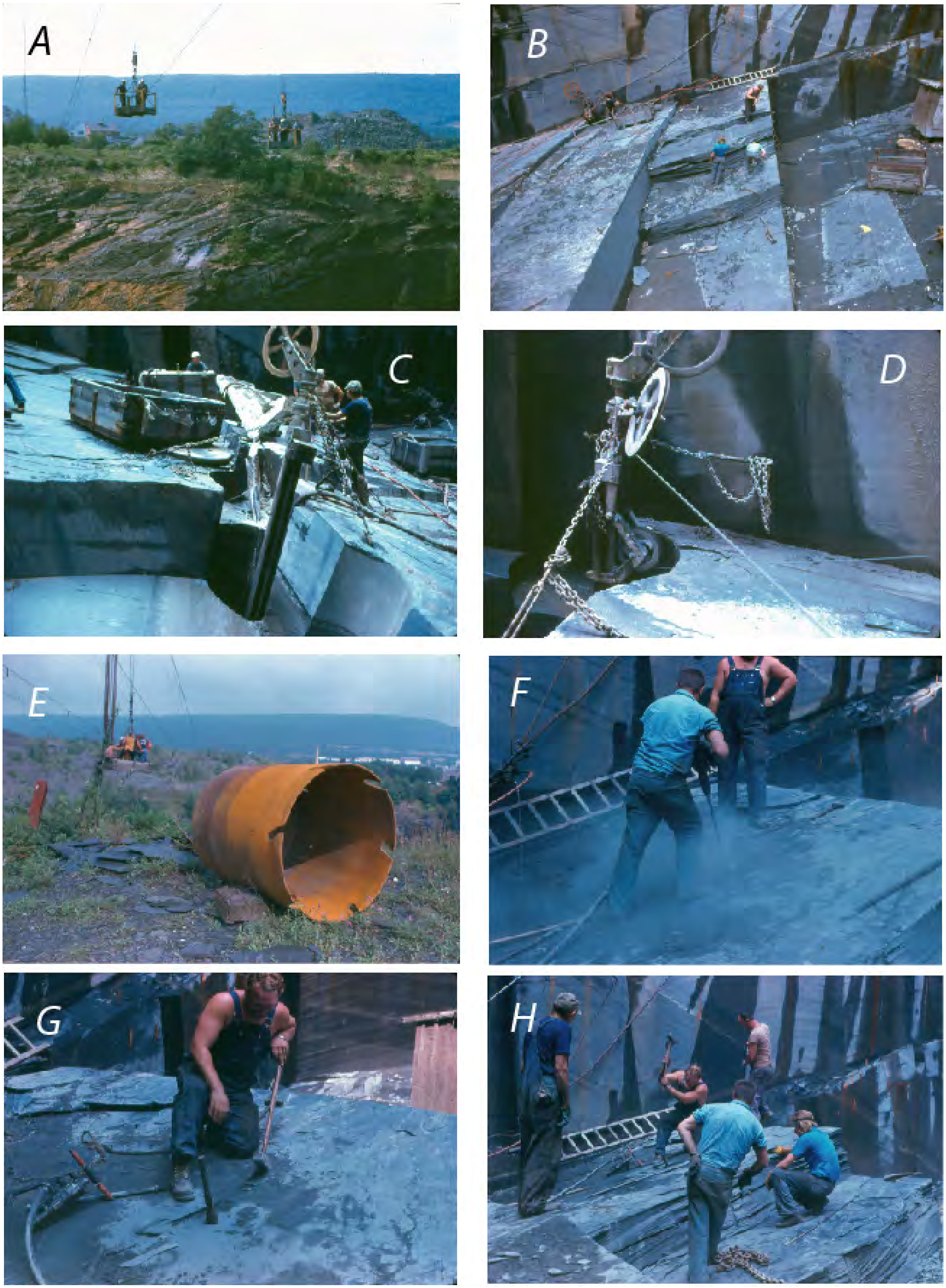
*Photos 23-27 from Penn Big Bed Slate Company website, **http://www.pennbigbedslate.com** (Accessed 9/17/2012)


A
B
C
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E
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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 perpendicular to the direction of tectonic compression.

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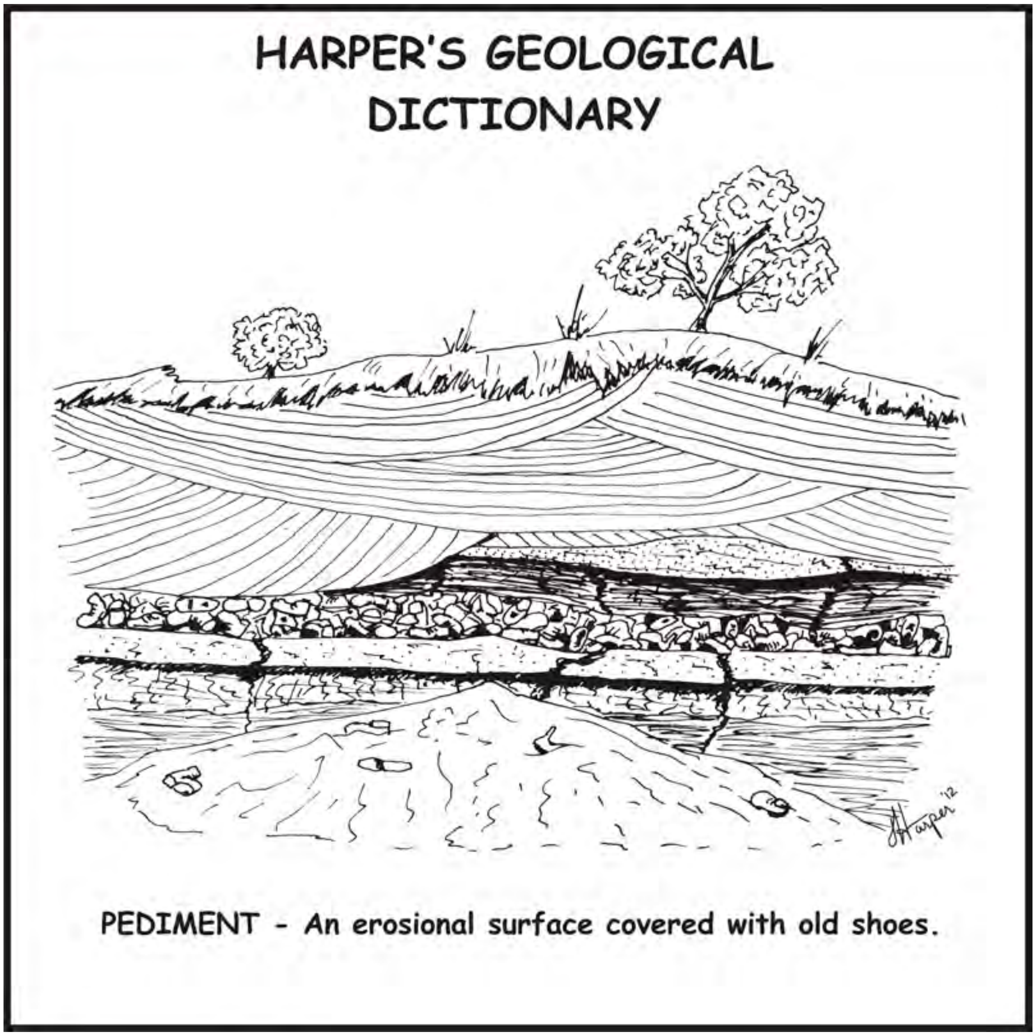


PEDIMENT - An erosional surface covered with old shoes.

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 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:

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.

> "*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.

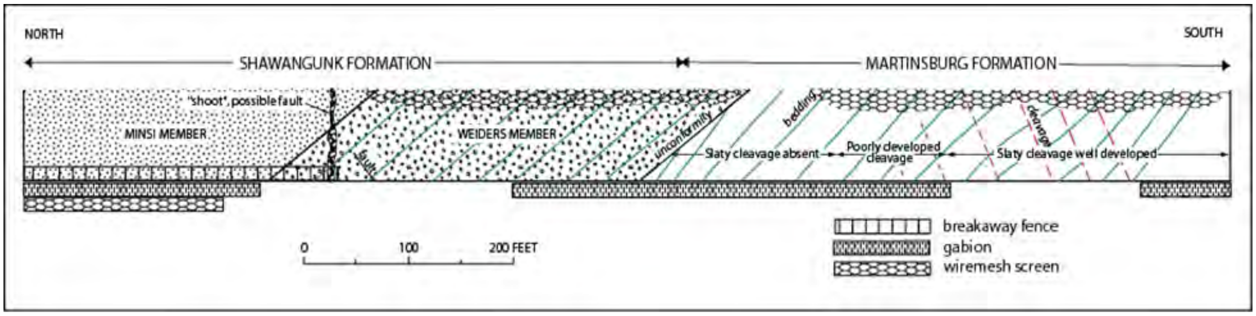


Figure 2. Geologic and engineering features seen along the abandoned railroad track at Lehigh Gap. See Figure 7 for details in the Martinsburg Formation.

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°, 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° 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

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° 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

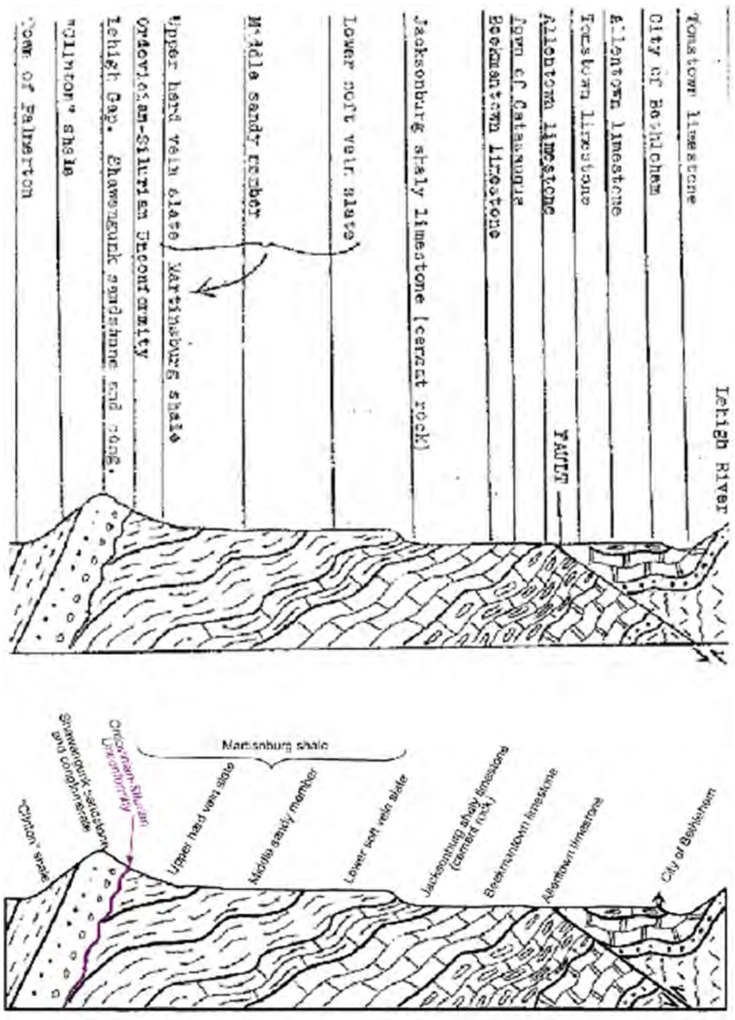


Figure 5. Cross section through Lehigh Gap showing the angular divergence between the Shawangunk and Martinsburg Formations to be about 45°.

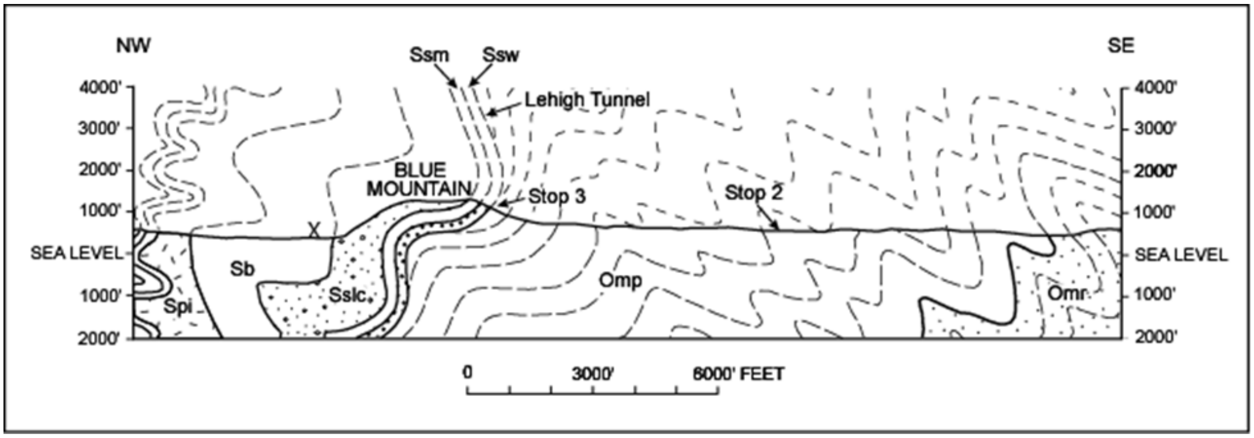


Figure 6. Geologic section 2,000 ft (610 m) east of Stop 3, Lehigh Gap. Spi, Poxono Island Formation; Sb, Bloomsburg Red Beds; Sslc, Lizard Creek Member of Shawangunk Formation; Ssm, Minsi Member of Shawangunk Formation; Ssw, Weiders Member of Shawangunk Formation; Omp, Pen Argyl Member of Martinsburg 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.

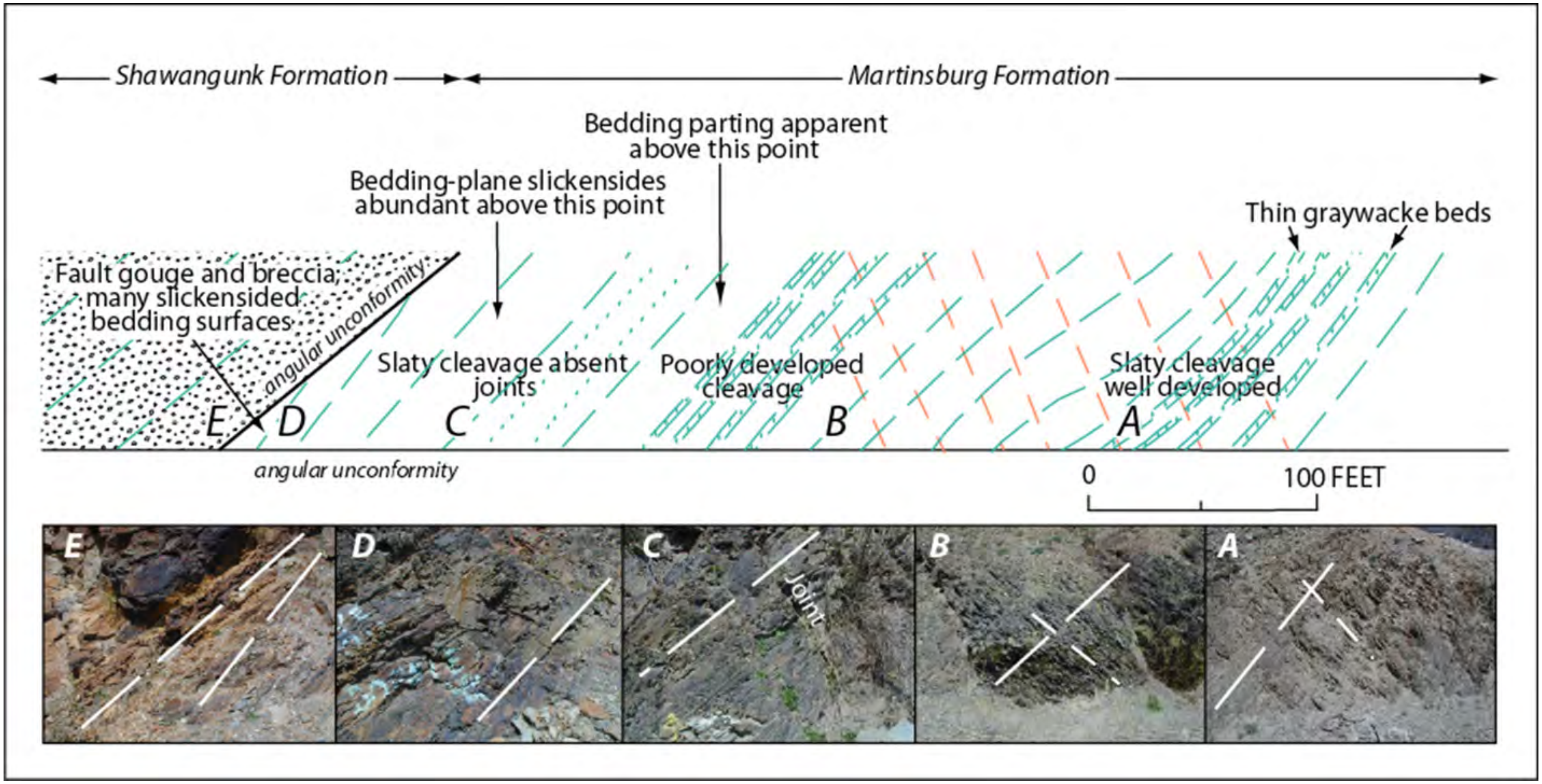


Figure 7. Diagrammatic geologic section through the Martinsburg-Shawangunk contact at Lehigh Gap, Stop 3, showing the dying out of the prominent slaty cleavage and increased development of bedding parting in the Martinsburg as the unconformable contact is approached. Bedding, long-dashed lines; cleavage,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

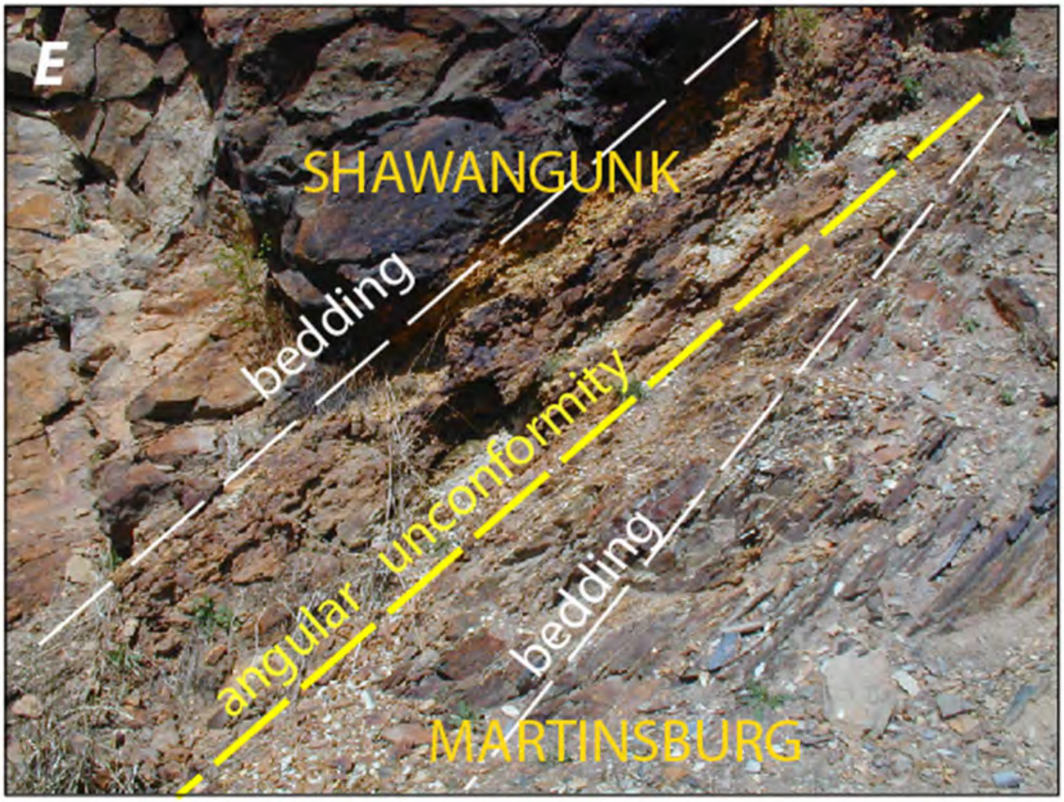


Figure 8 Closeup of Martinsburg-Shawangunk contact (also Figure 7E**). Note the absence of cleavage in the Martinsburg Formation.**

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.

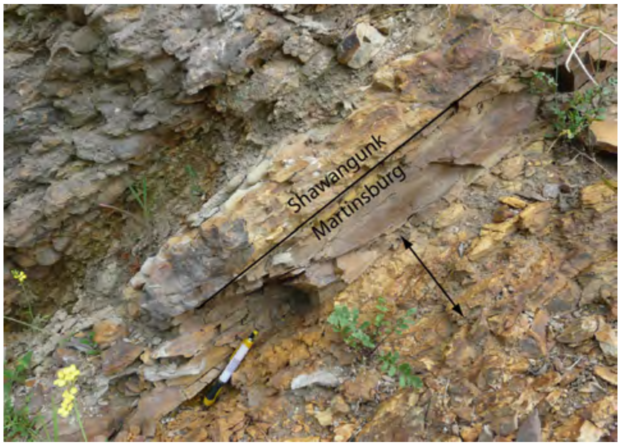


Figure 10. Shear zone about 8 in (20 cm) thick (arrow) underlying about 2 in (5 cm) of unsheared Martinsburg that is in contact with the overlying Shawangunk Formation. From bottom to top the zone consists of slickensided quartz and sheared slate (2 to 3 in [5 to 7 cm] thick), fault gouge of Martinsburg 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?

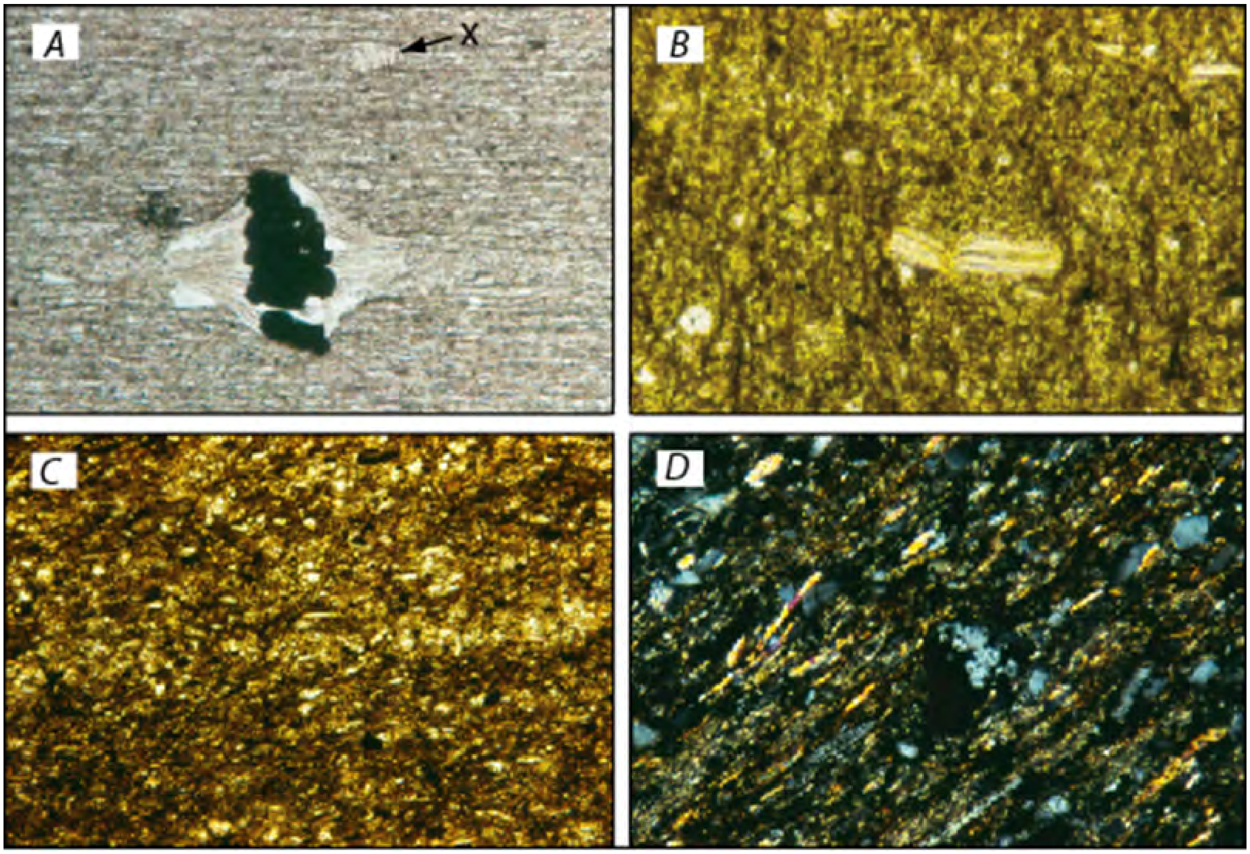


Figure 11.. Photomicrographs showing the slate to shale transition at Lehigh Gap and fissility in a typical shale. A - Slate from abandoned slate quarry about one mile south of Lehigh Gap. Slaty cleavage (dark folia) is horizontal; bedding is vertical and represented by alignment of black pyrite framboids. 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

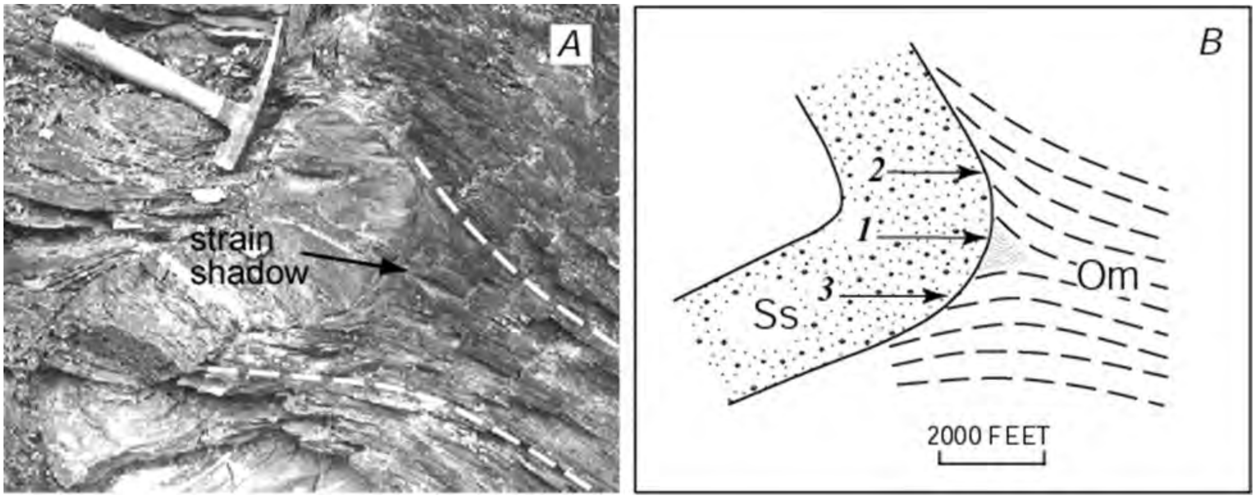


Figure 13. Strain shadows and arching of slaty cleavage in interbedded rocks at different scales and of different competencies. A - flattened folds near the base of Martinsburg Formation (Bushkill Member) along US Route 46, 1.8 mi (2.9 km) northeast of Belvidere, NJ, near the Delaware River. Cleavage (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.

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.

be 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.

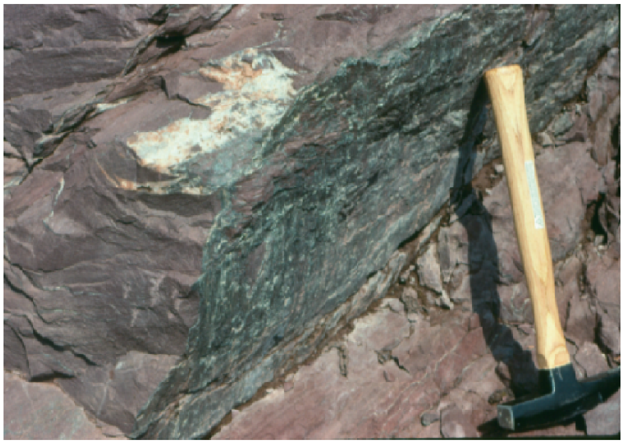


Figure 17. Green (chloritic) slickensides on basal sandstone bedding plane with steps showing movement of overriding beds down to the northwest (left).

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-

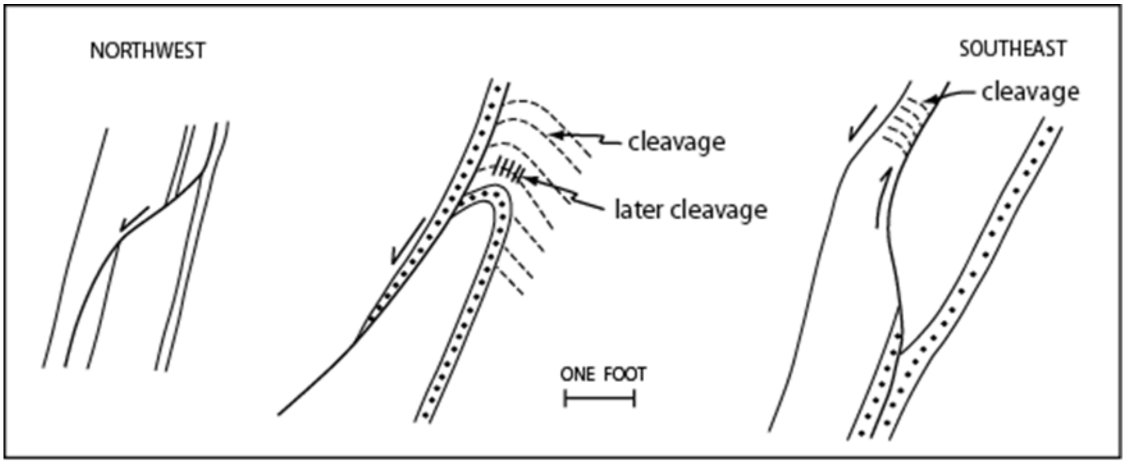


Figure 19. Diagrammatic sketches of wedges, bedding-slip faults, and rotated cleavage in the Bloomsburg Red Beds immediately south of Palmerton, Pa.

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).

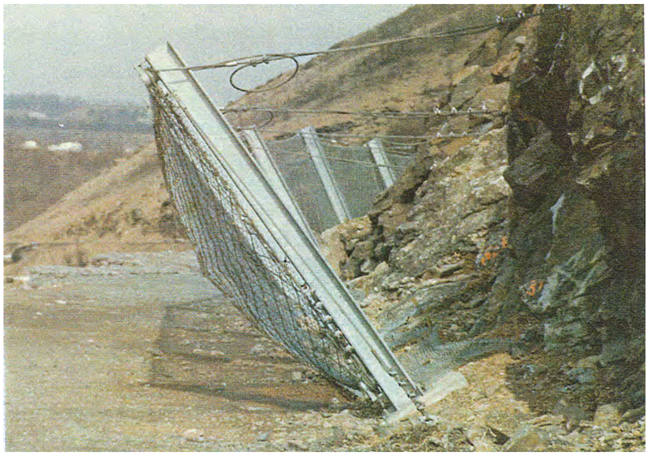


Figure 21. Rock fence installed in the contact area between the Minsi and Weiders Members of the Shawangunk Formation , about 200 ft (61 m) north of the Ordovician-Silurian contact. This is an area of abundant loose talus blocks, possibly within an area of faulting (Porto and Petrasic, 1996, fig. 23).

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.

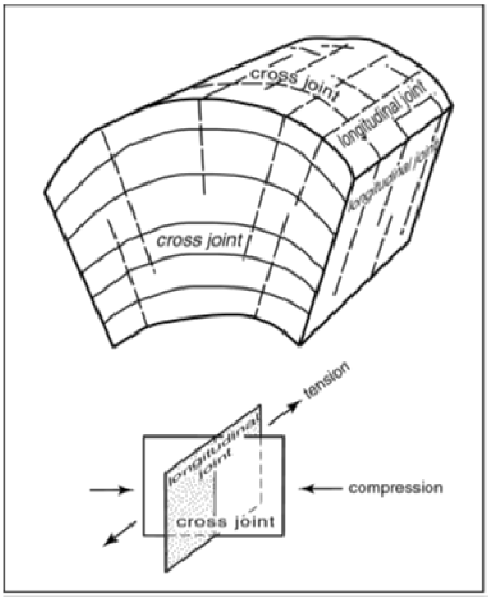


Figure 24. Diagram showing orientation of longitudinal and cross joints in folded rocks typical of the Appalachian Valley and Ridge province.

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.

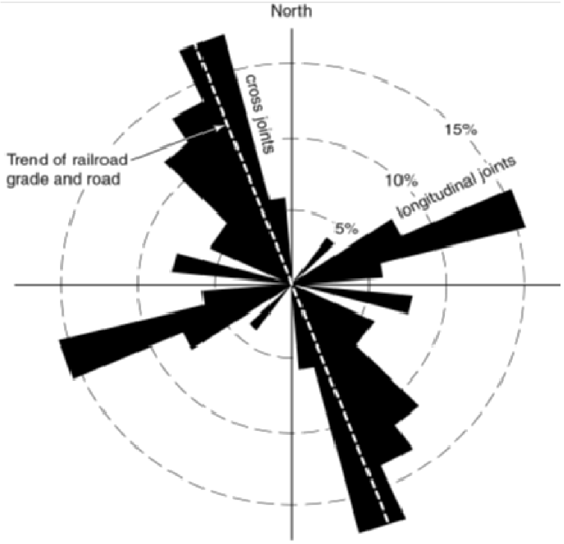


Figure 26 Rose diagram showing strike of 52 joints at Lehigh Gap, 29 mi (47 km) southwest of Delaware Water Gap. Dashed line shows trend of the abandoned railroad grade above PA 248.

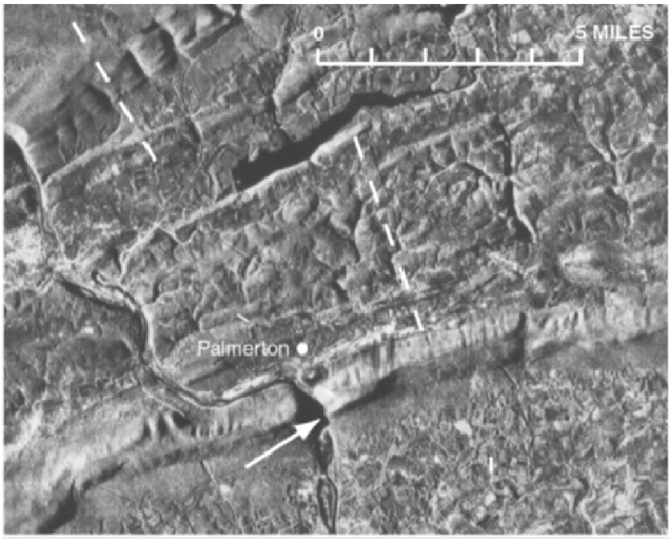


Figure 27. Radar image of the Lehigh Gap area showing location of the rockfall hazard along PA 248 south of Palmerton, PA (arrow) and fracture control of many of the NNW-trending lineaments (dashed line). From Newark, NJ; PA; NY radar mosaic.

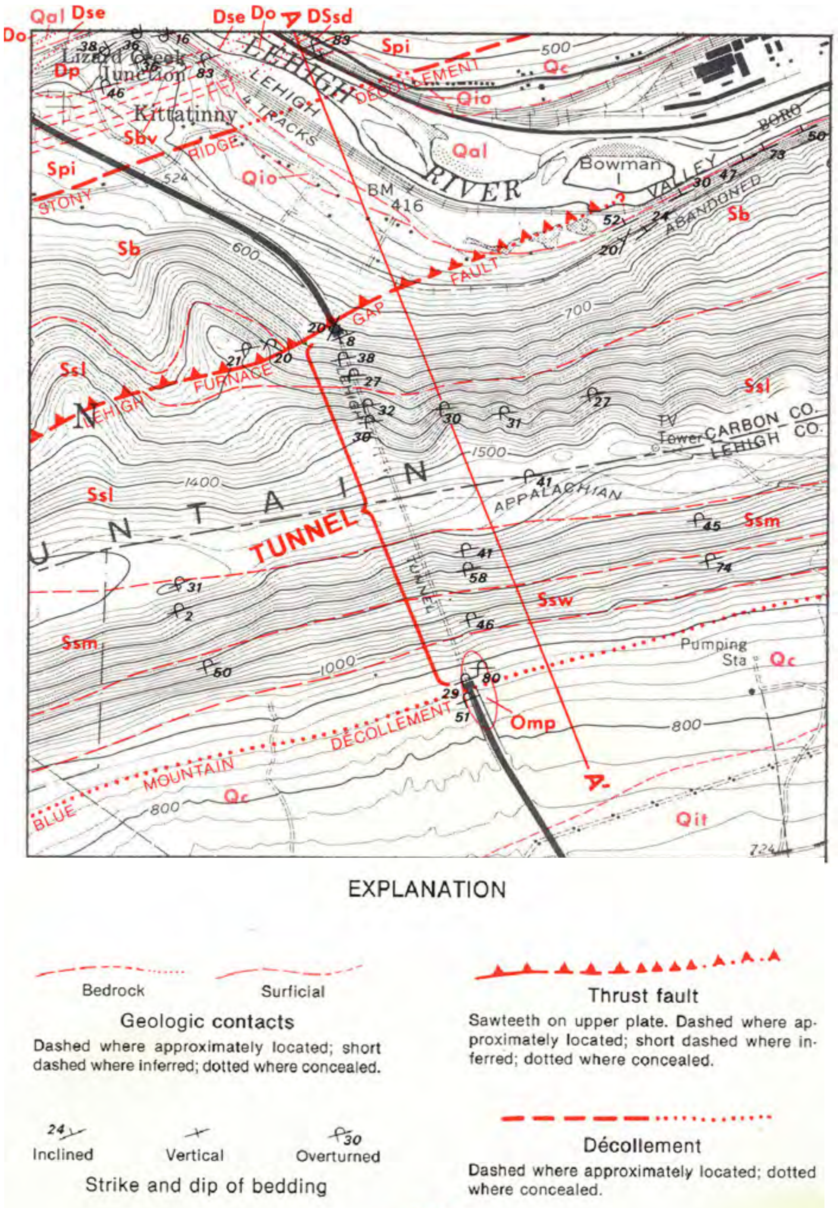
10 ft (3 m) long, each weighing many tons. Outward movement from these fractures were noted in 1989, and, because of the potential for these rocks falling on the highway below and because the site is adjacent to the Appalachian National Scenic Trail, the National Park Service requested the Federal Highway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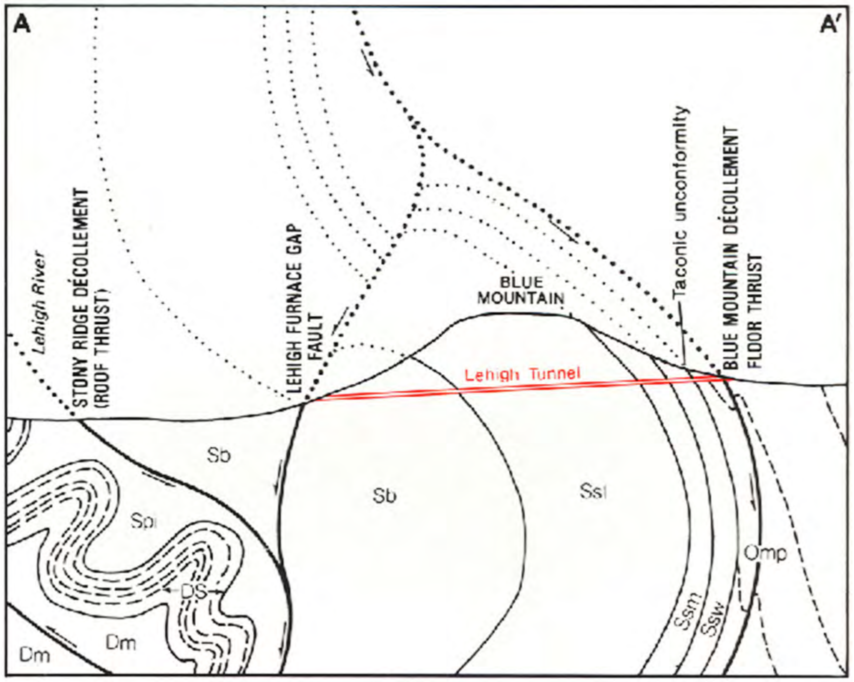

29B

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).

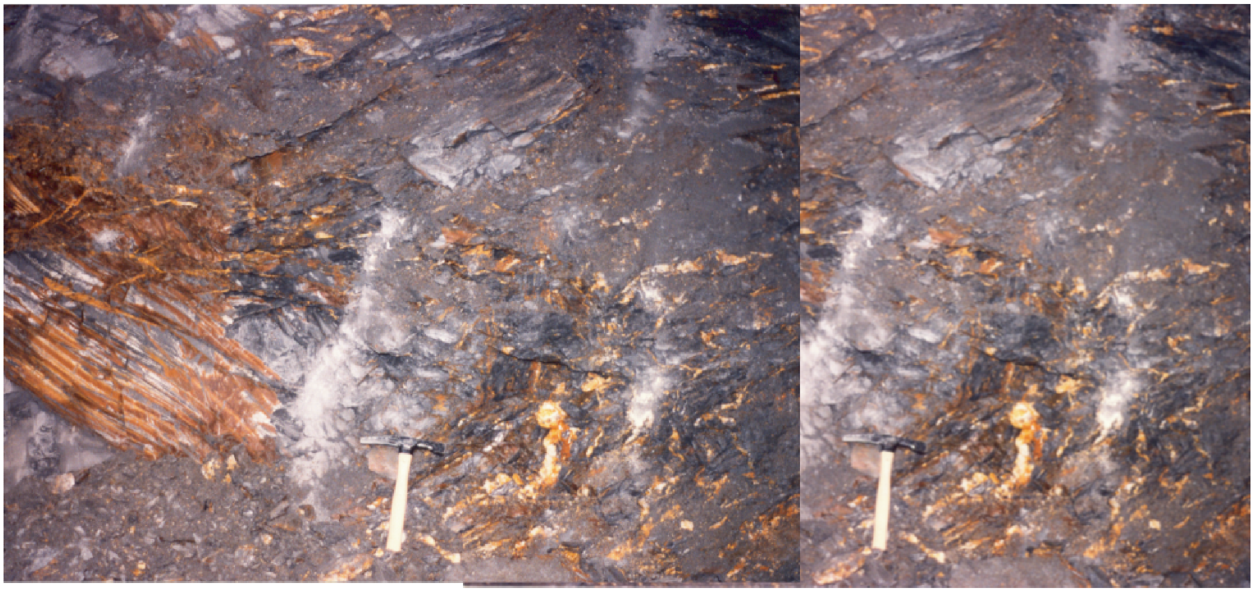

Figure 29. Stereo pair of part of the 27-ft (8-m) wide shear zone in the Martinsburg Formation showing rotated blocks of rock and abundant variously oriented quartz veins.

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

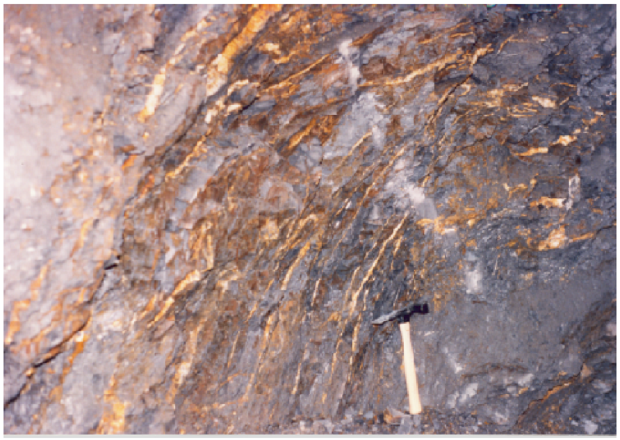

Figure 31. Fairly abrupt southernmost contact between Martinsburg pelite on the upper left with the 27-ft (8-m) wide quartz-veined shear zone, 90 ft (27 m) north of the south portal entrance.

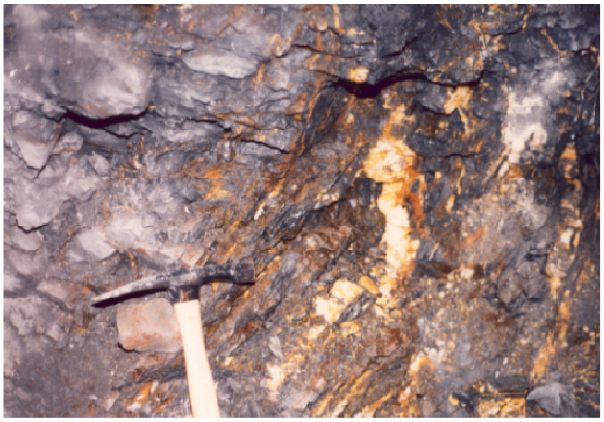

Figure 32. Closeup between shear zone and bedded pelite of the Martinsburg Formation.

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).

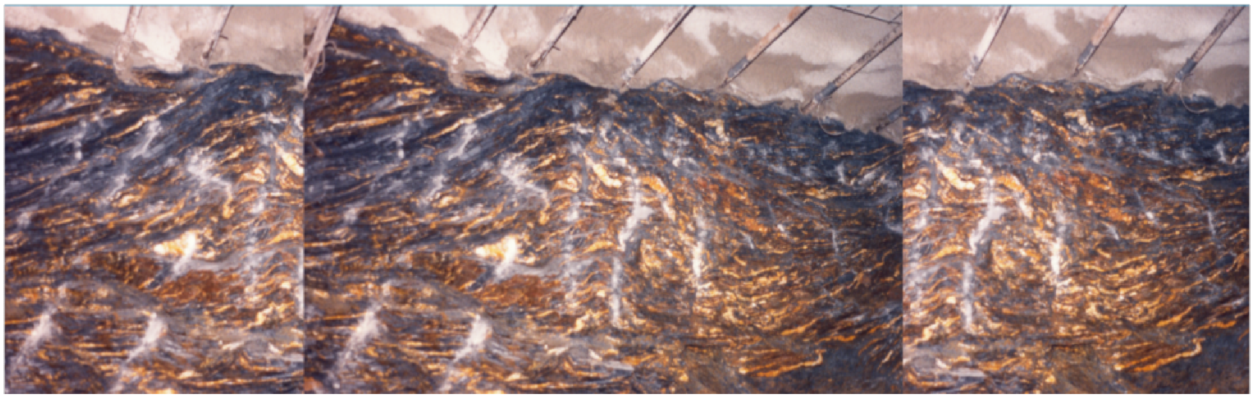

Figure 33. Stereo triplet showing shear zone in the Martinsburg Formation exposed in the second Lehigh Tunnel on January 24, 1990, believed to be the floor thrust of a duplex in the Shawangunk Formation and Bloomsburg Red Beds.

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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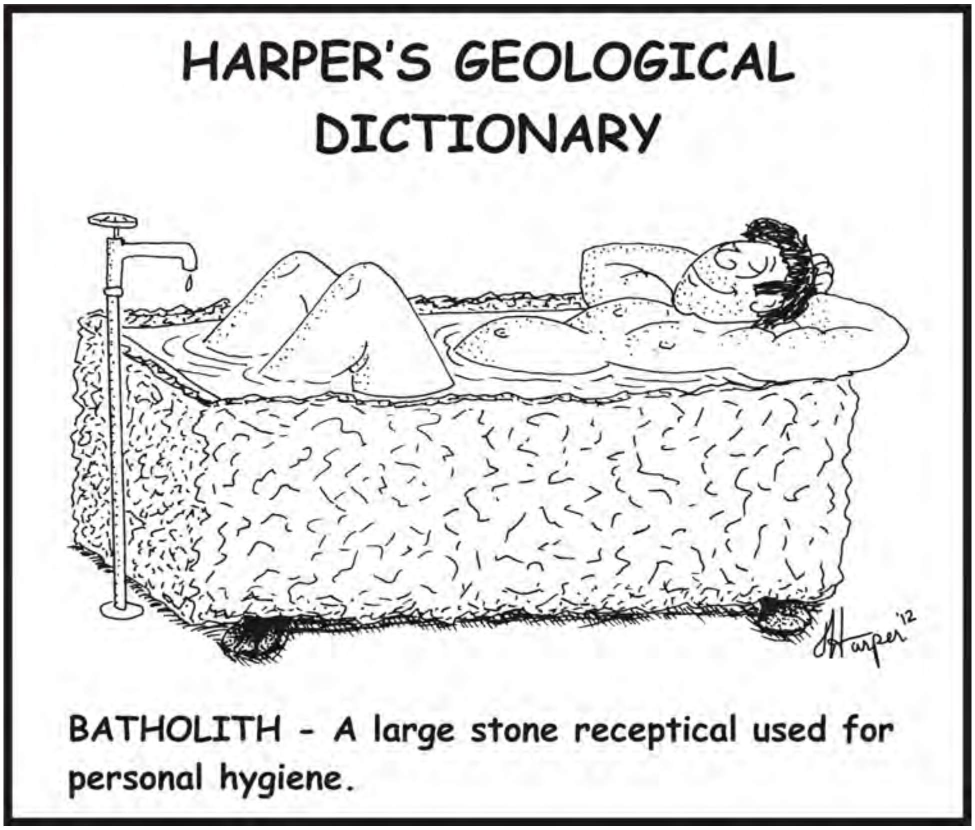


STOP 4: DELAWARE WATER GAP

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).

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

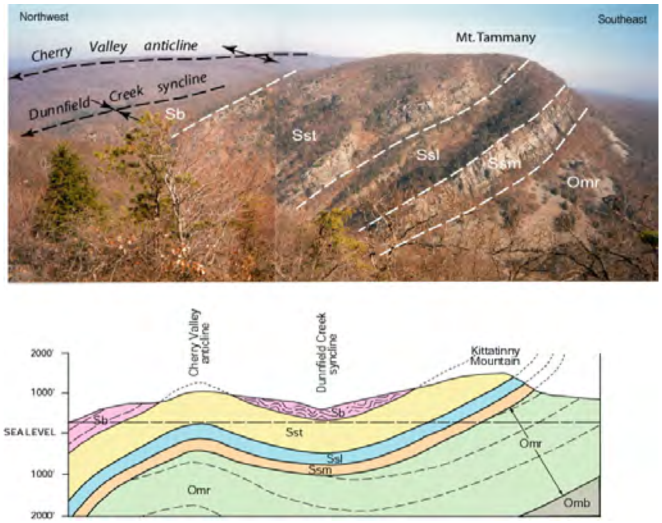


Figure 3. Delaware Water Gap in New Jersey as viewed from atop Kittatinny Mountain (Mt. Minsi) on the Pennsylvania side. Omb, Bushkill Member of the Martinsburg Formation; Omr, Ramseyburg Member of the Martinsburg Formation; Ssm, Minsi Member of the Shawangunk Formation; Ssl, Lizard Creek Member of the 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

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° 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

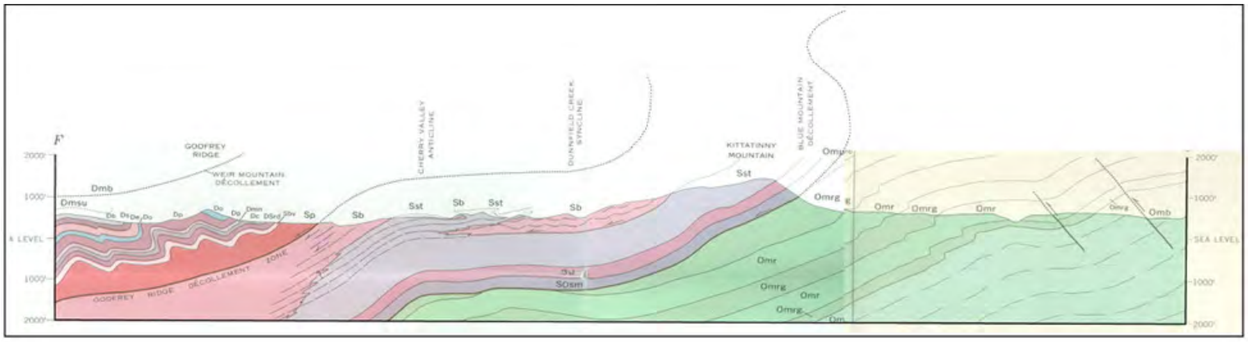


Figure. 4. Cross section in the Delaware Water Gap area (from Epstein, 1973, and Drake et al., 1969) showing the disharmonic relations between rocks of differing ages and lithic types. The contact between the Martinsburg Formation of Ordovician age and the Silurian Shawangunk Formation marks the Taconic 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

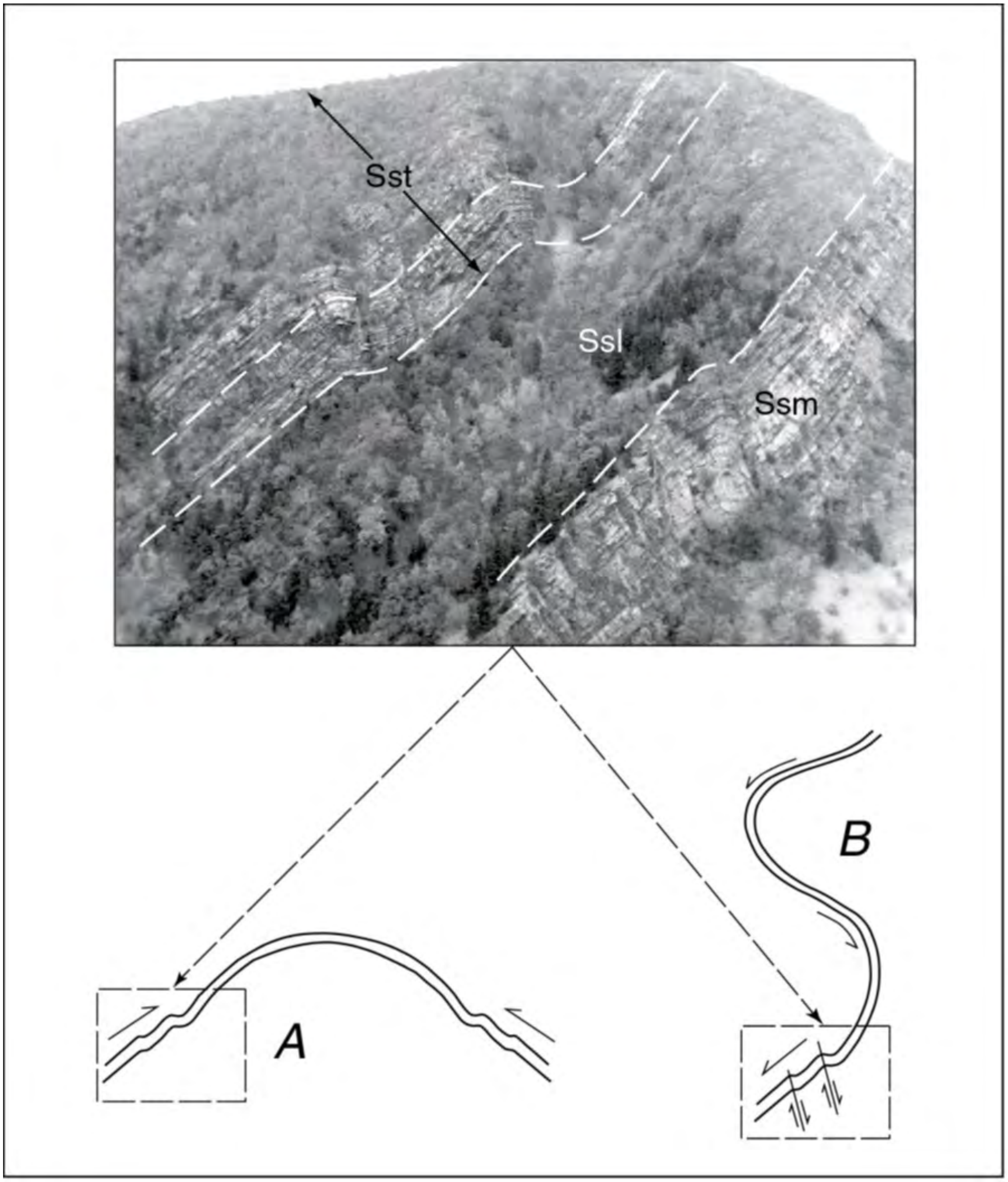


Figure 6. Satellitic folds in the Shawangunk Formation in Delaware Water Gap, New Jersey (Ssm, Minsi Member; Ssl, Lizard Creek Member; Sst, Tammany Member). A—Interpretation of an anticlinal crest to the southeast as shown in Figure 5 with "drag folds", due to interbed shear, verging towards the anticlinal 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*).

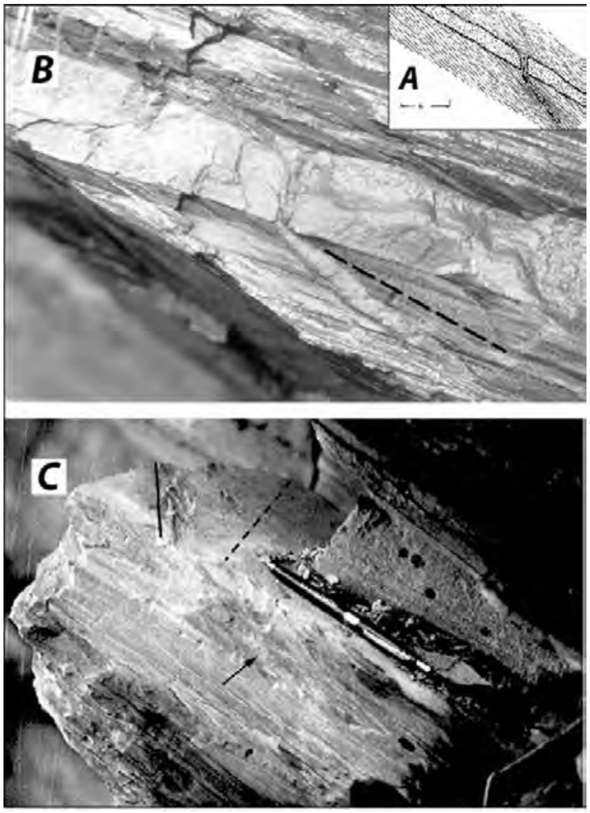


Figure 7. Sandstone dikes in the Martinsburg Formation along US Route 46 south of Delaware Water Gap. A—Dike illustrated by Maxwell, 1962, his Fig. 4; B—Actual dike shown in A and #1 in Figure 8. Cleavage (dashed line) dips 8° less than the dike. Mud from the overlying bed replaced the evacuated sand 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

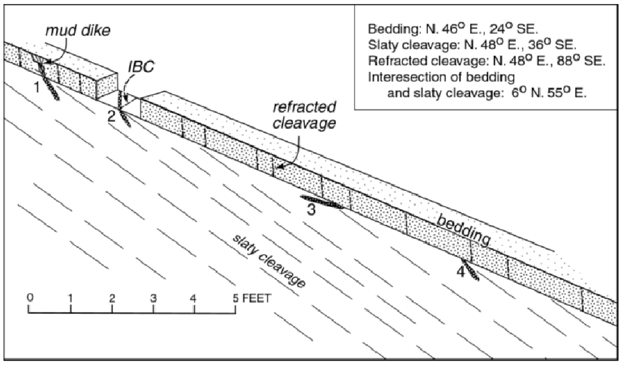


Figure 8. Sandstone dikes extending down from a graywacke bed into slate in the Ramseyburg Member of the Martinsburg Formation, along US 46, 5 mi (8 km) south of Delaware Water Gap. North is to the left. 1—Sandstone dike shown in Figure 7B and portrayed by Maxwell (1962, p. 287). The dike does not parallel 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.

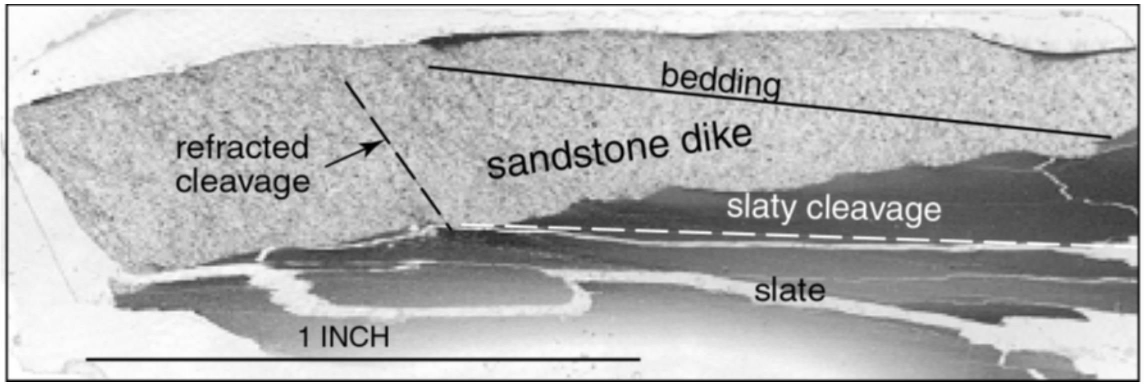


Figure 9. Scanned thin section of sandstone dike # 3 shown in Figure 8. The dike dips to the southeast (to the right) 4° less than bedding and slaty cleavage dips 9° more than the dip of the dike. Irregular fracture at word "slate" is pull apart in thin section.

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).

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

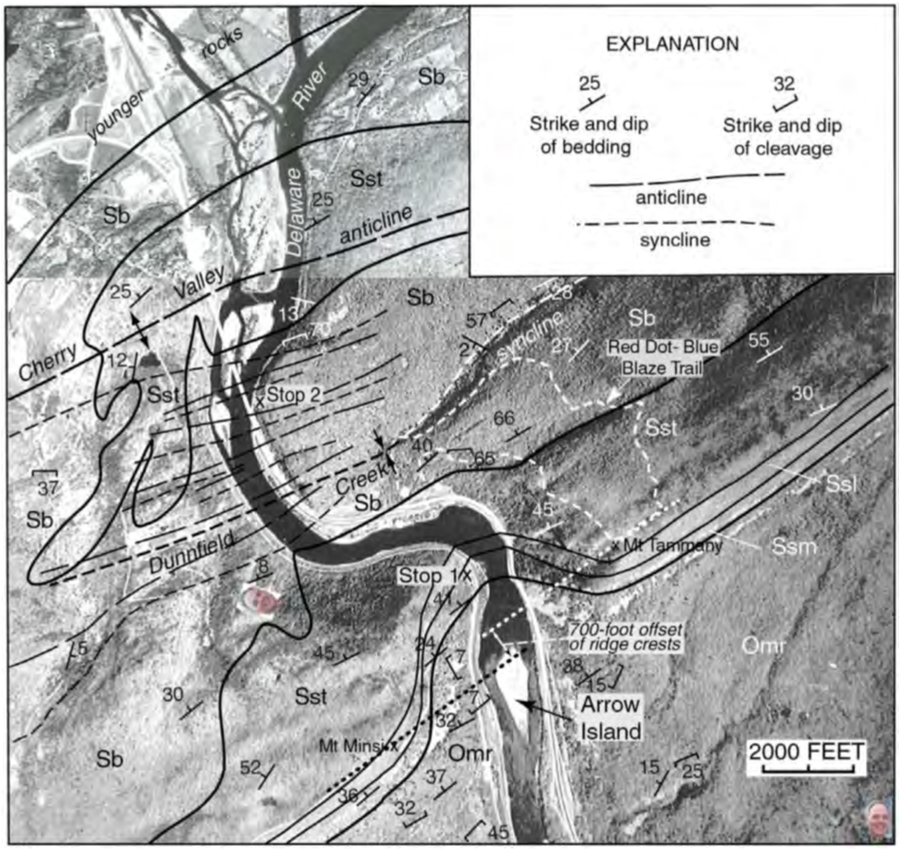


Figure 10. Aerial photograph and geologic map of Delaware Water Gap showing that at about 500 ft (152 m) southeast of the Shawangunk contact, southeast-dipping slaty cleavage in the Martinsburg Formation becomes northwest-dipping closer to the contact. Also note the 700-ft (213-m) offset of the ridge 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).

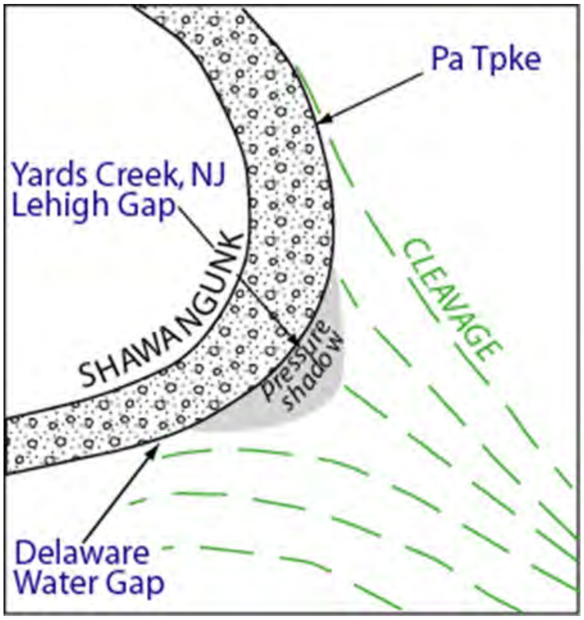


Figure 11. Strain shadows and arching of slaty cleavage in interbedded rocks of different competencies. This is a generalized cross section showing the structural relations of cleavage in the Martinsburg Formation (Om) near the contact with the more competent Shawangunk Formation (Ss). The northwest 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.

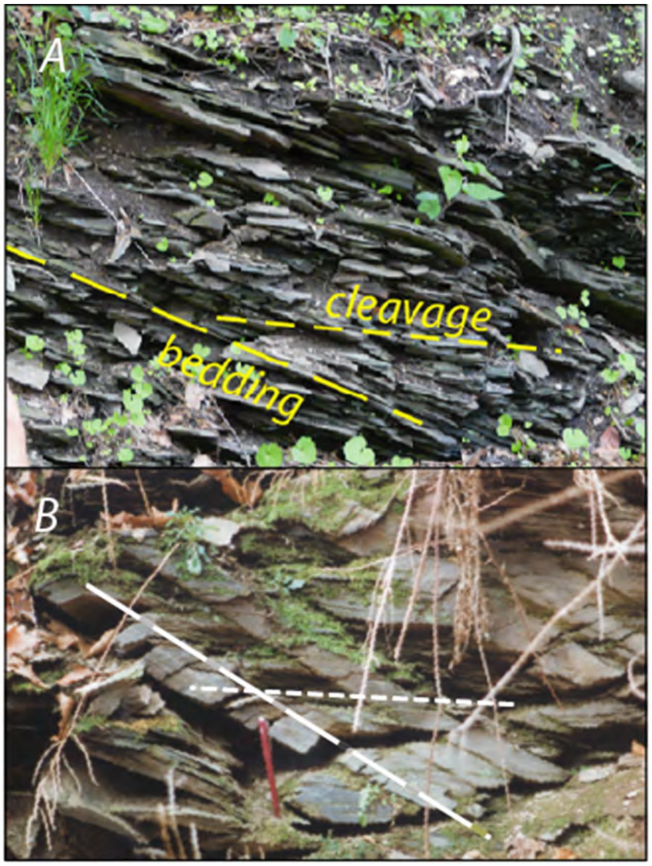


Figure 12. The bedding (solid line) and cleavage (short dashes) are well displayed in the quarry; both dip to the northwest. Note well-developed sleavage in the slate beds compared to the fractures in the graywackes.

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^o. 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.

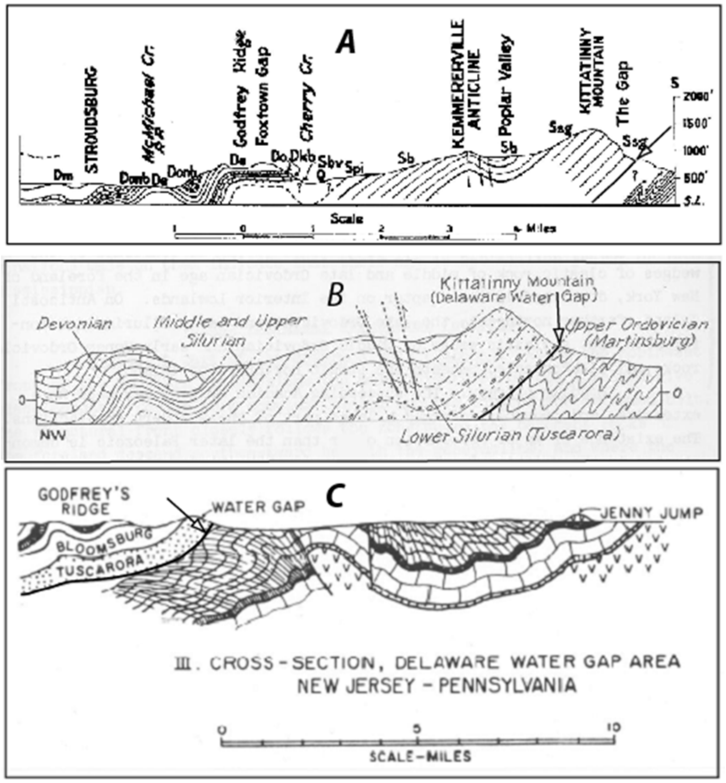


Figure 13. Cross sections showing previous interpretations of the angular relations of bedding above and below the Taconic unconformity (at arrow). A, Willard, 1938; B, King, 1951; C, Maxwell, 1962. Note in C that below the Tuscarora (= Shawangunk) slaty cleavage is shown as axial planar to folds in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

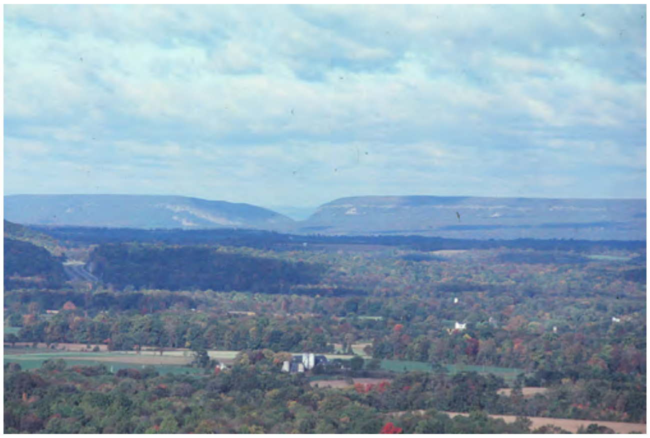


Figure 14. View of flat-topped Kittatinny Mountain looking north from the New Jersey Highlands.

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.

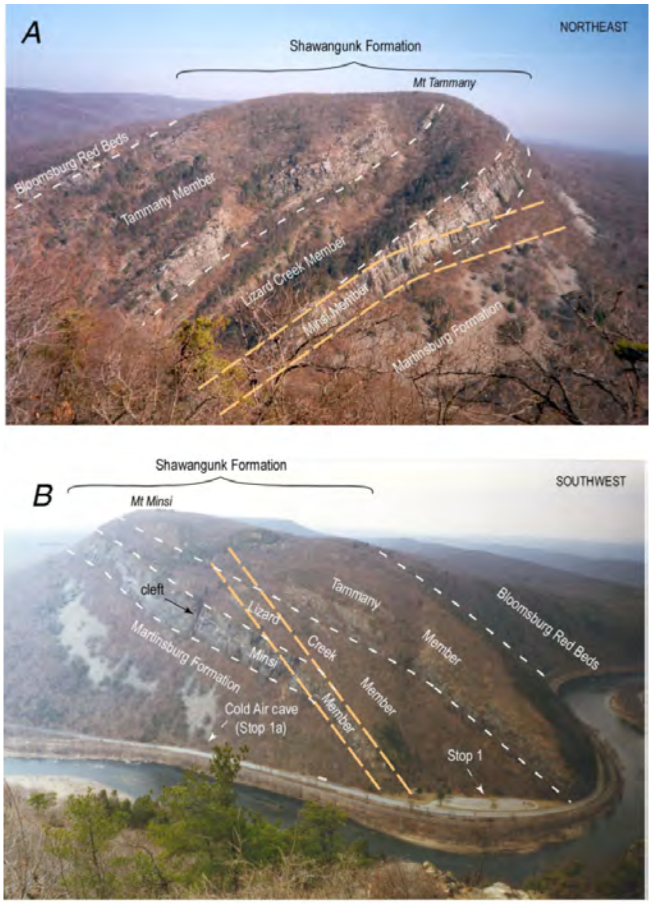


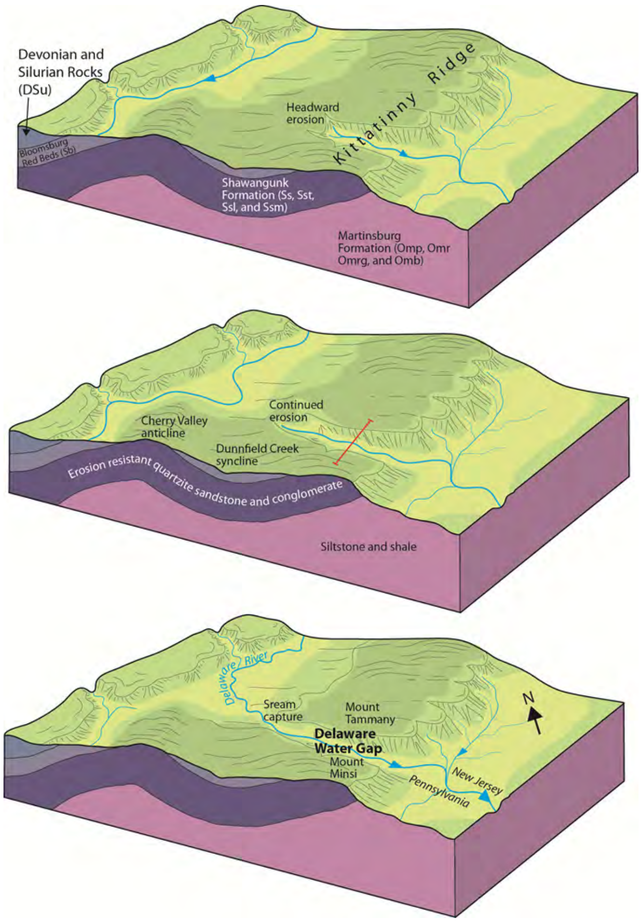
Figure 15. Middle Silurian rocks in Kittatinny Mountain in New Jersey (A) and Pennsylvania (B) at Delaware Water Gap. Long-dashed lines are the projected structural configuration of the Minsi Member of the Shawangunk Formation projected across the Delaware River from the opposite side of the gap. Figure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

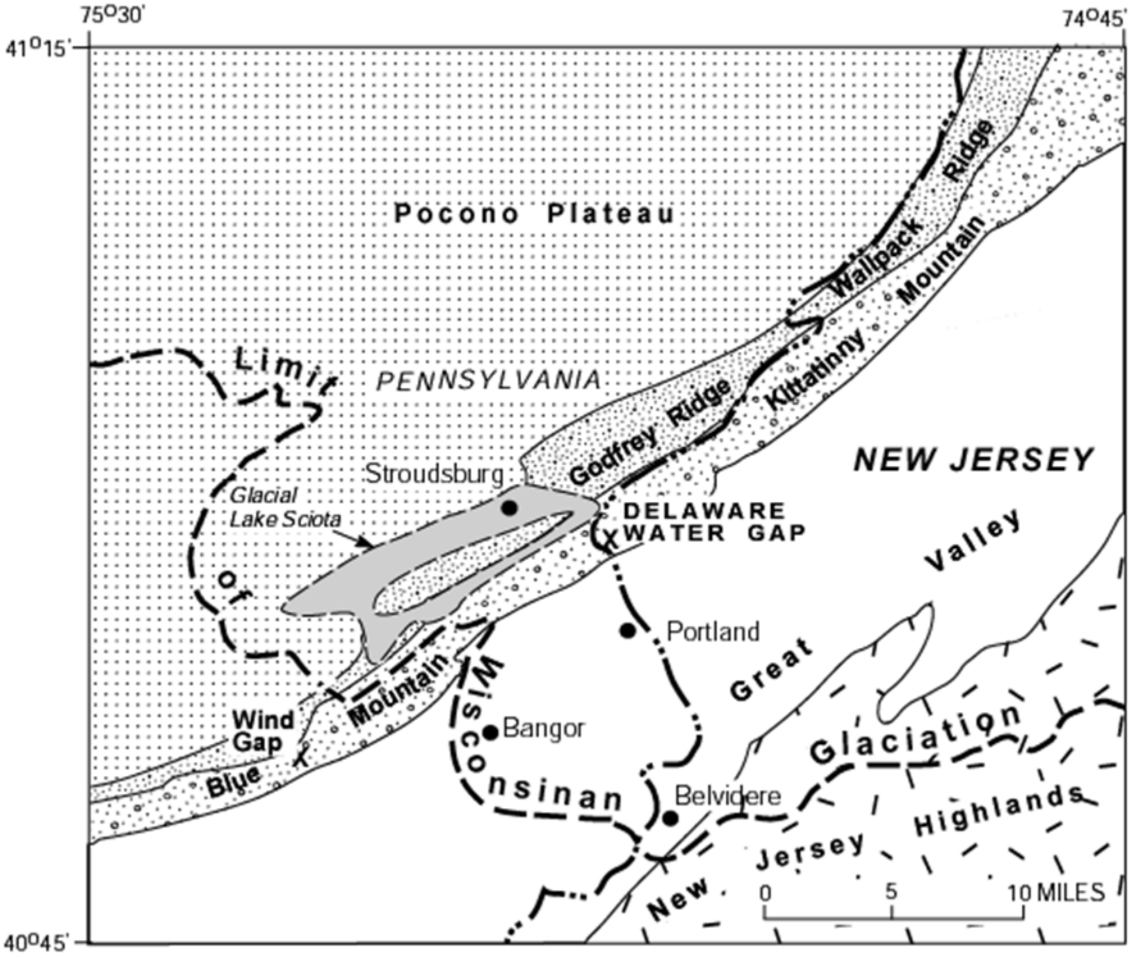


Figure 18. Physiographic map of part of easternmost Pennsylvania and northwestern New Jersey showing the position of the maximum advance of the Wisconsinan glacier. Modified from Epstein (1969).

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°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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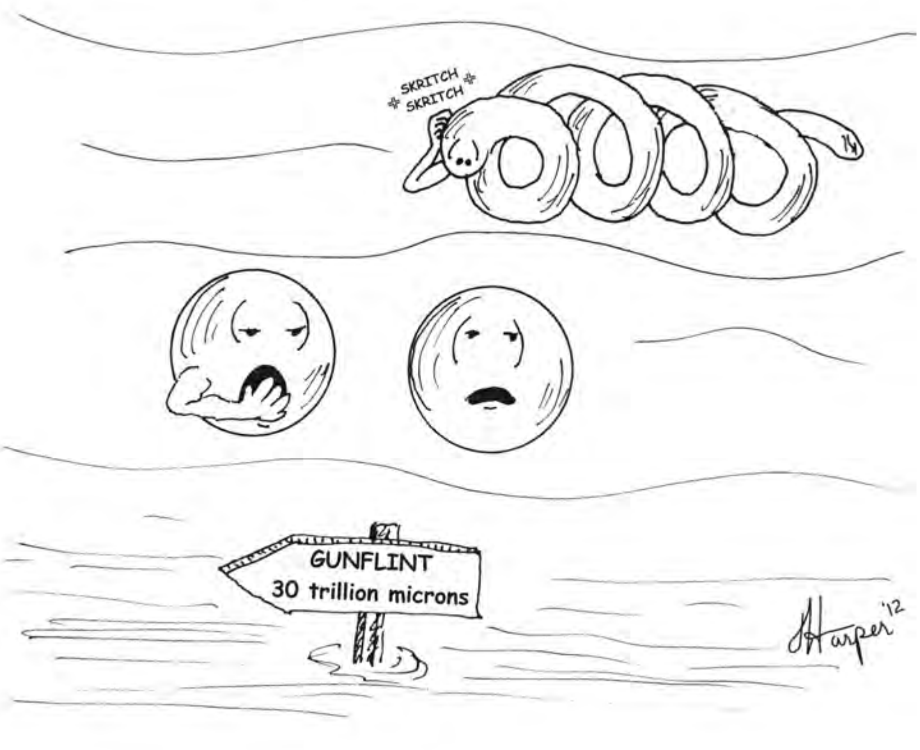
GREAT MOMENTS IN GEOLOGIC HISTORY
Part 6: The Precambrian



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.

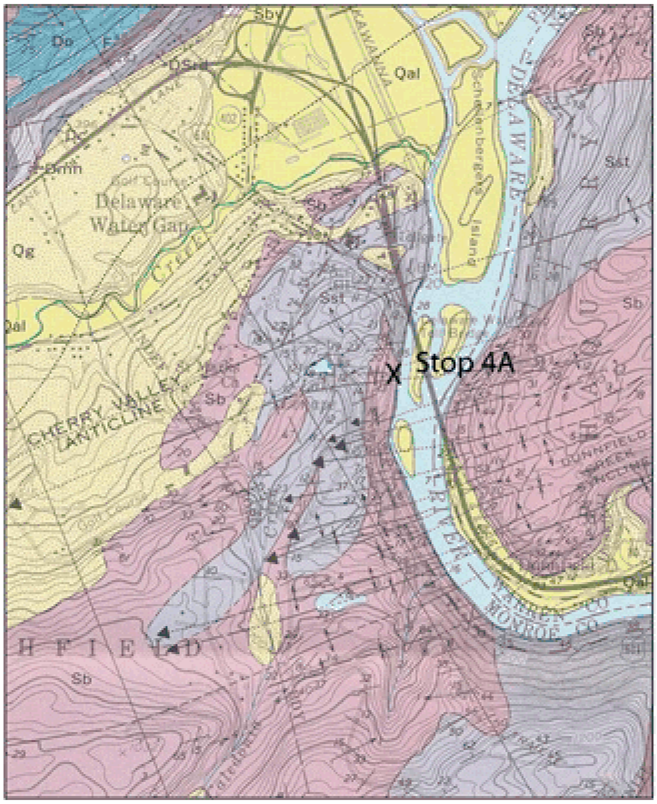


Figure 3. Geologic map of the Delaware Water Gap area (Epstein, 1973) showing the boundary between the Tammany Member of the Shawangunk Formation (Sst) and Bloomsburg Red Beds (Sb). Qal, alluvium; Qg, Wisconsinan stratified drift; Do, Oriskany Sandstone; Dc, Coeymans Formation; DSrd, Rondout Formation;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

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STOP 5: . YARDS CREEK PUMP-STORAGE GENERATING STATION

Ordovician-Silurian Unconformity; Taconic/Alleghanian Deformation; Origin of Slaty Cleavage.

Leader: Jack B. Epstein.

This site was last visited by the Field Conference in 2001 (Epstein, 2001). The present description is from that publication because at the time of this writing we were not allowed to visit the site because of security reasons and nesting of endangered bald eagles. If we do not visit the site, we will instead go to the visitors center where some of the geology can be seen (Figure 1) and descriptive plaques may be seen.

Figure 1. Cliff of Shawangunk Formation with the contact with the Martinsburg Formation faintly visible through the trees above the Penstock, as viewed from the visitor's Center parking lot..

The Yards Creek Pumped Storage Generating Station is owned by Jersey Central Power and Light and Public Service Electric and Gas Companies. It is a large hydrologic storage battery, taking advantage of the height of Kittatinny Mountain and utilizing a reversible pump-turbine (**http://delawarewatergap.org/TOCKS_ISLAND_DAM_PROJECT.html**; accessed 9/22/2012). There is a storage reservoir at the top of the mountain and one at the bottom on the south, 737 ft (225 m) below. A penstock and tunnel connects the two reservoirs (Figure 2). During peak hours, water from the upper reservoir flows through a turbine at the bottom, generating a maximum 400,000 kW of electricity. At night, when there is less demand for power, the generator reverses to become a pump that lifts water back to the top of the mountain, thus storing energy for the next day. The operation is about 70 percent efficient, but the

Figure 2. Penstock at Yards Creek from where it enters Kittatinny Mountain just below the Ss/Om contact, to the generating pump plant near the lower reservoir. It is 19 ft (6 m) in diameter, 1,861 ft (567 m) long, and with a 20 percent slope. Three 10-ft (3-m) diameter conduits extend into the plant. Hills of the the Martinsburg Formation (Om) are separated by fault-bounded carbonate rocks of Cambrian and Ordovician age in the Paulins Kill Valley. The New Jersey Highlands, comprising Precambrian rocks are in the distance.

Epstein, Jack, 2012, Stop 5: Yard Creek Pump-Storage Generating Station, *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. 294-301.

low-cost of the surplus off-peak power makes the process economically feasible. The engineering geology of the project area was summarized by Smith (1969).

When the project was initiated in 1963, at the time when the Tocks Island Dam was planned on the Delaware River immediately to the north, it was anticipated that the impoundment behind the dam would serve as a additional storage area necessitating an increase in size of the reservoir on top of the mountain. This project was nullified because the dam was never built and was officially deauthorized in 1992.

Geology

Figure 3 shows the geology in the area. The power plant and lower part of the penstock are in the Ramseyburg Member of the Martinsburg Formation. The penstock continues into a tunnel near the top of the exposed Martinsburg and continues through the Minsi and Lizard Creek members of the Shawangunk Formation and intersects the upper reservoir and the base of the Tammany Member (Figure 3). The penstock has cut through more than 1,000 stratigraphic ft (305 m) of the Martinsburg, affording an unparalled opportunity to study the changes in slaty cleavage that takes place as the contact with the more competent overlying quartzites and conglomerates of the Shawangunk are approached. Note that the uppermost member of the Martinsburg, the Pen Argyl, is missing, having been removed along the Taconic unconformity. The Pen Argyl-Ramseyburg contact disappears under the Shawangunk about 1

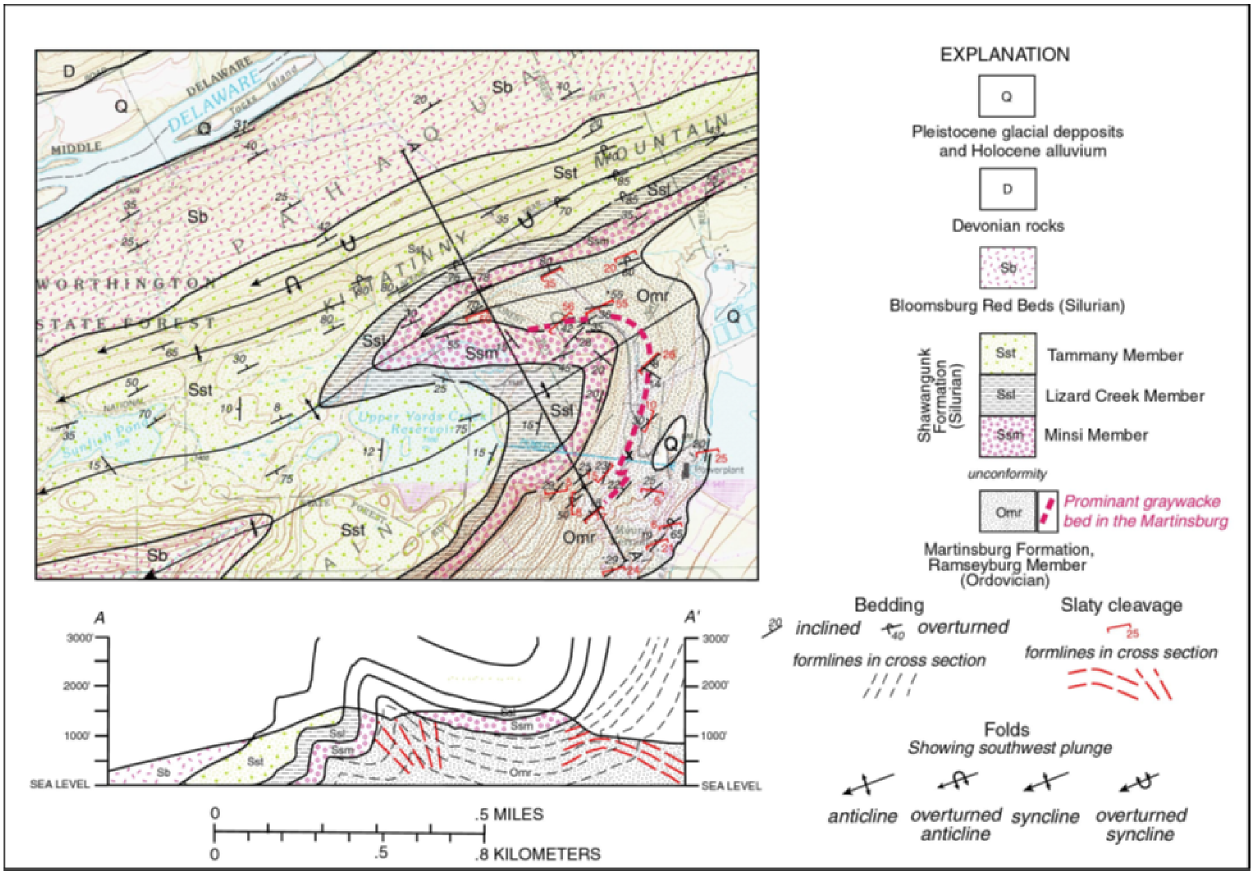

Figure 3. Geologic map and cross section of the Yards Creek-Tocks Island area, New Jersey. Geology modified from Alvord and Drake, 1971, Drake et al., 1969, and Epstein, J.B., unpublished data.

Figure 4. Northwest-dipping interbedded graywacke and shale exposed near the penstock tunnel at the base of the Shawangunk cliff, January 18, 1964. No cleavage is developed in the shales.

Figure 5. Contact (at arrow) between the dark-colored shale and greywacke of the Martinsburg below the sandstone and conglomerate of the Shawangunk. The slight angular discordance is not noticeable.

mi (1.6 km) west of Delaware Water Gap (Epstein, 1973; Stop 4, Figure 10), 8 mi (13 km) southwest of Yards Creek. At the time of my visit in 1964, the interbedded greywacke and shale were well exposed in the tunnel entrance near the base of the cliff (Figure 4).

Erosion of the resistant rocks of the Shawangunk in a syncline-anticline couplet resulted in the offset of Kittatinny Mountain here. Some of the beds are overturned, more so than farther southwest and less so than to the northeast (compare with Stop 8, Figure 7). The Martinsburg is fairly well exposed and its structural characteristics can be seen in different parts of the folds. Of particular interest is the gradual decline and disappearance of cleavage as the unconformable contact with the overlying Shawangunk is approached. That contact lies about 70 ft (21 m) above where the penstock enters the tunnel. (Figure 5). Along with the decrease in cleavage development towards the contact is the gradual “arching” of the cleavage as its dip to the southeast away from the contact changes to a northwestward dip as the contact is approached (Figure 4).

The lowest beds in the Martinsburg can be seen at the power plant under the transmission lines (Figure 6A). Here, cleavage dips slightly to the southeast and is fairly well developed, although not as well developed as in slate quarries farther from the Shawangunk contact. Higher, just above the picnic area, cleavage is more poorly developed, but is still a noticeable parting in many pelites (Figure 6B), although is not readily apparent in some nearby beds (Figure 6C). Finally, within a few tens of feet (meters) of the contact with the Shawangunk, cleavage is not visibly present, although there may be indications to be seen in thin section. The effects of the dying out of cleavage can be seen under the microscope (Figure 7). Many papers have described the petrographic characteristics of slaty cleavage (see Epstein and Epstein, 1967, 1969).

Figure 7D is typical. Cleavage parting is controlled by dark folia that have resulted from the pressure solution of soluble minerals, such as quartz, with a residue of dark carbonaceous material and iron oxides. Interstratal quartz grains between the folia have smooth edges parallel to the cleavage direction due to solution and hackly terminations at right angles, partly due to solution and re-precipitation (a in Figure 7D). Chlorite and muscovite may grow along the cleavage direction in the pressure fringes of hard pyrite grains (b in Figure 7D). Large chlorite-

Figure 6. Development of cleavage in the Ranseyburg Member of the Martinsburg Formation at Yards Creek. A—Fairly well-developed slaty cleavage, dipping 9°SE, exposed at the power plant at an altitude of 880 ft (268 m) and about 1,250 ft (381 m) stratigraphically below the Shawangunk contact. Bedding dips 28°NW; B—Outcrop just above the picnic area, altitude 1,020 ft (311 m), about 650 ft (198 m) stratigraphically below the Shawangunk contact. Cleavage, dipping 6°SE, is not as well developed as below, and the parting planes are further apart. Bedding dips 23oNW; C—Martinsburg outcrop at the same level as B and at the penstock to the west. A pelitic bed with cleavage dipping a few degrees to the northwest, 1 ft (0.3 m) above the hammer, is sandwiched between two beds that lack cleavage. A couple of bedding-plane faults with quartz veins in shear zones as much as 1-ft (0.3-m) thick, are present just to the right of this locality. A second-generation crenulation cleavage has developed in these zones. Elsewhere in the Martinsburg, as well as in younger rocks, slickensides on these faults indicate northwest translation of the overlying beds; D—Exposure a few feet (a meter) below Northwest-dipping bedding is the only parting present. Slaty cleavage is absent.

muscovite grains, a magnitude larger than the groundmass minerals, with mineral cleavage at high angles to the slaty cleavage and commonly cutting across cleavage folia, appear to be porphyroblasts (c in Figure 7D). As the Shawangunk contact is approached and cleavage dies out, these features gradually disappear. Quartz grains have their original shape. Pressure fringe growth around pyrite grains is lacking. Large chlorite-muscovite grains are missing. All this occurred after the folding of the Shawangunk, and by inference, after all of the overlying rocks which were probably about 20,000 ft (6,096 m) thick. Clearly, the process of cleavage development occurred under conditions of heat and pressure (metamorphism), and based on conodont geothermometry, in the neighborhood of 300°C (Epstein, 1974).

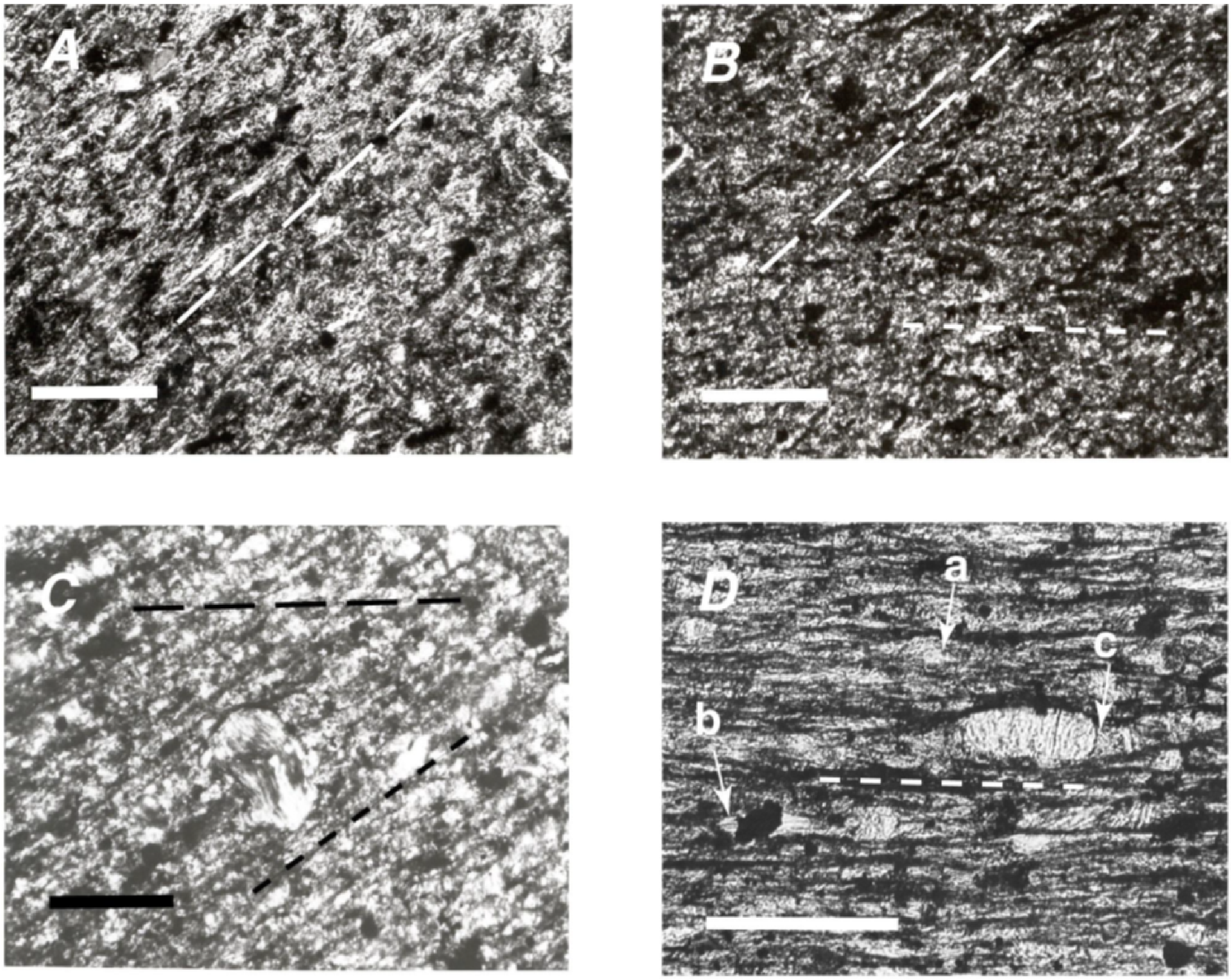

Figure 7. Photomicrographs showing development of cleavage (short dashed line) at the expense of bedding mineral orientation (long dashed line) in the Martinsburg Formation. Bar scales are all 0.1 mm long. A-C are from outcrops of the Ramseyburg Member of the Martinsburg along the penstock at Yards Creek. D is from an abandoned slate quarry in the Pen Argyl Member of the Martinsburg Formation, 1.5 mi (2.4 km) south of the Shawangunk contact at Lehigh Gap, in the abandoned David Williams slate quarry (Epstein and others., 1974, p. 348); it is typical of all well-developed slate throughout the Martinsburg. A—2.5 ft (0.8 m) below the Shawangunk contact. Muscovite and chlorite grains are parallel to bedding. There are no presolved hackly edges on quartz grains. No cleavage is apparent; B—2.5 ft (0.8 m) below the Shawangunk contact. Bedding is defined by muscovite grains dipping to the left (northwest in the outcrop). Cleavage is incipient and appears as dark carbonaceous folia with minor muscovite parallel to it; C—860 ft (262 m) below the Shawangunk contact. Bedding is horizontal but cleavage development has reoriented most grains parallel to it. Quartz grains (white) have hackly edges due to pressure solution. Chlorite-muscovite grains that are much larger than the groundmass minerals and whose mineral cleavage is at a high angle to bedding, make an appearance suggesting that they may be prophyroblasts; D—Well-developed slaty cleavage characteristic of most of the Martinsburg pelites in eastern Pennsylvania and northern New Jersey. Flattening of quartz grains (a), pressure-shadow mineral growth around pyrite grains (b), and growth of muscovite-chlorite along cleavage (c) is typical. Orientation of minerals parallel to bedding is not evident.

As discussed at Stop 3 and 4, Lehigh and Delaware Water Gaps, the arching of cleavage as the trough of a syncline in the competent rocks of the overlying Shawangunk is approached, which is accompanied by a dying of the cleavage, can be ascribed to a pressure-shadow mechanism.

Small-scale outcrop as well as microscopic versions of this phenomenon are numerous. The significant point is that it occurs at different levels within the Martinsburg (within the middle of the Ramseyburg Member here, at the top of that member at Delaware Water Gap, and high in the youngest Pen Argyl Member at Lehigh Gap). Thus, the controlling factor is the overlying Shawangunk, which had to be present at the time the cleavage developed. Since the Shawangunk is post-Taconic in age, the cleavage must be post-Taconic, i.e., Alleghanian (there is little evidence for significant Acadian (Devonian) deformation in this part of the Appalachians).

Nowhere in Eastern Pennsylvania and New Jersey is the contact between the Shawangunk and Martinsburg in the overturned limb of a syncline exposed to demonstrate the complementary arching of the cleavage as shown in Figure 13 at Stop 3. The contact between overturned beds of both formations was temporarily exposed, however, during construction of an additional tunnel for the northeast extension of the Pennsylvania Turnpike in 1989, 2 mi (3 km) southwest of Lehigh Gap and 31 mi (50 km) southwest of Delaware Water Gap (Epstein and Buis, 1991). At the overturned contact the Martinsburg dips 35° SE and the Shawangunk is 10° steeper. Cleavage dips 5° less than bedding in the Martinsburg, conforming to the model shown in Figure 13 of Stop 3. These beds are in the southeast overturned limb of the same fold in which, up-plunge at Lehigh Gap, the contact is at the exact trough of the fold and cleavage dies out within 200 ft (61 m) of the contact (Epstein and Epstein, 1969).

There are few exposures of the Martinsburg-Shawangunk contact in eastern Pennsylvania. Yards Creek is the best. The contact is about 70 ft (21 m) above the top of the penstock as it enters the tunnel (Figures 5, 8A). The angle of discordance between the two formations is hardly measurable, and probably no more than a couple of degrees. An attempt to get bedding attitudes readings in both units at the contact resulted in N20°E/24° NW for the Martinsburg and N26°E/25° NW for the Shawangunk. The basal Shawangunk is sandstone and conglomerate with pebbles as much as 0.75 in (1.9 cm) long with slightly irregular bedding planes. A bed in the Martinsburg rises to the southwest along the contact and is cut out within a few tens of feet (meters) under the lowest bed in the Shawangunk (Figure 8*A*).

Figure 8. Contact between the Ranseyburg Member of the Martinsburg Formation (Omr) and Shawangunk Formation (Ss) at Stop 6. A—View looking southwest showing the rising of bedding in the Martisburg (dotted line) as the contact is approached. B—The unconformable contact is marked by a 2-in (5-cm) thick clay fault gouge (at arrows). Note the lack of slaty cleavage in the

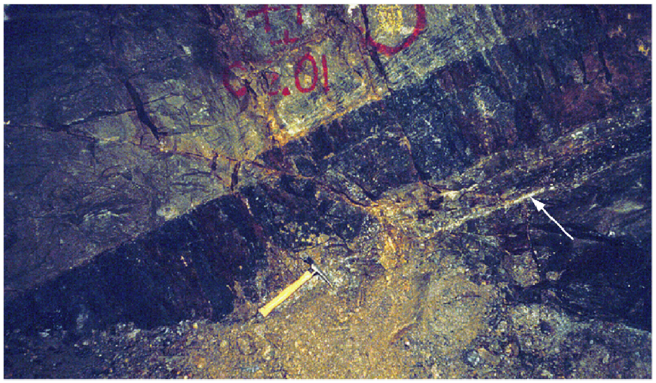

Figure 9. Exposure in January, 1964, showing a small thrust fault (translation of overriding bed to northwest) and thin fault gouge at the Martinsburg-Shawangunk contact.

At the contact, between the pelites of the Martinsburg and the feldspathic sandstone of the Shawangunk, there is a 1- to 2-in (2.5- to 5-cm) thick yellowish-gray (5Y 8/1) to light-greenish-gray (5GY 7/1) clay. The color is in marked contrast between the dark-gray pelite of the Martinsburg and the grayish-orange weathered color of the basal Shawangunk. It is undoubtedly the result of leaching by ground water, which is common at this type of contact. However, the clay contains sheared, fragmented, contorted and disoriented clasts of pelite, showing that it is a fault gouge. The gouge is damp and fragile and difficult to photograph. However, it was seen when the penstock tunnel was excavated (Figure 9). Surfaces carefully cut with a sharp razor blade clearly show the brecciated shale fragments. Movement during folding might be normally expected with overriding beds moving up towards the crest of adjacent anticlines. However, elsewhere at the contact, such as at Lehigh Gap (Epstein and Epstein,1967, 1969; Stop 3), slickensides show that movement has been in an opposite direction, to the northwest, conforming to the regional northwest translation of bedding-plane faults and vergence of folds in overlying Silurian and Devonian rocks.

The angular discordance at the unconformity, attributable to Taconic deformation of the Martinsburg prior to deposition of the Shawangunk, is only a few degrees here. Along the entire length of Kittatinny Mountain in northern New Jersey and into Shawangunk Mountain in southeastern New York (as least to near Ellenville, NY), and in the opposite direction to the southwest to Hawk Mountain in Pennsylvania, several miles (kilometers) east of Stop 1, the angular discordance does not exceed 15°, showing that this is a zone of low-amplitude Taconic folding. This will be discussed at Stop 10.

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STOP 6: BUSHKILL MEMBER OF THE MARTINSBURG FORMATION AT THE NEWTON, NJ HOME DEPOT PARKING LOT

Leaders - Don Monteverde and Greg Herman

Introduction

Stop 6 is at a large excavation of the Bushkill Member of the Martinsburg Formation alongside the Home Depot parking lot in Newton, NJ (Figure 1). The purpose of this stop is to examine bedding and cleavage structures in the Martinsburg Formation that are attributed to Alleghanian deformation within the Ridge and Valley thrust system in the NJ Kittatinny Valley (Figure 2). The features that we will see in outcrop are a result of combined shear and flattening strains in the footwall of a major overthrust fault that places Cambrian dolomite on top of Ordovician slate. Remnants of a large over thrust sheet are now locally preserved at various places along the thrust front as dolomite klippen resting atop the Martinsburg Formation. One of these klippen occurs only about 0.5 mi (0.8 km) northeast of this stop behind a commercial building (Figure 1) We will discuss the timing and geometry of slaty and crenulation cleavage with respect to bedding in the Martinsburg Formation, and show that these features result from progressive strain within a thrust system that cuts and juxtaposes a Cambrian-Ordovician foreland-fold sequence resulting from earlier Taconic deformation. Various geological interpretations of the sequence of folding and thrusting will be discussed, and examples of representative structures will be included from a series of nearby outcrops that were recently exposed and/or removed as a result of urbanization.

The area of focus is in the western part of the Newton East 7.5-minute topographic quadrangle near the Newton West quadrangle boundary (Figure 1). Newton is the capital of Sussex County and has experienced siginificant population growth over the past few decades. Associated highway and commercial construction during this period has periodically unearthed some unique geological features, some of which have been later removed by progressive urbanization. Access to some of these remaining outcrops can be compromised by aggressive foliation growth, including poison ivy that makes it impractical to use some of the best outcrops for field excursions. This is especially true for the carbonate klippe that was rapidly overgrown. This area was included in the 52nd Annual New York State Geological Association field trip (Drake and Lyttle, 1980). That trip included a stop at a cross-strike excavation through one of the carbonate klippe and subjacent thrust fault that was at the time located behind a Grand Union supermarket (Figures 1 and 2). Consequently, the klippe was named the "Grand Union klippe", which has historically led to some discord, with some visiting geologists providing comments such as "How can they identify the structure right if they can't even correctly identify the name of the food store?". The klippe and thrust fault exposure are still there, but the degraded nature of the outcrop from prolonged weathering, robust vegetative cover, and cramped access precluded us from visiting this local. However the fresh excavation of the subjacent Martinsburg slate at the Home Depot location provides an excellent opportunity to examine structures developed in the footwall of the overthrust that emplaced the klippe.

Monteverde, Don and Herman, Greg, 2012, Stop 6: Bushkill Member of the Martinsburg Formation at the Newton, NJ Home Depot parking lot, *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. 302-313.

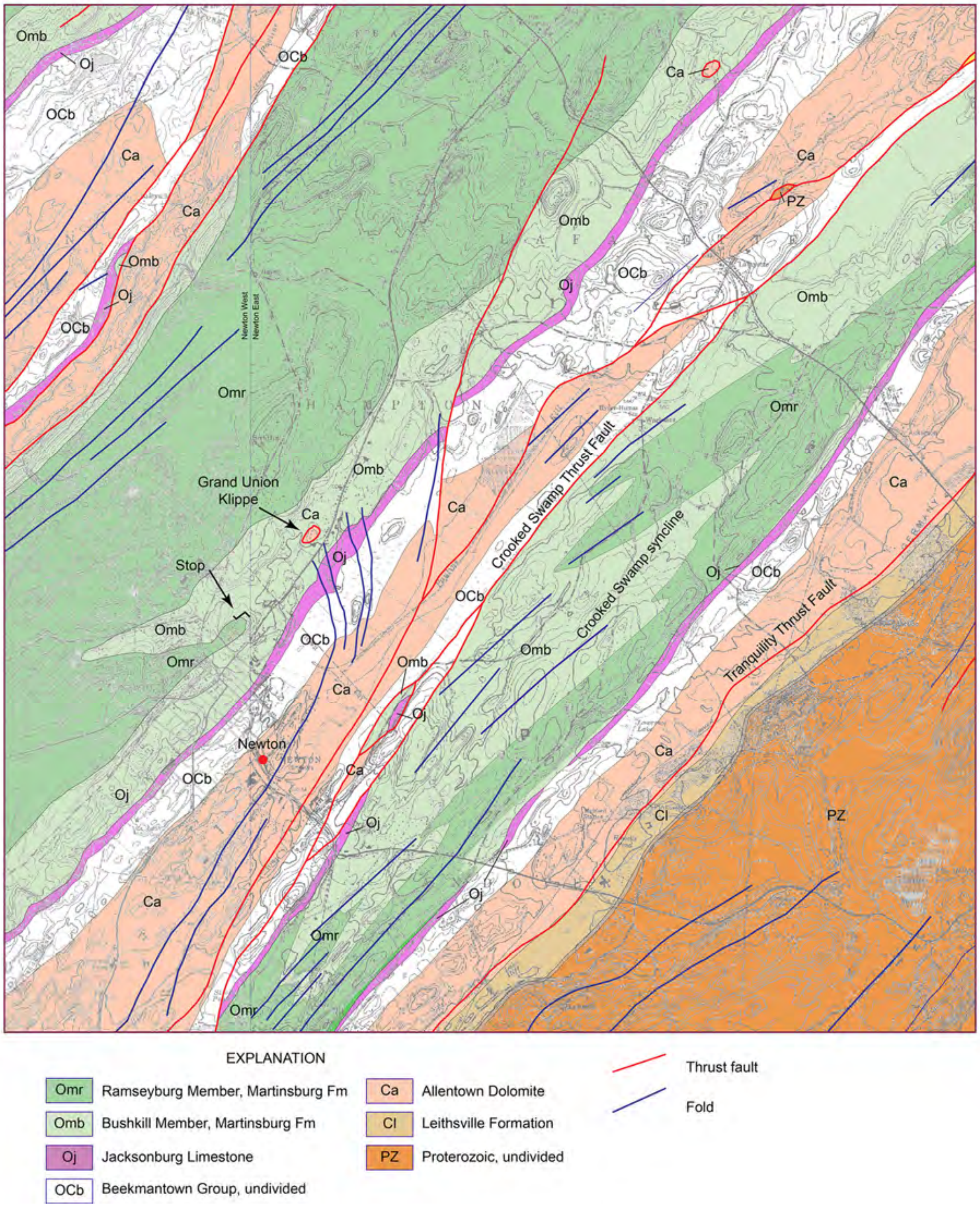

Figure 1. Regional geology of parts of the Newton East and West 7.5' quadrangles. Linework is based on the 1:100,000 scale map of Drake et al., (1996) and unpublished data from R.A. Volkert, G.C. Herman and D. Monteverde.

Figure 2. Hope Depot parking lot stop. Stars locate positions where other figures were taken.

Regional Geology

The Cambrian-Ordovician carbonate bedrock in the Kittatinny Valley record early carbonate shelf deposition on a passive margin that later becomes perturbed and mildly strained by early phases of tectonic-plate convergence during the Taconic orogeny. Drake and Lyttle (1980) assigned the Cambrian-Ordovician platform-carbonate sequence into the Kittatinny Supergroup, that attains an average thickness of about ~3,200 ft? (975 m) in New Jersey. This sequence is predominantly dolomite and includes, from oldest to youngest, the Leithsville Formation, Allentown Dolomite, and Beekmantown Group. The latter is divided into upper and lower parts (Drake et al., 1996). The first evidence of tectonic disruption of the carbonate platform is a pronounced, Middle Ordovician unconformity with associated paleokarst facies, including localized pockets of alluvium (Monteverde and Herman, 1989). This "Beekmantown" unconformity probably stems from migration of a peripheral bulge toward the foreland (Jacobi, 1981; Quinlan and Beaumont, 1984; Flemings and Jordon, 1989; DeCelles and Giles, 1996). As the bulge continued its foreland journey (northwestward in current geographic direction), the weathered carbonate rocks on the Laurentian margin were resubmerged and carbonate deposition recommenced, resulting in deposition of the Jacksonburg Limestone. This unit contains a basal, shallow-water, fossiliferous facies (cement limestone, Figure 3; Miller, 1937), that grades upward into a deep-water limestone facies (cement rock, Figure 4; Kummel, 1901). This progression reflects the early stages of

Figure 3 Cement lime facies of the Jacksonburg Limestone. Unit is overturned with tops to the northwest (left side of photograph). Location of outcrop shown in Figure 2.

Figure 4. Cement rock facies of the Jacksonburg Limestone. Unit is overturned with a well developed cleavage parallel to pen in photograph. Location of outcrop shown in Figure 2.

development of a Taconic foreland basin. The basin gradually deepened as a result of sedimentary loading and tectonic stacking of an accretionary prism on the Laurentian margin in front of series of approaching island arcs. Eventually, the limey argillites in the upper part of the Jacksonburg gave way to siliceous turbidites in the lower part of the Martinsburg Formation (Bushkill Member; Drake and Epstein, 1967). Coarser-grained greywacke silt and sandstone in the upper parts of the Martinsburg (Ramseyburg Member; Drake and Epstein, 1967) reflect progressive foredeep infilling, then eventual inversion from continental suturing during the Alleghanian Orogeny.

In the Appalachian Great Valley of eastern Pennsylvania, New Jersey (Kittatinny Valley), and New York (Hudson Valley) the uppermost part of the Martinsburg has variable facies along strike. Thick-bedded slates of the Pen Argyl Member in eastern Pennsylvania (Drake and Epstein, 1967) overlie the Ramseyburg graywacke, reflecting renewed basin deepening in the area of the Pennsylvaia salient in comparison to areas to the northeast along strike in New Jersey and New York (Lash, 1987, 1988). Near Stop 8 at High Point State Park, NJ, Epstein and Lyttle (1987) mapped a coarse-grained facies in the uppermost part of the Martinsburg that contains medium-grained, medium- to thick-bedded sandstone with shale and siltstone rip-ups clasts within graywacke turbidites. They informally designated this facies as the Pine Bush that locally replaces the Ramseyburg Member. Drake (1991) later formalized the Pine Bush sandstone as the High Point Member. Thick-bedded sandstone of the High Point is thought to reflect a more proximal sedimentary source area than for the Ramseyburg Member. Epstein and Lyttle (1987) also informally described a shale and graywacke sequence lying atop the High Point Member that they called the Mamakating. They proposed the Mamakating as being the time equivalent as the Pen Argyl Member of eastern Pennsylvania.

Further to the southeast within the Ridge and Valley thrust system, the Martinsburg Formation does not adhere to the stratigraphic sudivision of the Martinsburg seen in the Great Valley. Open and upright folds in the carbonate platform were probably formed prior to Martinsburg deposition such that coarser-grained facies were deposited in more proximal positions while fine-grained wildflysch was deposited in the foredeep. Such is the case for the Crooked Swamp syncline (Figure 1), that includes both slate and graywacke facies that locally intertongue in the lower section of the Martinsburg. More work is needed in the New York Hudson Valley integrate facies changes seen there with respect to what is observed further southwest.

Tectonic Interpretations

Regional tectonic interpretations of Paleozoic folding and thrusting in the New York recess have widely varied. In the 1960s an alpine-type, fold-and-thrust nappe model was used for parts of the Great Valley and Reading prong in Pennsylvania and New Jersey based on the common occurrence of pronounced cover-layer strains including apparent, extensive panels of overturned Lower Paleozoic beds (Drake et al., 1961; Drake, 1967a, 1967b; Drake et al., 1967). Lesser deformed rocks involving mostly upright beds in the New Jersey Kittatinny valley and synthetic (southeast-dipping) thrust faults placing younger, hanging-wall rocks over older footwall rocks limited the extension of the nappe theory into this part of the region, and led to more recent interpretations that portray the composite fold-and-thrust belt as an imbricate thrust -fault system with an architecture that spatially varies based on the thickness of the Paleozoic cover, and the relative location with respect to foreland (NW) and hinterland (SE) areas. As more-detailed, quadrangle-scale mapping was conducted throughout the Valley and Ridge and Highlands provinces in New Jersey, popular support for the alpine-type nappe model waned and a basement-cored, imbricate thrust fault system gained credence (Lyttle and Epstein, 1987; Herman and Monteverde, 1988,1989; Drake, 1992; Drake and Volkert, 1993; Monteverde, 1992; Ghatge et al, 1992). The latter deformation style agreed with other early work in the region by Merchant and Teet (1954) and Offield (1967), and demonstrated a uniform strain gradient based on modern, balanced cross-section analyses that helped impart plausibility to a complex structural interpretation. This model includes Taconic folding of the Kittatinny Supergroup cover rocks that predated, or was synchronous with Middle and Upper Ordovician sedimentary deposition in the Kittatinny Valley. It also demonstrated increased tectonic strains progressing from the hinterland towards the foreland; emergent thrust faults and overturned fault-propagation folding in the southeast and southwest systematically diminish into blind faulting with broad and open cover folding to the northwest. Subsequent tectonic strains imparted during the Alleghanian orogeny included foreland-directed thrust faulting that cut and juxtaposed earlier cover folds, resulting in apparent, out-of-sequence complexities (Herman et al., 1997). The Jenny Jump-Crooked Swamp fault system (Herman and Monteverde, 1988;1989; Herman et al., 1997), later referred to as the Jenny Jump fault system (Drake, 1992; Drake and Volkert, 1993), include several major thrust faults of Alleghanian age based on the fact that they affect both Lower and Middle Paleozoic rocks.

Herman et al., (1997) interpreted the Crooked Swamp fault as the major overthrust fault in the Newton area that emplaced the thrust sheet from which three small klippen were derived, including the Grand Union klippe. The Crooked Swamp fault is shown as linking with the Jenny Jump thrust fault along strike to the southwest. The Jenny Jump emplaced the thrust sheet from which the large Hope klippe is derived that also sits atop Martinsburg slate within the Blairstown 7.5-minute quadrangle (Drake and Lyttle, 1985; Drake et al., 1996; Herman et al., 1997). The set of small klippen lying in front of the Crooked Swamp thrust fault were unmapped prior to the afformentioned commercial development and excavation of the thrust fault. Upon exposure, these structures drew attention from many different workers that invoked various explanations for their occurrence. For example, Pollock (1975) characterized the

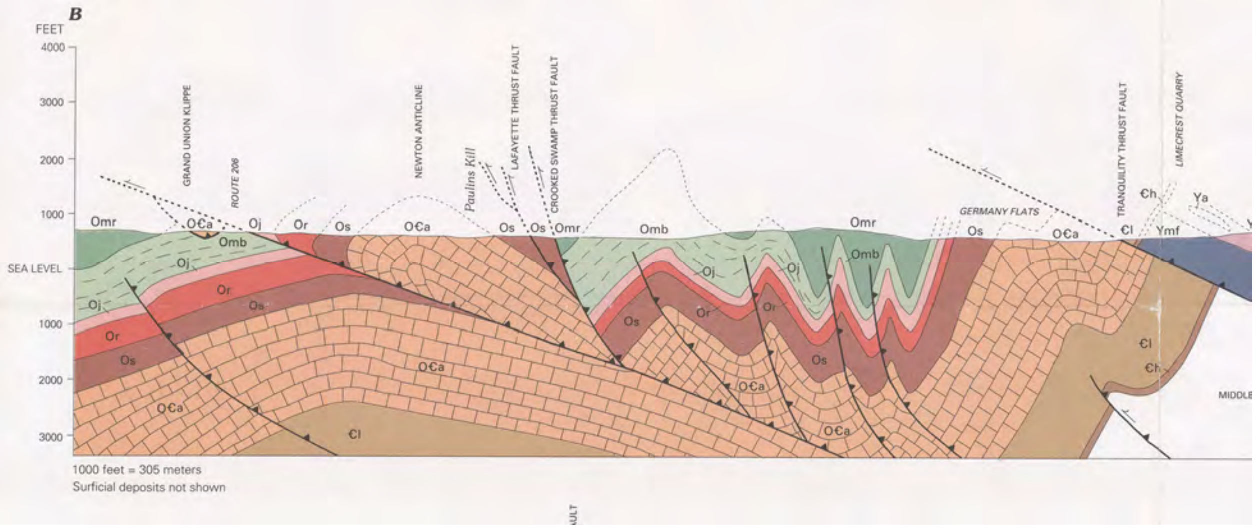

Figure 5. Cross section from Drake and Volkert (1993) depicting the "orphan" interpretation of the Grand Union klippe.

Grand Union klippe as a block of Allentown dolomite that slid onto the Martinsburg Formation prior to regional folding. Drake and Lyttle's (1980) field trip to the site described Martinsburg graywacke beds beneath the klippe as being disrupted and floating within a shale matrix. They suggested that the thrust fault responsible for its emplacment was folded and correlated it with the Jenny Jump thrust fault, which Bayley et al. (1914) portrayed long ago as having emplaced both Middle Proterozoic gneiss of Jenny Jump Mountain and Lower Paleozoic rocks in the Hope klippe on the younger Martinsburg Formation (Drake and Lyttle, 1980, 1985; Herman and Monteverde, 1989; Herman et al., 1997). These means that the slaty and spaced cleavage in the Martnsburg Formation predated these thrust faults because bedding and cleavage in the Martinsburg was folded as a result of thrusting. There are other smaller klippen near the Hope klippe that contain Middle Proterozoic gniess that were part of this vast overthrust sheet. All these erosional remnants of the extensive Jenny Jump thrust sheet require a late stage deformation to explain the generally southeast dipping thrust warping and developing a small fold that results in the klippen's eventual preservation. Later Drake and Volkert (1993) reinterpreted the lithology of the Martinsburg and suggested the klippe lies within the Bushkill, not the Ramseyburg as previously noted. They also proposed that the klippe represents an orphan, an isolated duplex that correlates to a hinterland footwall ramp (Lewis and Bartholomew, 1989) and rode to its present location on another unnamed thrust fault (Figure 5).

Field Results

Grand Union Klippe

Initial strip mall construction blasted through a small hill exposing a cross sectional view of the Grand Union klippe. The Grand Union food store is gone and replaced by a series of different commercial establishments but the exposure remains behind the establishments slowly succumbing to weathering and foliage reclamation (compare Figures 6 and 7). Northwest-dipping Cambrian Allentown Dolomite sits on top the Middle Ordovician Bushkill Member of the Martinsburg Formation separated by a northwest-dipping fhrust fault (Figure 6). The

Figure 6. View of Grand Union klippe cut. Cambrian Allentown Dolomite, to the left rests on Bushkill Member of the Martinsburg to the right. The north-dipping thrust parallels the Allentown bedding. Northeast striking, southeast dipping fracture in the Allentown form the main deformational pattern in the hanging wall rocks. Note box showing postion of photograph shown in Figure 8. Also note the degree of foliage growth as compared to the clean outcrop in Figure 7 just to the left of this location.

Figure 7. Photograph of the Allentown Dolomite in the Grand Union klippe hangingwall before the present foliage invasion. Bedding dips to the northwest (left) and fractures to the southeast (right).

Allentown, a shallow water carbonate contains stromatolites and oolites here indicating right side up bedding that parallels the fault trend. The klippe is relative small (Figure 2) and its western contact is not exposed. However the westernmost Allentown exposure has rotated into a southeasterly dip suggesting the thrust remains bedding parallel. This is different than the Hope klippe in the Blairstown quadrangle where the Jenny Jump fault initially appears to parallel bedding on the eastern edge of the Hope klippe, and then climbs upsection section close to 3,280 ft (1000 m) as the Hope klippe's western contact is in the middle of the Beekmantown Group. So the fault climbed through the Leithsville, Allentown, and half way through the Beekmantown before rotating back to a southeasterly dip again overriding the Martinsburg Formation.

Deformational features in the Allentown are relatively minor. Only spaced fractures orientated approximately normal to the fault surface cut the Allentown (Figure 7). These fractures are well developed, tighter spaced that commonly observed and initially makes one question what is bedding. The black ribbon slate of the Bushkill on the other side of the fault has absorbed the contractional stresses from fault propagation. Bedding is very difficult to find. Drake and Lyttle (1980) describe the Martinsburg here as an auto melange where detached fold hinges can be observed floating in a clayey matrix. Proximal to the thrust contact hints of bedding occur but cannot be traced any distance before merging with are not well developed enough to be definite (Figure 8). Bedding identification remains allusive in the Bushkill even 10 m away from the thrust contact, after one moves the poison ivy out of the way.

West of the Klippe

North and west of Home Depot, two large outcrops of the Bushkill ribbon slates sit in a footwall position where the Crooked Swamp thrust has returned to a southeast dip. Both cuts trend approximately northeast-southwest. Their bedding orientation changes from a gentle

Figure 8. Photograph of the Bushkill slates proximal to the overlying Crooked Swamp thrust. One small layer yields a hint of possible bedding in the clay rich Bushkill but it cannot be trace any distance away from the black line on the photograph.

Figure 9. Photograph of ribbon slates of the Bushkill west of the klippe and Home Depot stop (Figure 2). Bedding is nearly vertical with tops to the left and forms the steep limb of the asymmetrical anticline. Slaty cleavage is axial planar to the anticline. Thin gently southeasterly dipping calcite veins/shear planes display both normal and reverse sense of offset due to the shear and flattening strains from the overthrust sheet. Normal offset dominates. Shearing appears restricted to the steep limb of the northwest-verging anticline.

southeast dip in the east that rolls over into a steeply northwest dip outlining a northwest-verging asymmetrical anticlinal fold with an axial planar slaty cleavage. A similar northwest-verging asymmetrical anticline is observed at both cuts. These fold patterns suggest this is the western limb of a syncline. Gently southeast-dipping, calcite-coated shear planes display dominantly normal but also locally reverse offset of bedding suggesting a reaction to the combined shear and flattening strain (Figure 9) . Offset is limited to several centimeters at a maximum. These thin calcite slip planes appears restricted to the near vertical to steeply-dipping bedded Bushkill. Slip is not obvious where bedding is nearly horizontal.

Figure 10. Bushkill ribbon slates on opposite side of road from previous figure. This exposure has seen be removed to allow for further commerical construction. Bedding is approximately horizontal forming the shallow limb of the northwest-verging asymmetrical anticlinal fold across the street (Figure 9). Calcite veins rest parallel to bedding but have been cut and rotated showing a normal sense of offset due to the shear and flattening strains from the overthrust sheet.

Earlier road construction created an outcrop across the street from the previous two described above (Figure 2). Unfortunately population continued to grow, leading to further retail store development requiring increased parking space, which always scores higher than outcrop preservation, and we lost the exposure. The Bushkill here mirrors the other outcrops with a nearly horizontal bedding cut by several bed-parallel calcite veins that ranged from 8 mm to 3 cm thick. The steeply dipping limb of the anticlinal fold was never exposed here. Slaty cleavage cuts the calcite veins displaying a normal sense of rotation (Figure 10). Slip is different here than across the road where it occurs on the calcite veins. Cleavage probably formed early in the compressional event and, through the continuum, slowly rotated into a cleavage trough due to the shearing and flattening from the overriding Crooked Swamp thrust sheet. Normal rotation on the calcite developed during the flattening.

North of the Klippe

Climbing the hill north of the Grand Union klippe, one rapidly crosses through the Bushkill and into the Ramseyburg proper, meaning all the rock for several miles (kilometers) or more westward is Ramseyburg. The Bushkill-Ramseyburg contact trends southwestward, climbing the ridge and outlines the Bushkill pinch-out (Herman and Monteverde, 1989; Drake, 1992; Drake et al., 1996) (Figure 1). Not far from the klippe the Ramseyburg quickly loses the structual signature of the proximal Crooked Swamp thrust fault. Cleavage in the graywacke and slates has returned to regional trends both northeast strike and southeasterly dip. Several small fold pairs can be mapped in the Ramseyburg aligned along regional trends. The rapid loss of the deformation signature of the Crooked Swamp thrust sheet helps to explain why the highly skilled mapping geologists of the early 20th century and later failed to identify the Grand Union klippe before the creation of the artificial exposure. Maybe if they discovered it the name might be more geological as opposed to being named for a food store.

East of the Klippe

Lower Paleozoic carbonates crop out just across NJ 206/94 behind the commercial buildings. A uniform succession into the Jacksonburg has been mapped by various field studies (Herman and Monteverde, 1989; Drake and Volkert, 1993; Drake et al., 1996) (Figure 2). All show the carbonate bedding rotated over to overturned (Figures 3 and 4) in their approach to the thrust-deformed Martinsburg. Currently commercial development has eradicated most Martinsburg exposures east of the klippe. One remaining exposure north and east displays a much stronger degree of chemical weathering that hides the trend of bedding. Where exposures are slightly more evident cleavage has rotated into a southwestward dip and northwest strike. This reading completes the other limb of the cleavage trough with the klippe resident in the axial hinge of the trough.

Home Depot

Two faces of the Bushkill are exposed here. Along the far southern wall, the Bushkill dips gently, ~15° northwestward. Bedding strike is regional ranging from 45 ° to 65 ° east. Slaty cleavage has been deflected due to Crooked Swamp thrust loading and averages ~140° strike and dips ~ 5-18 ° northeastward toward the Grand Union klippe. The cleavage further defines the cleavage trough that developed from the shear and flattening strain imposed from the overriding thrust sheet. Bedding-cleavage intersection lineations trend northeasterly with an average of less than 10 ° plunge. Sedimentary structures indicate bedding is right side up. Widely separated thin (~2-3 mm thick) calcite veins cut across cleavage and trend with a north-northeast strike and moderate southeasterly dipping between 35-65°.

The second face running approximately parallel to the Home Depot building presents similar bedding and cleavage trends within the Bushkill. Bedding dips steepen slightly to a maximum recorded of 25° northwest. Again cleavage has a southeast strike and northeasterly dip toward the klippe. A widely spaced (3 to 7 ft [1 to 2 m]) joint system developed that has a northwest strike and southwest dip. Calcite veins and tension gash arrays are visible locally on the face. A weakly developed crenulation cleavage can be seen locally but is difficult to measure. Where best exposed the intersection lineation of the two cleavage trends subparallel to the bedding-cleavage intersections. Local small-scale slip surfaces occur that parallel the northeast dipping cleavage trend. Cleavage orientation here and around the klippe outline a cleavage trough common to klippen locations

Figure 11. Tongue of Ramseyburg Member within the Bushkill as the eastern edge of the Home Depot parking lot stop. Well developed cleavage refraction from the slates into the coarser-grained graywackes. Cleavage at the Home Depot location trend northwest striking and northeast dipping further defining the cleavage trough developed due to deformation from the overriding thrust sheet responsible for the Grand Union klippe.

Around the next bend the face parallels the entrance road and has poorly exposed Bushkill that is almost completely covered by colluvium. It is best not to climb this face due to the amount of loose slate fragments. A case of one step up and two slides down. No data were taken on this face due to the poor exposure.

Continuing along the face there is a gate in the fence that opens to an approximately 12 ft (4 m) high exposure of Ramseyburg. Across western New Jersey the Ramseyburg sits atop the Bushkill. Here several Ramseyburg beds are interbedded with the Bushkill and intertongue with the Bushkill (Figure 2). A similar architecture exists to the west, except there the Bushkill intertongues with the Ramseyburg. This is an example of a Ramseyburg facies pinches out into the shopping center (Herman and Monteverde, 1989; Drake and Volkert, 1993; Drake et al., 1996). The thicker graywacke beds of the Ramseyburg supply an excellent example of cleavage refraction (Figure 11).

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STOP 7: LUSSCROFT FARM AND THE BEEMERVILLE SYENITE
Leaders: Don Monteverde and Ron Witte

We have arrived at the Lusscroft Farm, administered by the New Jersey Department of Environmental Protection Division of Parks and Forestry. James Turner, a stockbroker from Montclair originally purchased the 575-acre (233-hectare) farm in 1914. He desired to create a scientifically advanced dairy farm (H&AA, 2012). Turner invested a large sum of money to establish and upgrade the farm. In 1931 the farm was donated to the State of New Jersey where it became one of the state's first research dairy farms, which was named theNorth Jersey Dairy Branch of the State Agricultural Experiment Station until 1970.

As you ascend the Explorer trail the slope becomes gentle and a unique building, Outlook Lodge can be seen to the east (left side of trail). Information from H&AA (2012) The lodge was built from antique timbers recouped from approximately 25 old barns and houses, including a large oak panel that arrived from Kent, England, in particular Lord Jerry Amherst's castle (Figure 1). James Turner's desire for the Amherst Castle oak panel relates to his college education at Amherst College.Various renovations and additions such as bathrooms and a kitchen have been built into the Lodge since its donation to the State of New Jersey. The building has some interesting cement sculptures along its outside walls, such as an owl resting in a tree (Figure 2), that that adds to the structure's uniqueness.

Figure 1. A look at the interior of the Outlook Lodge displaying its unique woodwork. Photo by Dan Balogh (H&AA, 2012).

An article in the online journal Dirt Magazine (2012) noted that church groups, Boy Scouts, 4-H members, and Future Farmers of America have also used the Lodge over the years.This eventually led to Cook College, recently renamed Rutgers School of Environmental and Biological Sciences, establishing a program in Forestry that has lasted until 1975. The Lodge has greatly deteriorated over the years and needs some

Figure 2. The Outlook Lodge, part of Lusscroft Farm, has some unusual cement artwork along its exterior walls.

Monteverde, Don and Witte, Ron, 2012, STOP 7: Lusscroft Farm and the Beemerville syenite, *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. 314-334.

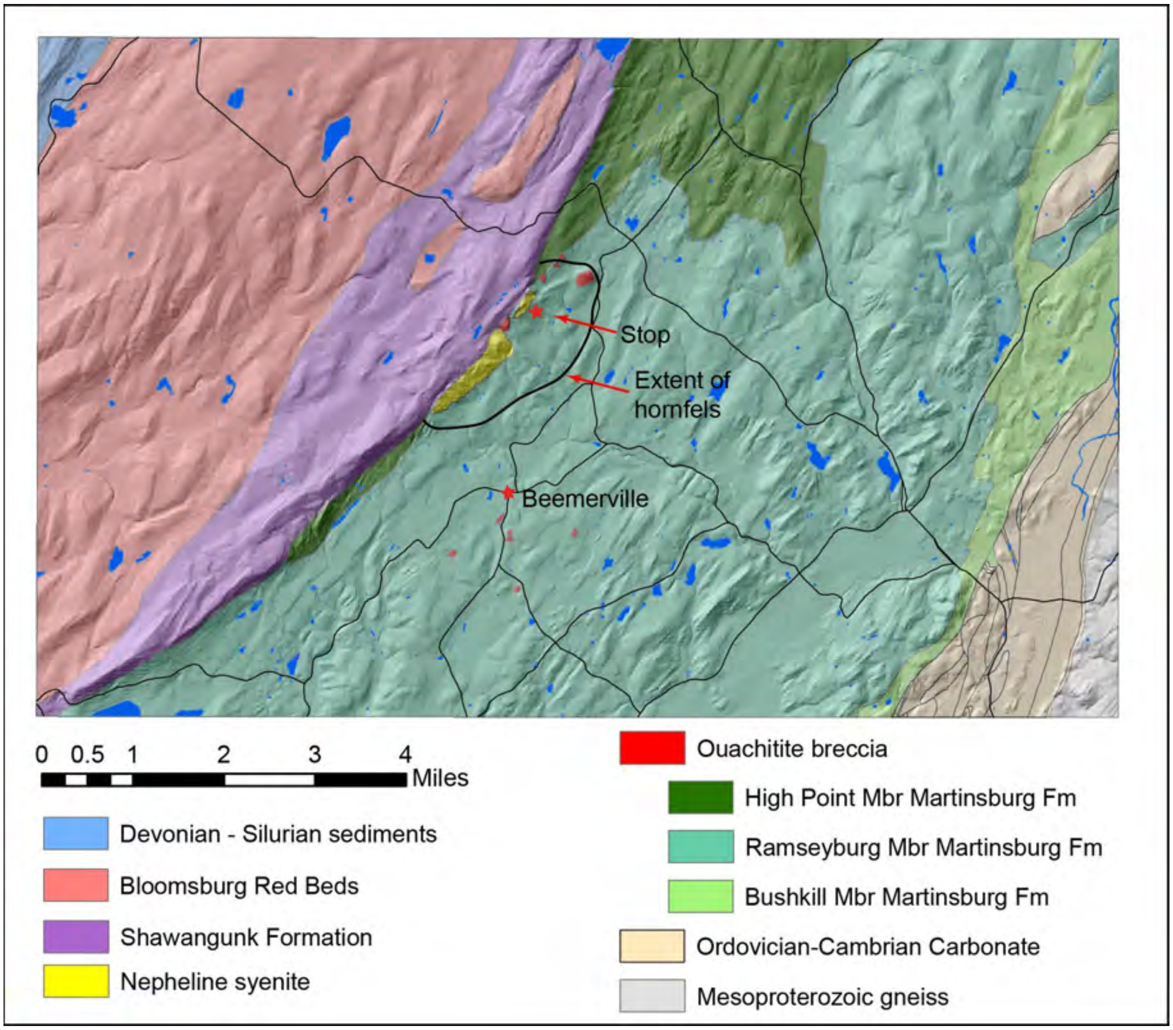

Figure 3. Regional map showing stop location and town of Beemerville. Two bodies of nepheline syenite and several diatreme exposures occur amongst the field stop. The Rutan Hill diatreme lies just northeast of the northern syenite body. A second accumulation of diatremes occur south of Beemerville. Modified from Drake et al. (1996)

rehabilitation that is being planned by a joint committee of the New Jersey State Park Service and the State Agricultural Development Committee, and the Heritage and Agriculture Association.

One note on location, this igneous assemblage is always referred to as Beemerville complex or intrusive suite or whatever. The small town of Beemerville is several miles to the south southeast of where we stand. There is a dike or two in Beemerville itself but the dominant outcrops are located in the region of this stop (Figure 3).

Regional Geology

This stop serves as an entry into several interesting geological topics, including:

1. Beemerville complex, its mineralogy and chemistry described by Nelson Eby later in this stop discussion. Unfortunately Nelson was not able to attend this trip to offer his expertise

in alkalic intrusions due to previous engagement. So I recommend reading his description of the rocks before the field trip (see p. 85 of this guidebook). Ratcliffe (1981, 2006) and Ratcliffe et al. (2012) discussed the tectonic significance of the Beemerville complex and how it relates to other intrusions of similar age to the east. The Beemerville's lateral extent is quite a bit larger than its small outcrop pattern.

2. Regional age of cleavage development – this is a much more interesting question. Data from nearby diatremes and their xenoliths have played a role in attempting to answer this question, but the information from the syenite's associated hornfels zone has not yet been fully investigated to either support or question previous interpretations.
3. Nepheline syenite erratics and the pattern of Late Wisconsinan ice flow will be discussed by Ron Witte, again later in this stop discussion. Because nepheline syenite only crops out at this location it forms an unique point source from which erratics may be traced.

Beemerville Complex

The Lusscroft farm lies on the Martinsburg Formation stratigraphically below and just east of the Taconic unconformity. Two nepheline syenite bodies crop out in the tree-covered upper reaches of the farm and farther to the southwest along regional strike both within the Martinsburg Formation (Figure 3). Maxey (1976) mapped a small body of syenite, southwest of the main syenite exposures as possibly intruding the Shawangunk. More recent investigations did not depict these suggestive syenite intrusions in the Shawangunk (Ratcliffe 1981; Drake and Monteverde, 1992). In accordance with new high resolution age date indicating the Beemerville intrusive age predates Shawangunk deposition (Ratcliffe, 2012), the syenite bodies described by Maxey (1976) are considered to be glacial erratics.

The Beemerville complex's subsurface extent is much greater than that assumed on the basis of outcrop coverage. Ghatge et al. (1992) analyzed Bouguer and residual gravity anomalies and illustrated a large subsurface extension of the Beemerville. They modeled a sill up to 2,000 ft (610 m) thick that continues 5 mi (8 km) to the southwest along regional strike of Kittatinny Mountain (Figure 4). A second syenite body was modeled farther to the south within Ordovician and Cambrian carbonate units. It appears as a southwest-trending sill that thickens dramatically towards the northwest (Figure 4).No evidence of these modeled syenite bodies were discovered during field mapping (Drake and Monteverde, 1992; Monteverde, 1992; Spinks, 1967). Ghatge et al. (1992) further suggested that the main intrusive body thickened dramatically with depth and also separated into two distinct bodies (Figure 4). Herman et al. (1996) characterized this separation as due to southeast dipping Alleghanian thrust movement (Figure 5).

Previous workers have outlined several other igneous bodies related to the Beemerville complex, which is also called Beemerville Intrusive Suite (Drake and Monteverde, 1992). These include several diatremes near the syenite bodies and others in a small cluster farther to the southeast (Spinks, 1967;Maxey, 1976; Drake and Monteverde, 1992). The most well known location is Rutan Hill approximately 0.6 mi (1 km) to the northeast. See description by Eby (p. 85 of this guidebook). The variety of xenoliths shows that the diatreme transected into the Mesoproterozoic Grenville metamorphics, through the lower Paleozoic dolomites and into the Martinsburg (Figure 6). We will not visit Rutan Hill, but will see some diatreme material at this stop.

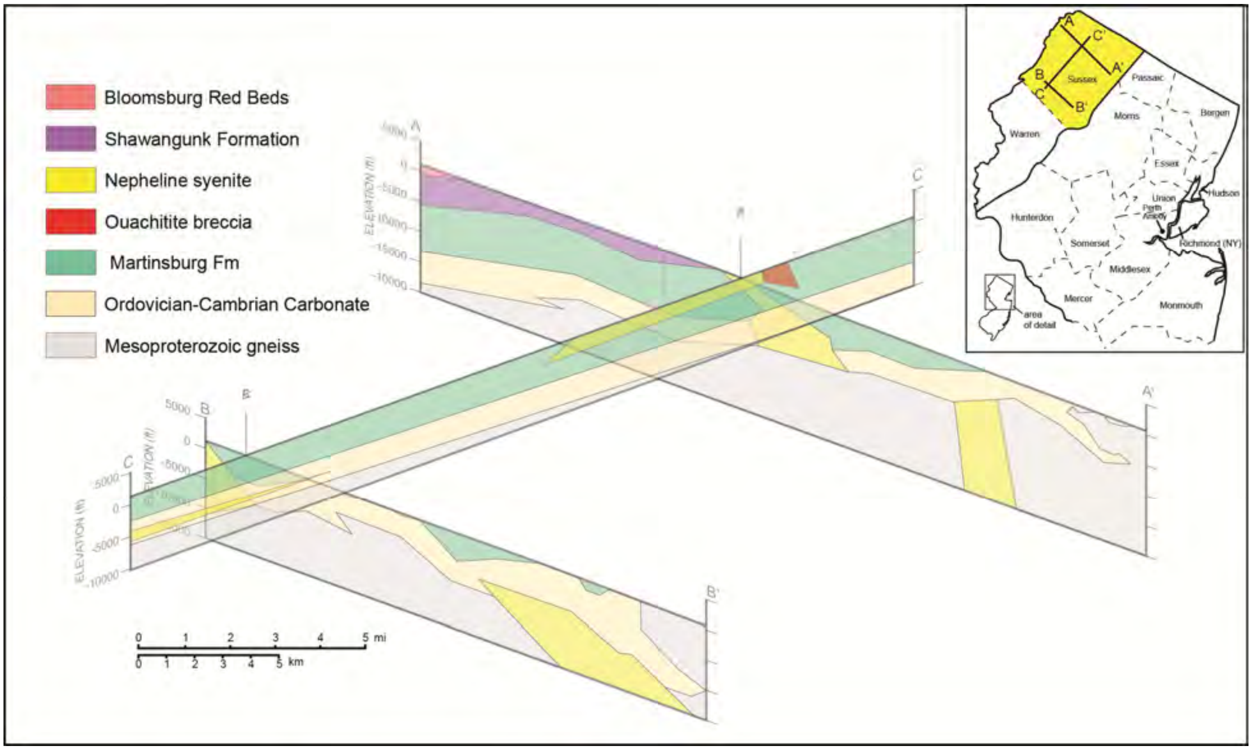

Figure 4. Cross sectional interpretation of the subsurface extent of the Beemerville complex based on Bouguer and residual gravity anomalies (modified from Ghatge et al., 1992)

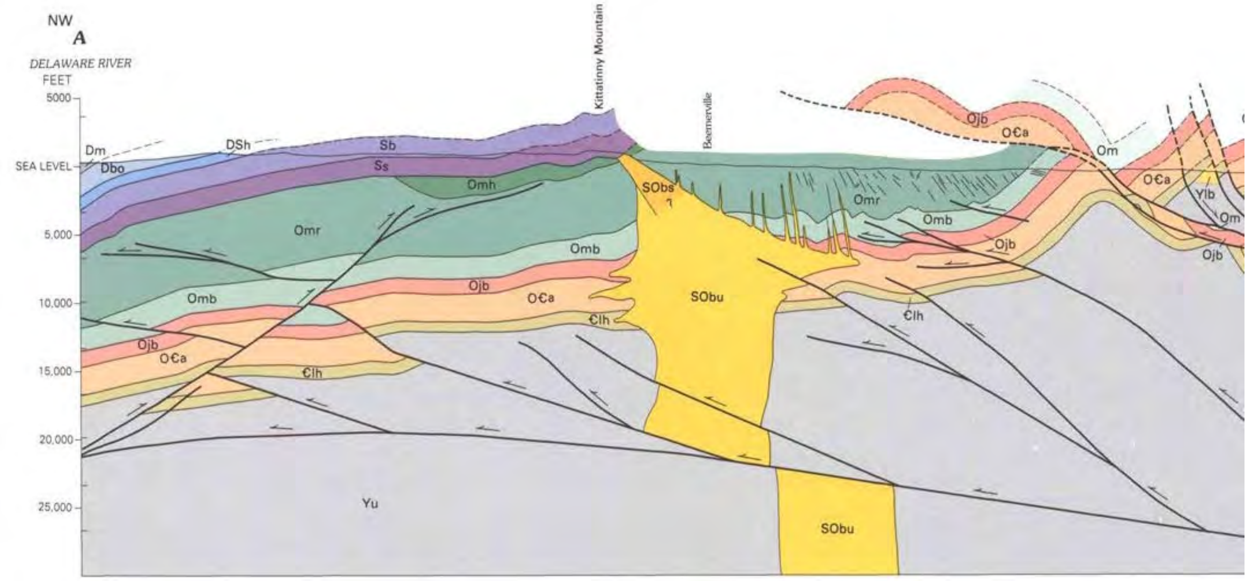

Figure 5. Regional cross sectional interpretation through the Beemerville complex constructed by Herman et al. (1996) at a scale of 1:100,000. Note the foreland translation interpretation of the upper section of the Beemerville complex by Alleghanian thrust faults to explain the gravity model of Ghatge et al., (1992).

Figure 6. Examples of xenoliths including gneissic basement, Paleozoic passive margin platform carbonates, and foreland basin turbidites of the Martinsburg Formation within slabbed diatreme samples. Additional autoliths of earlier Beemerville intrusive material occur as blocks within the diatreme.

Ratcliffe et al. (2012) recorded a U-Pb TIMS age of 447±2 Ma on titanite from the Beemerville complex. It agrees with some K-Ar and Rb-Sr age dates on biotites from the nepheline syenite and Rutan Hill diatreme of 435±20 Ma (Zartman et al., 1967) that Ratcliffe (1981) reinterprets to 444 Ma using "modern decay constants". Drake et al. (1996) listed a K-Ar date of 422-±14 Ma on a lamprophyre with biotite phenocrysts, considered part of the Beemerville complex. Eby (this trip) suggests the TIMS age represents the intrusive age while a 420 ± 6 Ma mean fission-track age on titanite (Eby, 2004) dates the cooling to a ~275 °C . Further cooling to ~100 °C was dated at 156 ± 4 Ma, a mean fission-track age onapatite (Eby, 2004; p. 85 this guidebook). Age and regional contact relationships of the Beemerville complex and several other igneous bodies to the east across New York and Connecticut have been used to mark the closure of the Iapetus ocean and determine the minimum age of Taconic Barrovian metamorphism (Ratcliffe et al., 2012).

Beemerville and Cleavage Development

Debate on the timing of cleavage development, either from Taconian or Alleghanian deformation, continues. Epstein and Epstein (1969) outlined the early conclusions on Martinsburg cleavage formation in eastern Pennsylvania. On this trip you will visit two important locales, Lehigh Gap (Stop 3) and here at Beemerville, in defining different conclusions on the timing of cleavage. Epstein and Epstein (1969) noted how the proximity to the Shawangunk impacts cleavage formation within the Martinsburg. As one moves from the Shawangunk contact into the Martinsburg over approximately 165 ft (50 m) the rocks change from an initial mudstone lacking any cleavage though a pencil cleavage and into a slaty cleavage. This change from mudstone into slate across Lehigh Gap led Epstein and Epstein (1969) to propose a "strain shadow" effect where proximity to the Shawangunk inhibited cleavage development in the Martinsburg and indicates a post-Taconic age. In addition, the similarity of Martinsburg cleavage with younger Silurian and Devonian cleavage-bearing units led Epstein and Epstein (1969) to conclude cleavage formation in all these units results from Alleghanian deformation. The Lehigh Gap "strain shadow" intrigued many researchers who documented the phyllosilicate recrystallization and magnetic anisotropic fabric across the mudstone to slate transition at Lehigh Gap (Holeywell and Tullis, 1975; Wintsch, 1978; Woodland, 1982; Lee et al., 1986; Housen and van der Pluijm, 1991; Wintsch et al., 1991; Housen et al., 1993; Ho et al., 1995; Wintsch et al., 1996; Hirt et al., 2004).

Wintsch et al. (1996) used $^{40}Ar/^{39}Ar$ whole rock age spectra to further investigate the time of cleavage formation. They sampled the least deformed mudstones and graywackes with abundant new muscovite defining cleavage planes. Mudstone samples defined three plateau ages that Kunk and Wintsch (1996) and Wintsch et al. (1996) interpreted as first a Late Proterozoic plateau (maximum age 644.75 $\underline{+}$1.28 Ma) defining detrital mica formation, second a medial Late Silurian to Earliest Devonian (average apparent age 413 Ma) characterizing phyllosilicate diagenesis and lastly a 50 Ma minimum age (Kunk and Wintsch, 1996; Wintsch et al., 1996). Graywacke slate samples contain muscovite in three orientations, detrital mica parallel to bedding, authigenic muscovite randomly orientated that the authors suggest formed during diagenesis, and lastly a late muscovite aligned at an angle to bedding that defined regional slaty cleavage. Two slate samples recorded a maximum age of 710.05 $\underline{+}$1.88 Ma to 636,15 $\underline{+}$5 Ma that correlate to mudstone detrital micas (Kunk and Wintsch, 1996; Wintsch et al., 1996). Other slate samples define a maximum average 462 Ma associated with diagenesis that slowly descends to a 360 Ma plateau. This age plateau marks cleavage formation and correlates to the Alleghanian deformational event (Wintsch et al., 1996).

To date cleavage studies from Beemerville reside in the camp suggesting the presence of a Taconic age cleavage. Two main types of data interpretation, Martinsburg xenoliths displaying apparent cleavage traces within a diatreme south of Beemerville and structural arrangement of dike emplacement within the Martinsburg, support the older cleavage age conclusion. Rowlands (1980) first described evidence of cleaved Martinsburg xenoliths within the Beemerville complex that required a Taconic age of cleavage development. Ratcliffe (1981) followed with further examples of cleavage bearing xenoliths in a diatreme outcrop. His examination also outlined another cleavage with the diatreme and along the hornfels rim of the xenolith indicating a second cleavage ascribed possibly to the Alleghanian. Ratcliffe (1981) further described an example of Martinsburg hornfels against a dike to the east of Beemerville that showed contact metamorphic actinolite growing across and parallel to an older southeast dipping slaty cleavage. However Ratcliffe (1981) went as far to suggest the dominant cleavage in the Beemerville region may be Alleghanian in age. Offield (1967) suggested that Taconic deformation left a regional structural landscape marked by broad open folds just across the New York border. Offield (1967) described a weak cleavage suspected of Taconic age associated with the open folds. Later, Drake and Monteverde (1992) described finding cleavage planes within a xenolith from a visual inspection of a Martinsburg hand specimen taken from a Rutan Hill diatreme exposure. They did not conclude that all regional cleavage in northern New Jersey was caused by Taconic deformation, but there could have been a continuum in cleavage development to account for older cleavage in more hinterland regions and younger cleavage in more foreland areas. Ratcliffe et al. (2012) also stated that Martinsburg xenoliths within Beemerville complex diatremes displayed a chlorite grade, foliated fabric deemed of Taconic age, suggesting the Beemerville is post tectonic and marked the closure of the Iapetan ocean. Drake and Lyttle (1980) presented evidence of an initial Taconic cleavage age for the

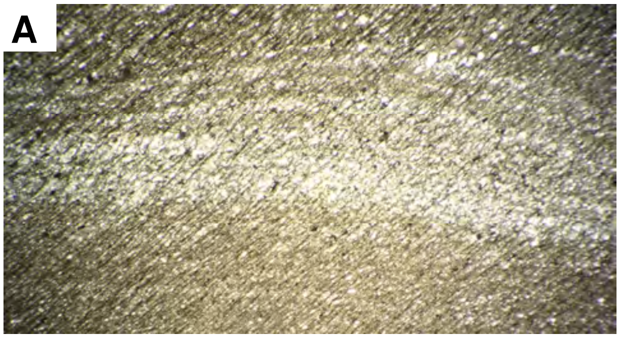

Figure 7. Examples of well-developed cleavage within slate and graywacke of the Martinsburg. A – Slate sample of the Bushkill Member, Martinsburg Fm., from the region of the previous stop just west northwest of the Home Depot exposure. The actual outcrop was removed for further commercial construction; B – Cleavage in graywacke of the Ramseyburg Member, Martinsburg Fm., from the Branchville quadrangle. Both photomicrographs were taken under crossed Nicols.

Martinsburg based on the Martinsburg xenoliths of Rowlands (1980) and Ratcliffe (1981) and preliminary mapping data. They also discussed the concept of progressive cleavage development wherein Taconic aged cleavage could develop in basal and more hinterland exposures of Martinsburg and Alleghanian aged cleavage form in upper beds of the Martinsburg in more foreland locations.

In the northern Appalachians radiometric cleavage dating is sparse and results portray Taconic and Acadian players. Chan et al. (2000) investigated three cleavage domains, S2, S3, and S4, within rocks of the Taconic Allochthons along the New York Vermont border. Cleavage selvages were targeted as opposed to whole rock samples that would record ages from different events including detrital and all cleavage phyllosilicates. S2 slaty cleavage dates were inconclusive due to reduced thickness of the cleavage selvages. Ages range from 650±24 to 196.0 ±7.4 Ma with most ages younger than 434 Ma. Chan et al. (2000) offer two interpretations: S2 is between 370-434 Ma, which would require a reinvestigation of the Taconic duration; or S2 is pre-434 Ma and requires further analysis. S3 occurs as a crenulation cleavage with a weighted mean of 370.7±1.0 Ma and correlates to main phase of Acadian deformation. The S4 spaced phyllitic cleavage that becomes the dominant cleavage to the east resulted in a weighted mean of 345.5 ±1.7 Ma interpreted as “localized late Acadian cleavage-forming event” (Chan et al., 2000). So data from the north within the Taconic allochthons present an initial suspected Taconic cleavage followed by two possible Acadian cleavages without any indication of Alleghanian influenced cleavage planes.

The metamorphic aureole surrounding the Beemerville complex nepheline syenite outlined by Martinsburg hornfels offers another location to investigate a possible older cleavage with the Martinsburg. Xenoliths have been rotated during the initial magma wall rock interaction and later ascent within the diatreme. So any structural data from a xenolith cannot be compared to regional structural relations. The hornfels zone offers the opportunity to look for cleavage knowing the orientation of regional trends. Various sample of contact metamorphic Martinsburg were sampled for thin section analysis.

Cleavage occurs regionally within the Martinsburg and varies from slaty in the Bushkill and finer grained beds of the Ramseyburg to a tightly spaced in graywacke beds (Figure 7). Proximal to the Shawangunk contact cleavage becomes weakly developed. The hornfels zone crosses the boundary from weakly to well developed cleavage. If a Taconic cleavage existed in this region of the Martinsburg it should be evident in the hornfels rocks. Hornfels samples show no evidence of cleavage (Figure 8). Cleavage selvages are generally parallel to bedding and are interpreted to be detrital. Martinsburg xenoliths present a high degree of recrystallization and present a poorly developed grossly planar habit. The problem is what these fabrics represent. Could they be a recrystallized bedding trend? The reconnaissance data have not discovered xenoliths that display a secondary planar fabric that cross cuts bedding and is suggestive of regional cleavage. Hornfels samples that have undergone a lower degree of thermal metamorphism, display bed parallel phyllosilicates that are suggestive of a detrital component. So these data add another piece of information that is not definitive, but seem to indicate the absence of a pre-intrusion cleavage within hornfels samples. A more detailed sampling program is needed to verify or negate our initial results and compare data with previous studies that characterized cleaved Martinsburg xenoliths.

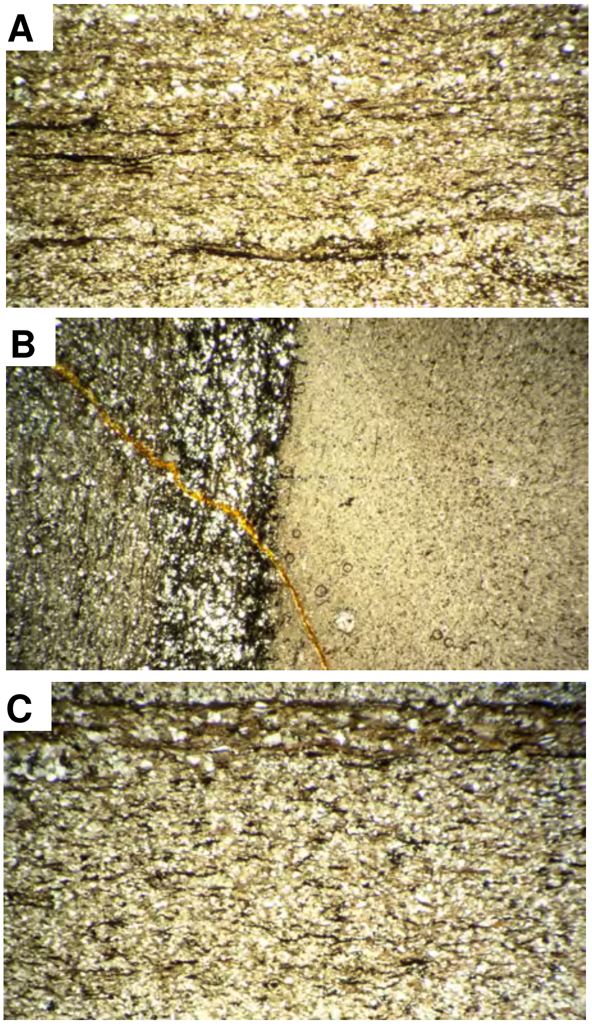

Figure 8. Hornfels samples from three different locations all show phyllosilicates that align parallel to bedding, suggesting a detrital origin. A – Ramseyburg member hornfels. Slide is oriented so bedding appears horizontal on the photomicrograph. Mica accumulations follow the trend of bedding and are suggested to be detrital; B – Ramseyburg hornfels. Slide is oriented so bedding is depicted as inclined; C – Ramseyburg hornfels. Slide is oriented so bedding appears horizontal on the photomicrograph. Sample location is on the road heading east from Lusscroft main building between the bar structures. No definitive cleavage was noted within any of the Martinsburg hornfels samples. All photomicrographs were taken under crossed Nicols.

Nepheline Syenite Erratics in Northwestern New Jersey

"The peculiar igneous rock (elæoite syenite) near Beemerville, Sussex County, affords another illustration of the determination of the direction of movement by the distribution of material." R. D. Salisbury, 1902

Distribution of Nepheline Syenite Erratics

During the late 1800s boulders of nepheline syenite (Obs) were found in the fields and forests of Kittatinny Valley, in an area of Wisconsin glacial drift. Discussed in Salisbury (1902), the erratics defined a dispersal fan (Figure 9) that extended 20 mi (32 km) south from the intrusive body at Beemerville. Salisbury observed that the Obs erratics in Kittatinny Valley are not distributed equally, there existing a slight aggregation in belts that are oriented transverse to glacial flow. A belt near Middleville and one near Myrtle Grove and a third area of concentrated Obs erratics on the northern end of Culvers

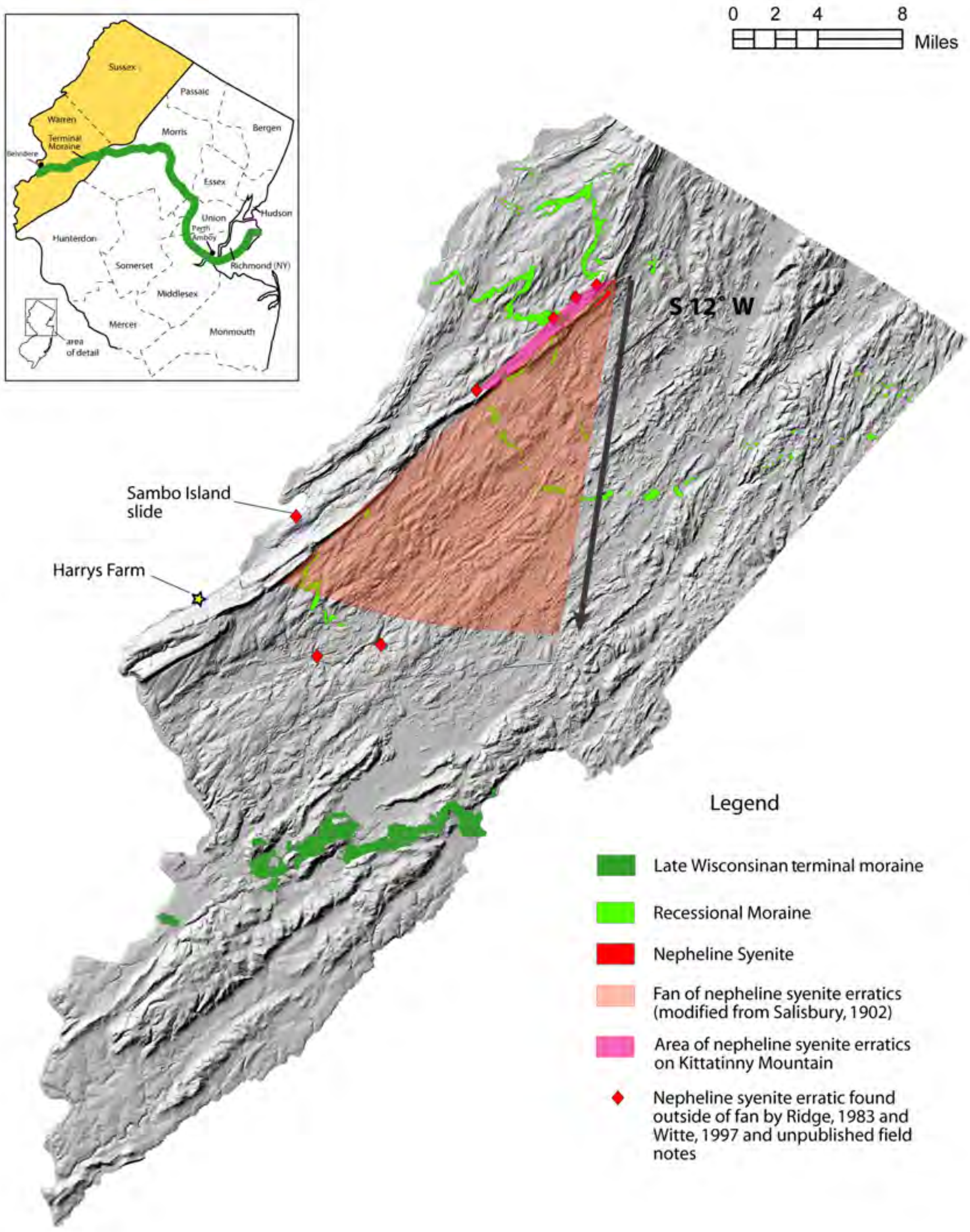

Figure 9. Location of nepheline syenite (Obs) erratics and source in northwestern, New Jersey. The original limits of the boulder fan were delineated by Salisbury (1902). Later glacial investigations by Ridge (1983) extended the erratic dispersal farther south in Kittatinny Valley and Witte (1997) found several syenite erratics on the west side of Kittatinny Mountain. The northern-most occurrence of Obs erratics defines an ice flow of S74˚W measured from the northern tip of the Obs outcrop.

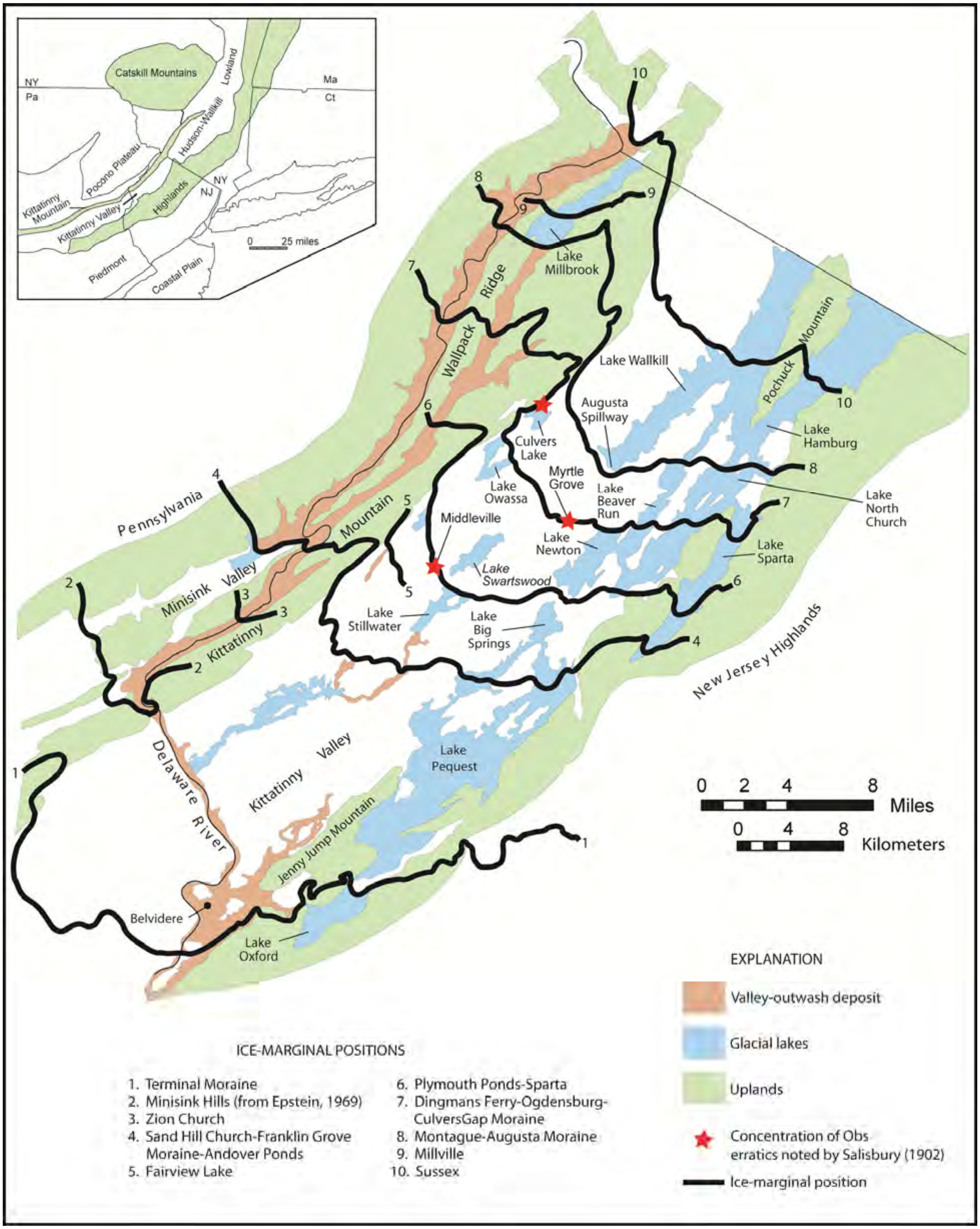

Figure 10. Late Wisconsinan ice margins of the Kittatinny and Minisink Valley ice lobes, and location of large glacial lakes in northwestern New Jersey. Modified from Witte (1997).

Pond (Culvers Lake) were pointed out as the most conspicuous. All of these areas lie along mapped ice-recessional positions (Figure 10) of the Kittatinny Valley ice lobe, where heads-of-outwash (mostly ice-contact deltas) and recessional moraines were deposited. These marginal positions represent a period where an ice lobe's margin remained in a relatively stable position, neither advancing nor retreating except within a narrow zone marked by ice-marginal deposits. These periods may have lasted several hundred years, more than enough time for the glacial conveyor belt to aggregate Obs erratics along the glacial margin.

Figure 11. Nepheline syenite erratics, Glacial Geology Trail, Stokes State Forest, New Jersey (*New Jersey's iconic glacial erratic*). The rebar-encaged syenite boulders were derived from a small outcrop area located two miles to the northeast on the southeast-facing flank of Kittatinny Mountain and 300 ft (91 m) below its ridgeline. Their position indicates ice flowed in a direction between south 50º and 70º west, a flow direction that cuts across the more southwesterly trend of the mountain and one that shows divergent flow at the margin of the Kittatinny Valley lobe. Many people have speculated about the erratics' peculiar method of preservation, perhaps there will be time for discussion at the Beemerville stop.

Salisbury also noted that Obs erratics were found west of the outcrop on Kittatinny Mountain, and several hundred feet higher. Ridge (1983), Witte (1997), and Witte and Epstein (2004, 2012) further expanded the fan south and westward (Figure 9). With one notable exception (I'll get to this shortly), Obs erratics on Kittatinny Mountain and westward to the Delaware River have only been found as far south as the Culvers Gap area. Most of them occur northward in a narrow area that extends along the mountain's western slopes. A concentration of erratics has been noted on the Ogdensburg-Culvers Gap (Figure 11) and Augusta moraines similar to that observed by Salisbury along belts in Kittatinny Valley.

Although they are not as definitive as glacial striations in determining ice flow, erratics are still very useful determining ice flow history. Quartzites and quart-pebble conglomerates of the Shawangunk Formation are found throughout western New Jersey and eastern Pennsylvania in all ages of glacial drift. They are great indicators of glaciation, but given their extensive source area and propensity to weather very slowly they are not that useful defining a detailed ice flow chronology. Obs erratics on the other hand are very useful in defining an ice flow chronology because: 1) they were glacially transported from a known, small area; and 2) their rapid weathering negates the recycling of material over multiple glaciations, restricting their erosion and transport to the Late Wisconsinan glaciation.

Direction of Ice Flow as Indicated by Obs Erratics

For this discussion, the Obs dispersal fan (Figure 9) is divided into two fans. The large fan in Kittatinny Valley shows that ice flow ranged from S 12° W to S 46° W with the farthest erratics found 23 mi (37 km) south of the Obs outcrop. The S 46º W direction is nearly identical to the valley's topographic grain, a westward position that is bounded by the steep southeast facing escarpment of Kittatinny Mountain. The smaller fan on Kittatinny Mountain shows that ice flow ranged from S 46° W to S 72° W with the farthest erratic found at the southern end of Kittatinny Lake, 8 mi (13 km) southwest from the Obs outcrop. Erratics along the most westerly flow direction were found about one mi (1.6 km) from the outcrop. Salisbury (1902) attributed the dispersal of Obs erratics to the "spreading of ice" related to divergent ice flow associated with a large ice lobe in a valley. Salisbury also noted ice flow may change during glaciation, especially as it thins and becomes more controlled by topography. Obs erratics indicate a range in ice flow from S 12° W to S 72° W, a large change in the direction of ice motion. How is this large range defined within the context of a single glaciation? The Obs fans define both regional and local ice flow patterns. The larger fan in Kittatinny Valley shows that ice flow at one time was directed southward across this area's southwesterly topographic grain. This flow direction is assumed to have occurred when ice was thickest, the time around the Late Wisconsinan glacial maximum (21 ka). During deglaciation ice thinned and ice flow turned to the southwest, paralleling the areas topographic grain. The Obs fan on Kittatinny Mountain also shows southwest ice flow, but also indicates a local westerly flow occurring near the Obs outcrop. This latter flow direction occurred along the margin of the Kittatinny Valley lobe during deglaciation and it represents a spreading or divergence of ice flow along the glacier's lobate margin.

The Big Picture

The initial late Wisconsinan advance of ice into the upper part of Kittatinny Valley is unclear because striae and glacial drift that record this history have been eroded or were buried by younger Late Wisconsinan deposits. If the ice sheet advanced in lobes as suggested by the lobate course of its terminal moraine (Figure 10), then its initial advance was marked by lobes of ice moving down the Kittatinny and Minisink Valleys. Sevon et al. (1975) speculated that ice from the Ontario basin first advanced southward into northeastern Pennsylvania and northwestern New Jersey. Later, ice from the Hudson-Wallkill lowland, which initially had lagged behind, overrode Ontario ice, and ice flow turned to the southwest. In this scenario, the course of the terminal moraine in Kittatinny Valley (Figure 10) was controlled by ice flowing from the Hudson-Wallkill lowland. Connally and Sirkin (1986) suggested that the Ogdensburg-Culvers Gap moraine represents or nearly represents the terminal Late Wisconsinan position of the Hudson-Champlain lobe based on changes in ice flow noted by Salisbury (1902) in the vicinity of the moraine. Ridge (1983) proposed that a sublobe of ice from the Ontario basin overrode Kittatinny Mountain and flowed southward into Kittatinny Valley. Southwestward flow occurred only near the glacier margin where ice was thinner, and its flow was constrained by the southwesterly trend of the valley. Analyses of striae, drumlins, and the distribution of erratics in the upper part of Kittatinny Valley (Witte, 1997) and on Kittatinny Mountain (Witte, 2008; Witte and Epstein, 2004) support Ridge's view (Figure 12). These data further show that by the time the Ogdensburg-Culvers Gap moraine was formed, ice flow in Kittatinny Valley had turned completely to the southwest with extensive lobation at the glacier's margin. These changes in ice flow are summarized in Figure 13. Ice flow determined from the distribution of Obs erratics is consistent with the above ice flow chronology. Not only do the erratics document changes in ice flow, they also define a timeline whereby the more westerly locations on Kittatinny Mountain represent the final stage of deglaciation.

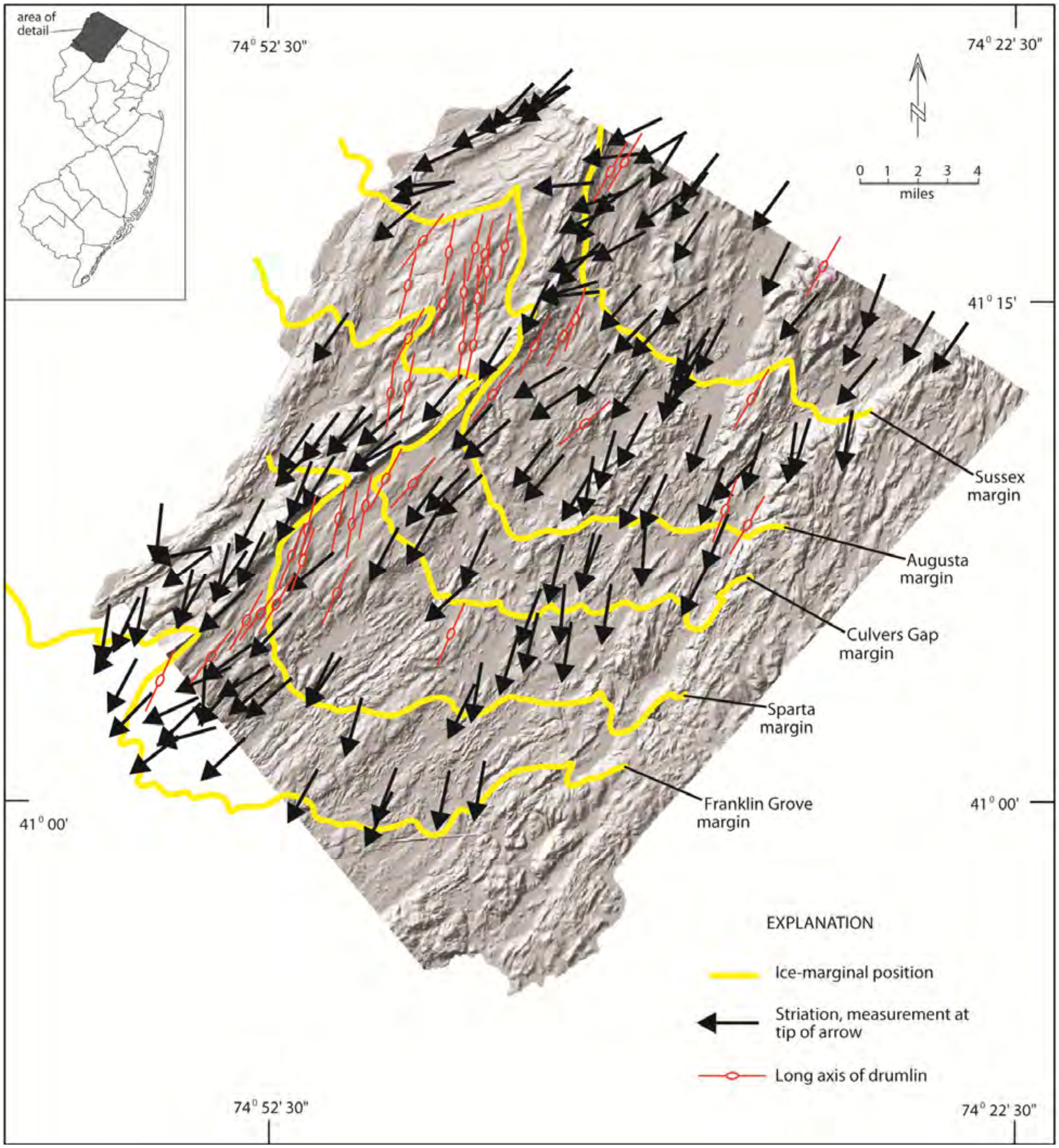

Figure 12. Orientation of striae, and drumlins in the upper part of Kittatinny Valley and surrounding area in Sussex and Warren Counties, New Jersey. Figure modified from Witte (1997).

Sambo Island Slide

Several small boulders and cobbles of nepheline syenite found in the Delaware Valley downstream from Wallpack Bend near Sambo Island (Figure 14) were a fortuitous discovery that provided a "*what the @*#!"* moment. The erratics were first observed in the toe deposit of a small landslide that was described by Epstein (2001). The Obs clasts, located 18 mi (29 km) from their source, appeared to be from till that mantles the lower part of the valley slope.

Samples have been identified as nepheline syenite, the same rock as the large intrusion west of Beemerville.

Excluding the slide area, Obs erratics on Kittatinny Mountain have been found only as far south as Kittatinny Lake near Culvers Gap. They have not been observed elsewhere south on the mountain or westward in the Delaware and Wallpack Valleys. Over a dozen syenite clasts have been recognized at the Sambo Island slide ranging from subangular to subrounded large cobbles to pebbles. They lie on the lower part of the steep slope above the Delaware, either in slide debris that lies as much as 40 ft (12 m) above the river or nearby along an old trail that runs along the base of the slope about 20 ft (6 m) above the river.

There are three explanations for the Sambo Island Obs erratics (SI Obs). Firstly, the syenite clasts are from till that mantles the lower part of the slope above the Delaware. Some of these clasts were uncovered by the slide and others were weathered out of the thin soil largely by frost heave. Their location suggests they were carried here by the initial advance of Late Wisconsinan ice into this area and that ice from the Hudson-Wallkill lowland may have been the first to reach the area. Based on the erratics' location at the slide, ice would have had to flow S 55º W across Kittatinny Mountain, from the small area of nepheline syenite outcrop near Beemerville. Later as the ice thickened and the Kittatinny and Minisink Valleys lobes coalesced, ice flowed turned southward. Secondly, SI Obs may have been derived from glacial

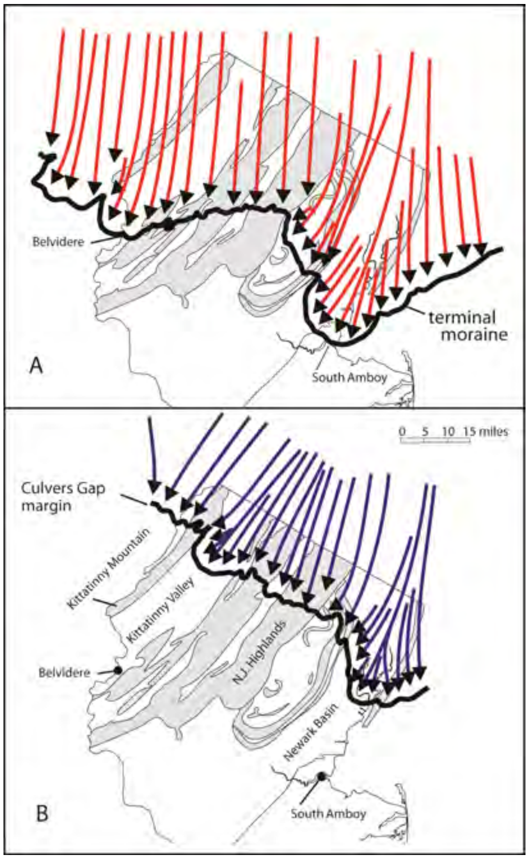

Figure 13. Generalized direction of ice movement in northern New Jersey during the late Wisconsinan. Lines represent regional ice-flow movement at the base of the ice sheet. Flow directions are based on striae, drumlins, dispersal of erratics, and till provenance. Shaded areas represent major uplands. A – Direction of ice flow when the glacier margin was at the Terminal Moraine. Field data in the Kittatinny Valley area indicates ice flowed southward across the valley's southwest-trending regional topographic grain; B – Direction of ice flow during deglaciation. Flow lines in Kittatinny and Minisink Valleys and surrounding uplands are oriented in a southwest direction with well-developed lobate ice flow at the glaciers margin. The change in regional ice flow to a southwest direction appears to be related to thinning of the ice sheet at its margin, and reorganization of ice flow around the Catskill Mountains, and in the Hudson-Wallkill Valley. Figure modified from Witte (1997).

Figure 14. Lower section of the Sambo Island slide, Delaware Water Gap National Recreation Area, Warren County, New Jersey. Obs cobbles (inset photo) were found among the slide's debris and nearby along an old trail that traversed the lower part of the slope above the Delaware River. The slide scar is a dip slope on the Bloomsburg red beds.

outwash that forms a thin mantle on the lower part of the slope. In many places the outwash is covered by thin colluvium consisting of reworked till and Bloomsburg Red Bed regolith. Many of the syenite clasts are subrounded suggesting fluvial wear. Because they are only found at heights up to 40 ft (12 m) above the Delaware River, the level of outwash in this area, it is plausible that they were transported by meltwater. However, their occurrence in outwash is still significant because it also suggests an earlier ice flow across Kittatinny Mountain. Thirdly, nepheline syenite was used by Munsee Lenape as a tempering agent in pottery of Late Woodland age (Kraft, 1975). Three lumps of syenite and a ball of unfired clay were uncovered at the Harry's Farm site (Lattanzi, 2009) located about 6 mi (10 km) downstream from the Sambo Island slide (Figure 9).

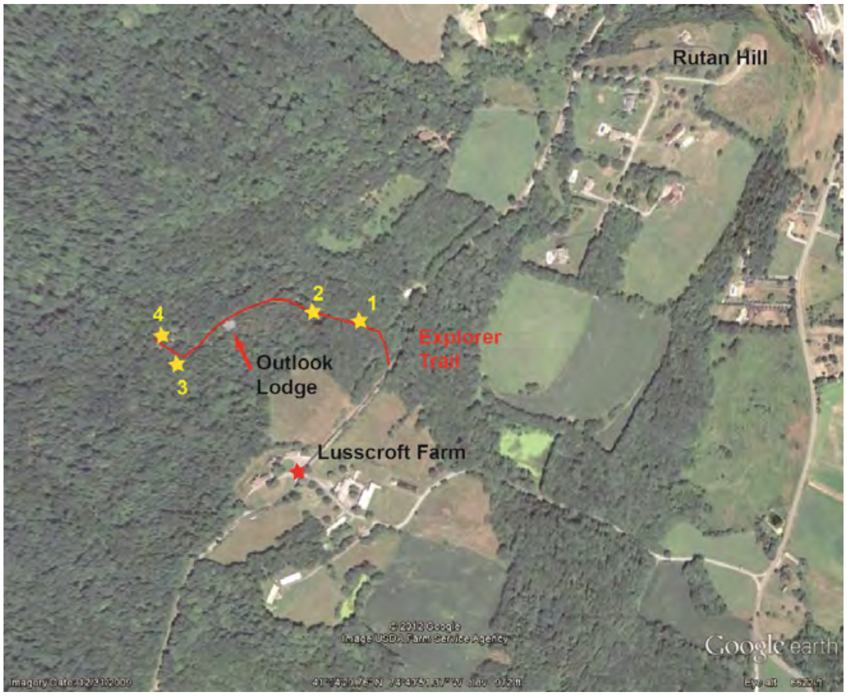

Figure 15. Explorer trail map marked with locations to observe/argue/call opposing side names the geology at this site.

It seems that the SI Obs found at the Sambo Island slide may have an anthropogenic context given the large number of erratics found there and their absence north to Culvers Gap. The SI Obs may have been carried from their source near Beemerville to the Delaware Valley. Whether the syenite was actively quarried or picked up loose near the outcrop has not been established. Other, rounded SI Obs may have been collected from glacial outwash or river gravel in Kittatinny Valley. The number of SI Obs at Sambo Island slide is quite puzzling even if we assume they were carried there by the Munsee Lenapi. The steep slope and rough ground is not favorable for encampments. However, a trail may have existed here along the lower part of the slope near the Delaware River. Did they fall out of someone's travelling pack, or were they placed here as a stockpile to support a burgeoning pottery industry? We may never know the truth, but apparently the Munsee Lenape recognized the value of nepheline syenite and there may have been an organized effort to collect and distribute the material.

Explorer Trail

The stop starts at the base of the Explorer Trail (Figure 15). We will walk up the trail mostly within Ramseyburg hornfels deposits. Degree of metamorphism will increase as we approach one of the two nepheline syenite bodies of the Beemerville complex. First unit encountered will be a phonolite at location 1 on the trail (Figures 15 and 16). See the write up by Eby concerning this unit (p. 85 of this guidebook), as the trip leaders will not be very helpful

Figure 16. Location 1 on Explorer trail map (Figure 15). Phonolite on left side (southwest) of trail.

Figure 17. Location 2 on Explorer trail map (Figure 15). Ramseyburg Member of the Martinsburg Formation hornfels on path. More examples of hornfels are on a northeast trending ridge across from the Outlook Lodge.

Figure 18. Location 3 on Explorer trail map (Figure 15). Float of diatreme containing various types of xenoliths near small out building.

Figure 19. Location 4 on Explorer trail map (Figure 15). Exposure of nepheline syenite.

with the different igneous units of the Beemerville. We only use them as a heat source or an erratic. Just past the phonolite (location 2) there will be an exposure of the hornfels in the roadbed (Figures 15 and 17). Take a look at this outcrop, as there will be more hornfels of a higher grade of metamorphism farther up the hill. Continue up the old road, as it turns left.

As the trail gentles, the Outlook Lodge is on the left (east) and a ridge of hornfels is on the right (west). Hold off on the hornfels as you might miss the diatreme float. Continue on the trail and, where it bends to the right, look at both sides for diatreme float at location 3 (Figures 15 and 18). Please don't take any samples, as there aren't many here. Mapping has outlined several diatremes north northeast of the present location several hundred ft (m) away (Spinks, 1967; Maxey, 1978; Drake and Monteverde, 1992). Rutan Hill is also close by. Any one of these locations could have supplied the material to a passing glacier. Now this material at location 3 is not very rounded, but it also probably hasn't traveled far. So the question becomes, is this truly glacial material or residuum suggesting another diatreme located beneath your feet? Now mosey up the ridge to the right and look at the hornfels, a bit different than exposed in the roadbed, which you can investigate again on our return trip.

Continue on the trail and large pieces of the syenite will become visible on your right. Continue on where the Explorer trail meets another trail. Just ahead lies the smaller of the two main syenite bodies at location 4 (Figure 15 and 19).

Now retrace your steps back to the bus as lunch is our next stop.

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HARPER'S GEOLOGICAL DICTIONARY

THESAURUS - A religious dinosaur.

STOP 8 AND LUNCH: GEOLOGY OF HIGH POINT STATE PARK, SUSSEX COUNTY, NEW JERSEY

Leaders – Don Monteverde, Ron Witte, and Jack Espstein

Park History

In 1890 Charles Saint John, Jr. purchased a 1,700-acre (688-hectare) tract of land from the Rutherford family that encompassed the summit of Kittatinny Mountain around the future site of High Point Monument. St. John built the High Point Inn on a ridge overlooking Lake Marcia. The Inn opened for business in 1890 as a summer resort. For a time it was a popular place, but in 1908 it was closed because it was not profitable. Colonel Anthony Kuser and his twin brother John purchased the property in 1910. In 1911, Anthony Kuser's father-in-law, John Fairfield Dryden, purchased an additional 7,000 acres (2,833 hectares) from the Rutherford family giving the Kuser's a combined estate of about 10,400 acres (4,208 hectares). In 1923, the Kuser's decided to donate their land for the creation of High Point State Park in memory of John Dryden (Figure 1). The park was originally administered by High Point Park Commission until their responsibilities were centralized in the State Park Service in 1945. During the 1930s, the Civilian Conservation Corps (CCC) operated two camps at High Point. CCC workers improved roads, constructed trails, picnic pavilions, and camping sites. They built the old Iris Inn, which is now the park office, and created Steeny Kill Lake by constructing a dam across Clove Brook. In 1965, C*edar Swamp* was set aside as The John Dryden Kuser Memorial Natural Area.

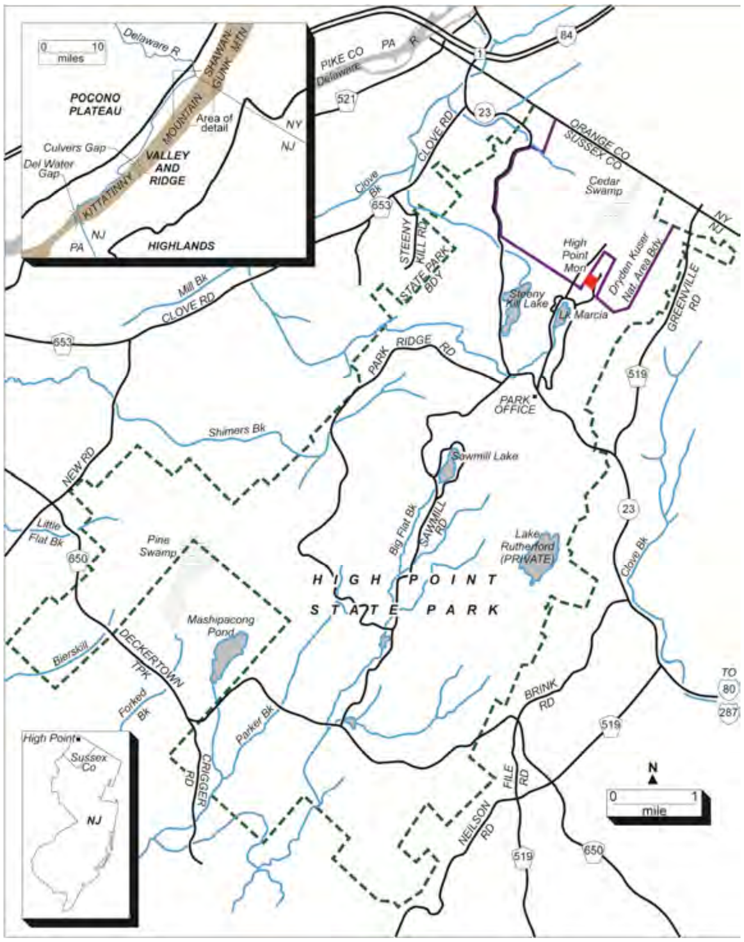

Figure 1. High Point State Park and vicinity, in northern New Jersey. STOP 8 of the field trip is located near the High Point Monument.

The High Point Monument (Figure 2) was built on the highest point in New Jersey (1,803 ft [550 m] above sea level) and was dedicated in memory of New Jersey's wartime heroes.

Monteverde, Don, Witte, Ron, and Epstein, Jack, 2012, Stop 8 and lunch: Geology of High Point State Park, Sussex County, New Jersey, *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. 334-353.

The monument's construction, which was funded by Colonel and Mrs. Kuser, began in 1928 and was completed in 1930. On June 21, 1930, several months after the Colonel's death, a dedication ceremony was held at the monument's base. The 220-ft (67-m) high monolith is faced with New Hampshire granite and local quartzite. For those used to the rigors of climbing, steps lead from the monument's base to the top of the structure. Unfortunately, the monument is closed for repairs. (Information about the History of High Point State Park is from New Jersey Department of Environmental Protection, Division of Parks and Forestry, office of Natural Lands Management publication, Dryden Kuser Natural Area, Management Plan, adopted in 1994, 53 p.).

Figure 2. High Point Monument, High Point State Park, NJ.

Comments on Bedrock Geology

The route from Beemerville to the High Point lunch stop traversed only through the Martinsburg. Starting in the Ramseyburg (Figure 3) and traveling northeastward along strike, the route intersected Route 23 and headed northwestward across the High Point Member of the Martinsburg (Figure 4). Several small folds that warp a general northwest dip marks the Ordovician turbidites at the foot of Kittatinny Mountain.

At the crest of Kittatinny Mountain the route turns north, entering High Point State Park (Figure 5). From the park entrance to Lake Marcia the road follows a narrow belt of the High Point Member forming an anticlinal crest exposed by Shawangunk erosion (Figures 5 and 6). The Martinsburg projects into Lake Marcia without reaching the Shawangunk-covered western, northern, and eastern shores. The anticline pairs with a Shawangunk-cored syncline to the east and both continue northward on either side of the High Point monument. Both limbs of the syncline have moderate dips while the western limb of the anticline is locally overturned. Though the route traversed the Taconic unconformity it remains elusive in the park being covered by colluvium, or glacial material. Lunch awaits on the glacially scoured Shawangunk, part of the southeast-dipping interlimb of the fold pair (Figure 5). This location offers vistas in all directions across New York, New Jersey and Pennsylvania. For the long-term Field Conference attendees, this will be your second lunch here (Epstein et al., 2001).

Figure 3. Example of Ramseyburg Member, Martinsburg Formation with graywacke interbedded with ribbon slate. Note hammer for scale.

Bedrock structures through the Silurian and Devonian sediments across the Milford and Port Jervis South quadrangles and into Pike County, PA portray a generally shallow westward dip (Sevon et al., 1989) (Figure 7). Several dip-trending seismic lines amounting to 75 mi (120 km) collected by Exxon Co. USA imaged this gentle westward dip (Herman et al., 1997). Seismic data collection, processing and correlation to regional sedimentary units through

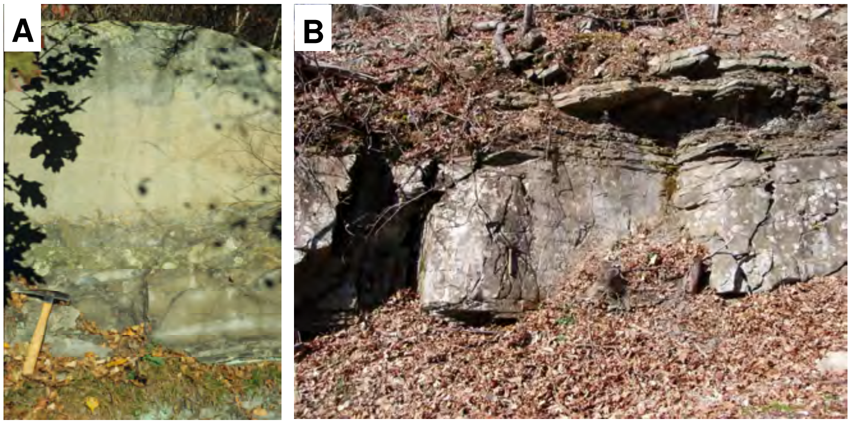

Figure 4. Examples of High Point Member, Martinsburg Formation originally defined as Sandstone at Pine Bush by Epstein and Lyttle (1987) and later formalized as a member of the Martinsburg by Drake (1991). A— Thick bedded graded sandstone with shale rip ups. Hammer for scale. Exposure is on Route 23 along the Field Trip route; B— Exposure of thick bedded sandstones interbedded with thin bedded slate and graywacke. Exposure along Route 23

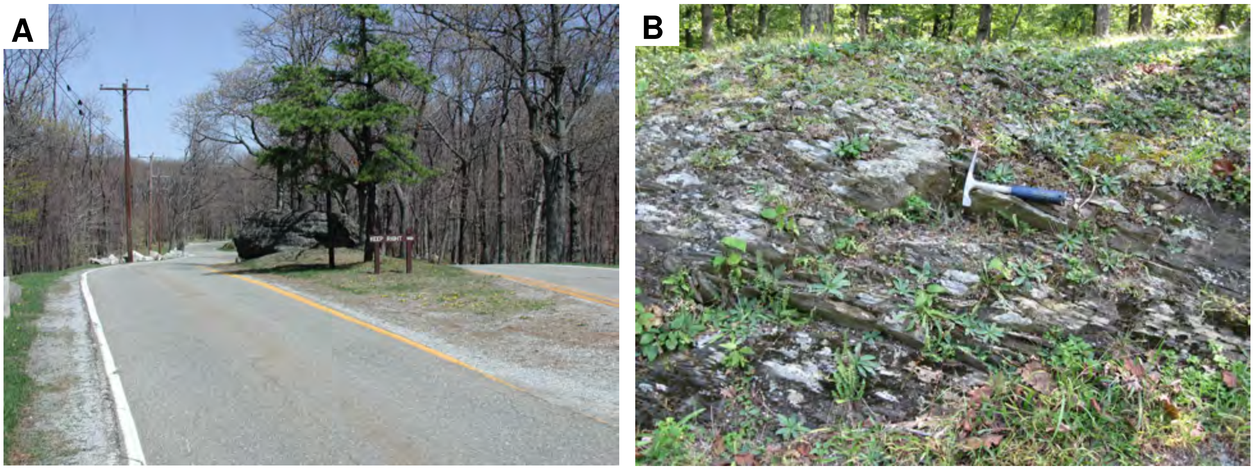

Figure 5. Entrance road to High Point State Park. A— glacial erratic of Shawangunk Formation. Outcrop of Martinsburg in 6b lies to the right (east) and below the road; B—Exposure of High Point Member, Martinsburg Formation. Thick bedded sandstones are absent here as unit resembles Ramseyburg Member.

construction of a synthetic at the Texaco State Forest C-1 well in Pike County, PA were all characterized in Herman et al. (1997). Three dip lines cut across Kittatinny Mountain, one line lies south of High Point State Park and the other two, lie to the north (Figure 8). Line SD-10 starts in Lower Paleozoic platform carbonates to the east and traverses through the Ordovician foreland basin and a northeast plunging belt of more carbonates. It continues through Culvers Gap entering the Silurian and Devonian strata ending in Pennsylvania (Figures 8 and 9). Composite seismic lines SD-11 and 12 collected along I-84 image the closest geology to the High Point lunch stop (Figures 8 and 10). The following description of seismic interpretations was taken from Herman et al. (1997) unless otherwise noted. Strata are combined into six seismic packages on the basis of seismic characteristics and prominence of major bounding reflectors which aids in ease of interpretation. Proterozoic basement (PZ on seismic Figures 9, 10 and 11) comprises the basal seismic group that is overlain in sequence by Cambrian and Ordovician carbonates (CO on seismic Figures 9, 10 and 11), and the Ordovician foreland basin flysch of the Martinsburg (O on seismic Figures 9, 10 and 11). Silurian and Devonian units form the upper three seismic units beginning with the Shawangunk through Bloomsburg and correlative units (Tuscarora through Bloomsburg) encountered in the C-1 well. This clastic unit (S on seismic Figures 9, 10 and 11) is overlain

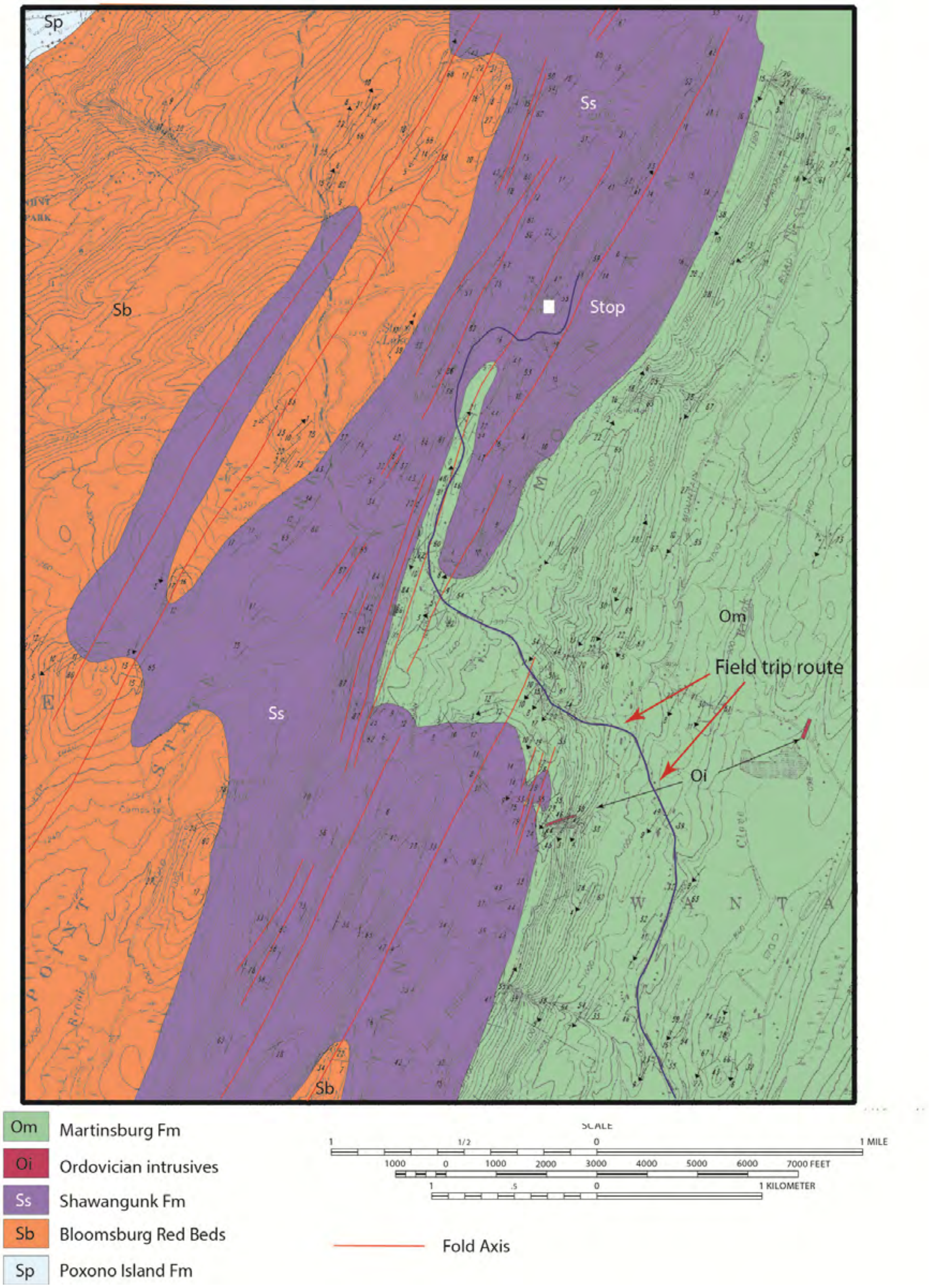

Figure 6. Geological map of Port Jervis quad (unpublished data from Monteverde, D.H. and Epstein, J.B.)

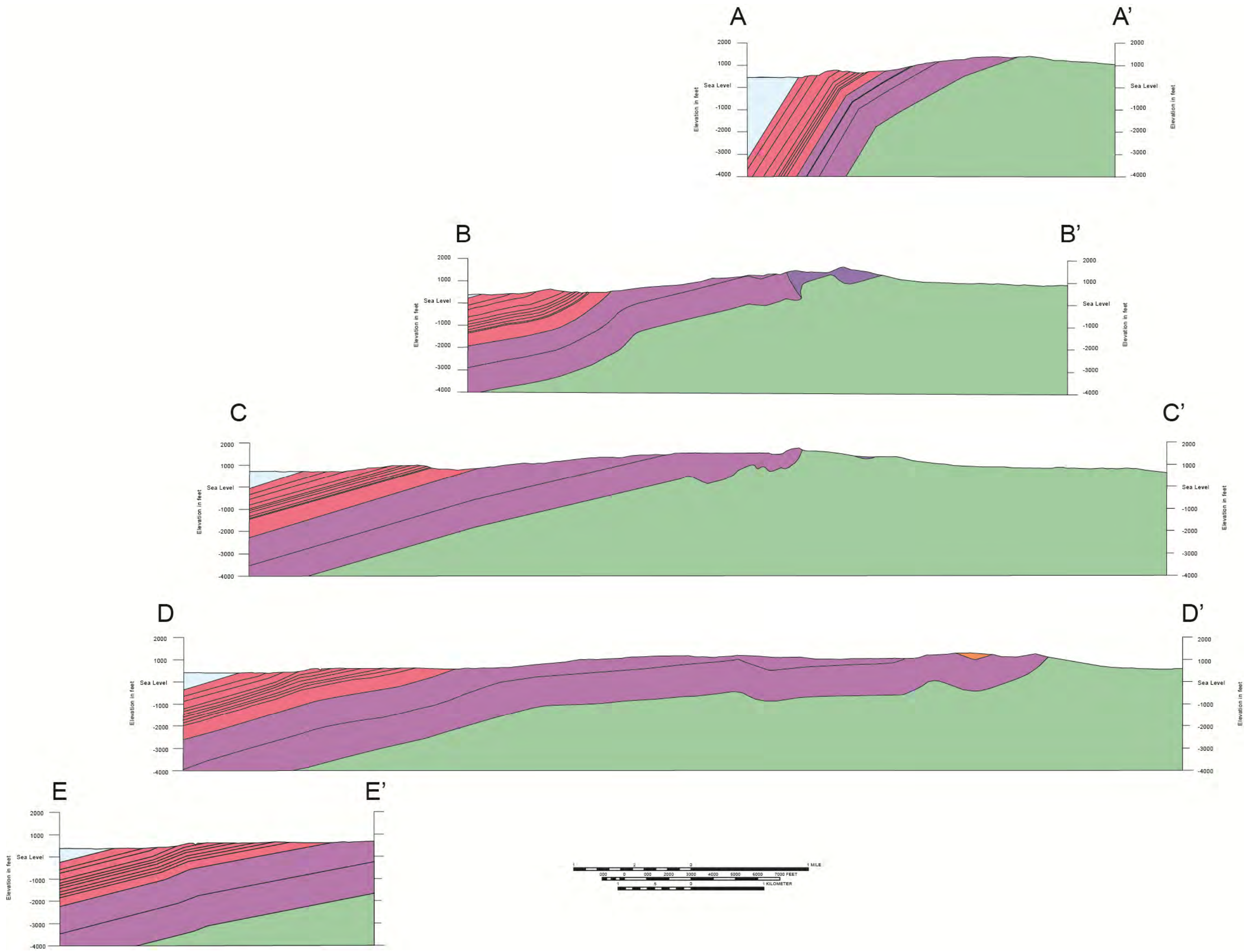

Figure 7. Geological cross sections from the Milford and Port Jervis South quadrangles. Colors reflect units on based on 1:24,000 scale field mapping

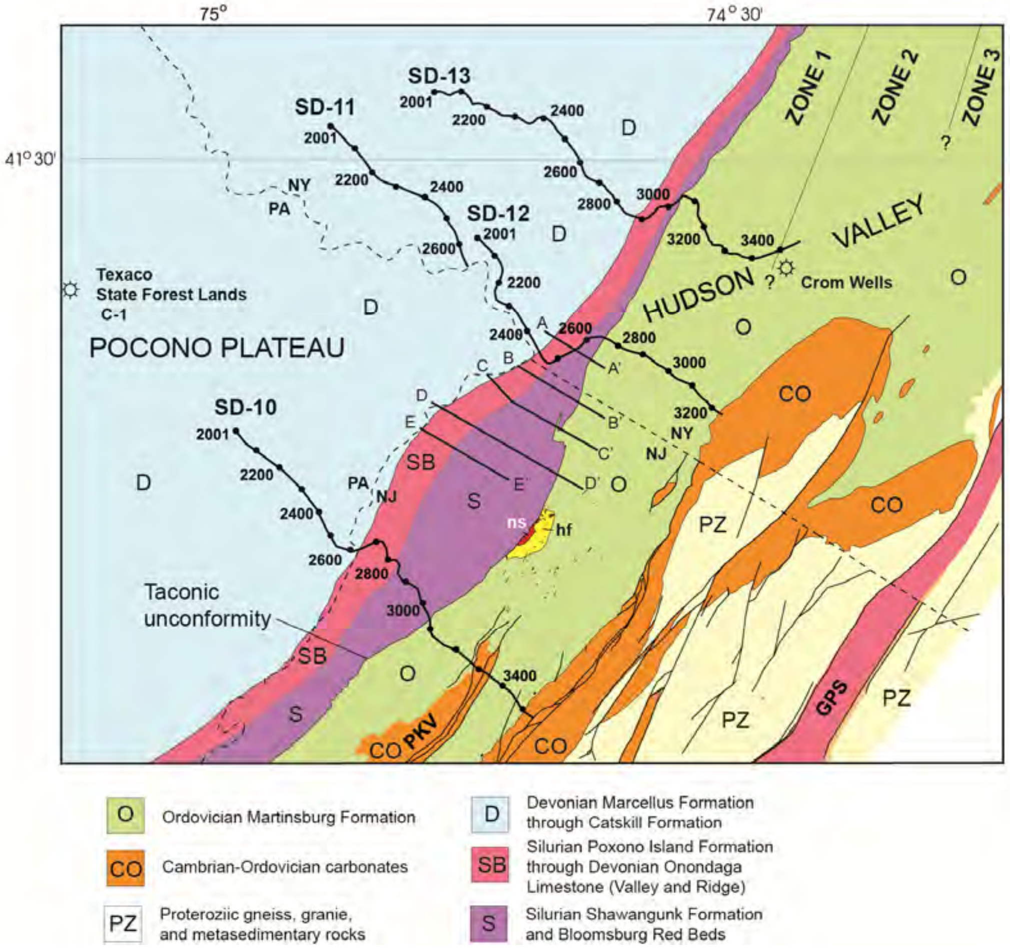

Figure 8. Location map of Exxon seismic lines (Figures 9, 10, and 11) and geological cross section based on 1:24,000 scale field mapping (Figure 7)

by Silurian and Devonian carbonate, siltstone and shale of all post-Bloomsburg through Buttermilk Falls/Onondaga Limestone (SB on seismic Figures 9, 10 and 11). The Marcellus defines the lower boundary of the youngest seismic unit that continues into the Catskill Formation (D on seismic Figures 9, 10 and 11). A uniformly west-dipping post Martinsburg section (seismic units S, SB, and D) is evident on lines SD-10 and SD-11+12. Fault displacement imaged on these seismic lines is primarily in pre-Shawangunk units (units PZ, CO and O on Figure 9, 10 and 11) and comprises a series of blind, gently easterly-dipping thrust faults in the east and younger moderately west-dipping antithetic faults in the western section of the two seismic lines. These faults propagate through the basement and into the Cambrian and Ordovician sections previously described as seismic units CO and O. Some of the blind faults end in broad and open cover folds in younger units and faulting just cuts the base of the Silurian on profile SD-10 suggesting post Taconic movement. Seismic line SD-13 is the farthest north, lying completely within New York (Figure 11). It images a marked increase in foreland directed faulting in the Silurian through Devonian seismic units (Figure 11). Herman et al. (1997) suggested this change marks a gradation into the increased foreland deformation of the Silurian and Devonian units (Marshak and Tabor, 1989; Burmeister and Marshak, 2006)

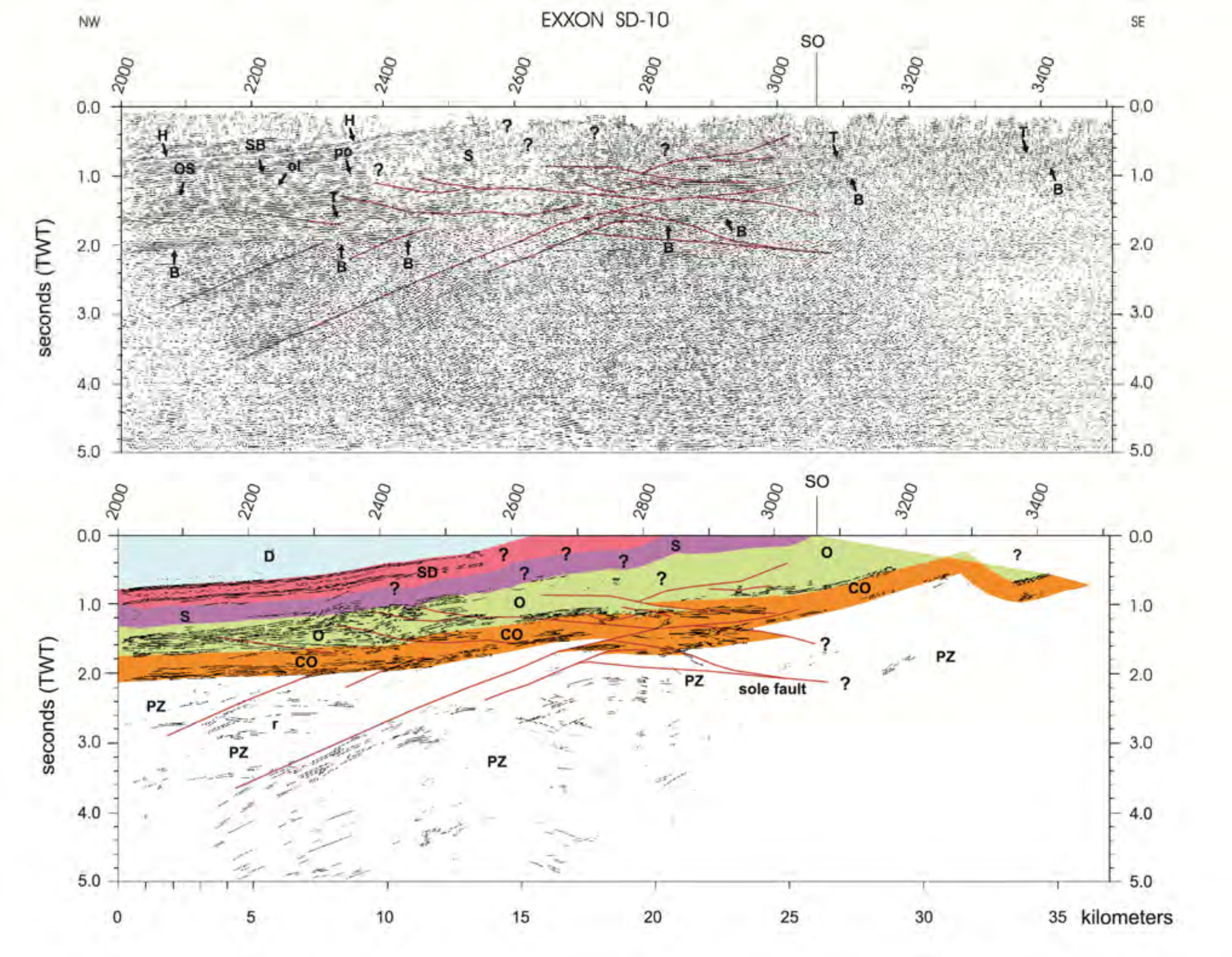

Figure 9. Exxon seismic-reflection profile SD-10. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing (bottom). PZ – Proterozoic, B – upper boundary of PZ unit, CO – Cambrian and Ordovician carbonates, T – upper boundary of CO unit, O – Ordovician Martinsburg flysch, OS – upper boundary of O unit, S – Silurian molasse, SB – upper boundary of S unit, SD – Silurian and Devonian, undivided, H – upper boundary of SD unit, D – Devonian undivided, r – rollover, ol – onlap, po – pinch out. SO on map is location of the Taconic unconformity. Heavy red lines are faults. (modified from Herman et al., 1997).

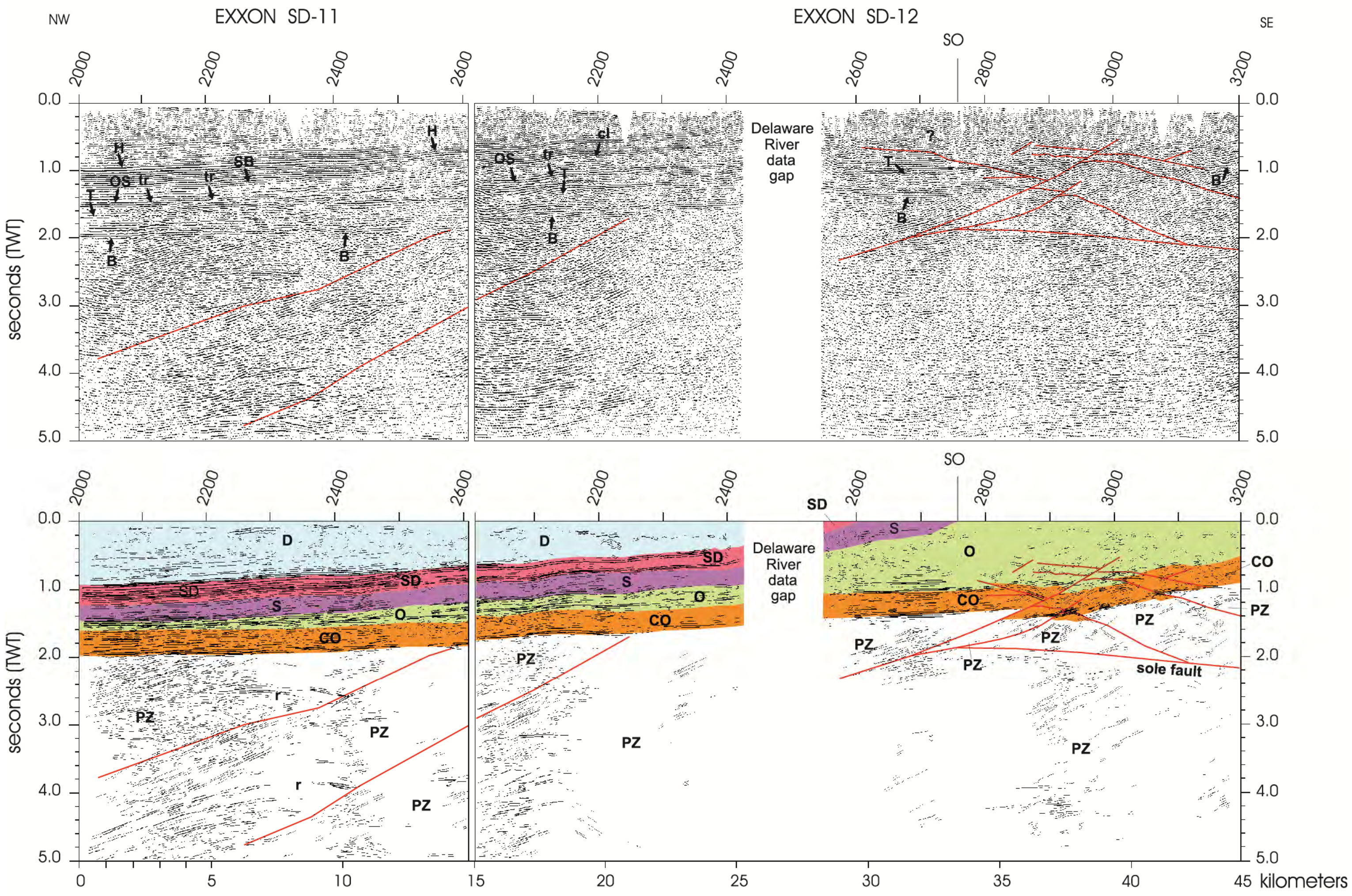

Figure 10. Exxon seismic-reflection profiles SD-11 and SD-12. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing (bottom). PZ – Proterozoic, B – upper boundary of PZ unit, CO – Cambrian and Ordovician carbonates, T – upper boundary of CO unit, O – Ordovician Martinsburg flysch, OS – upper boundary of O unit, S – Silurian molasse, SB – upper boundary of S unit, SD – Silurian and Devonian, undivided, H – upper boundary of SD unit, D – Devonian undivided, r – rollover, ol – onlap, po – pinch out. SO on map is location of the Taconic unconformity. Heavy red lines are faults. (modified from Herman et al., 1997).

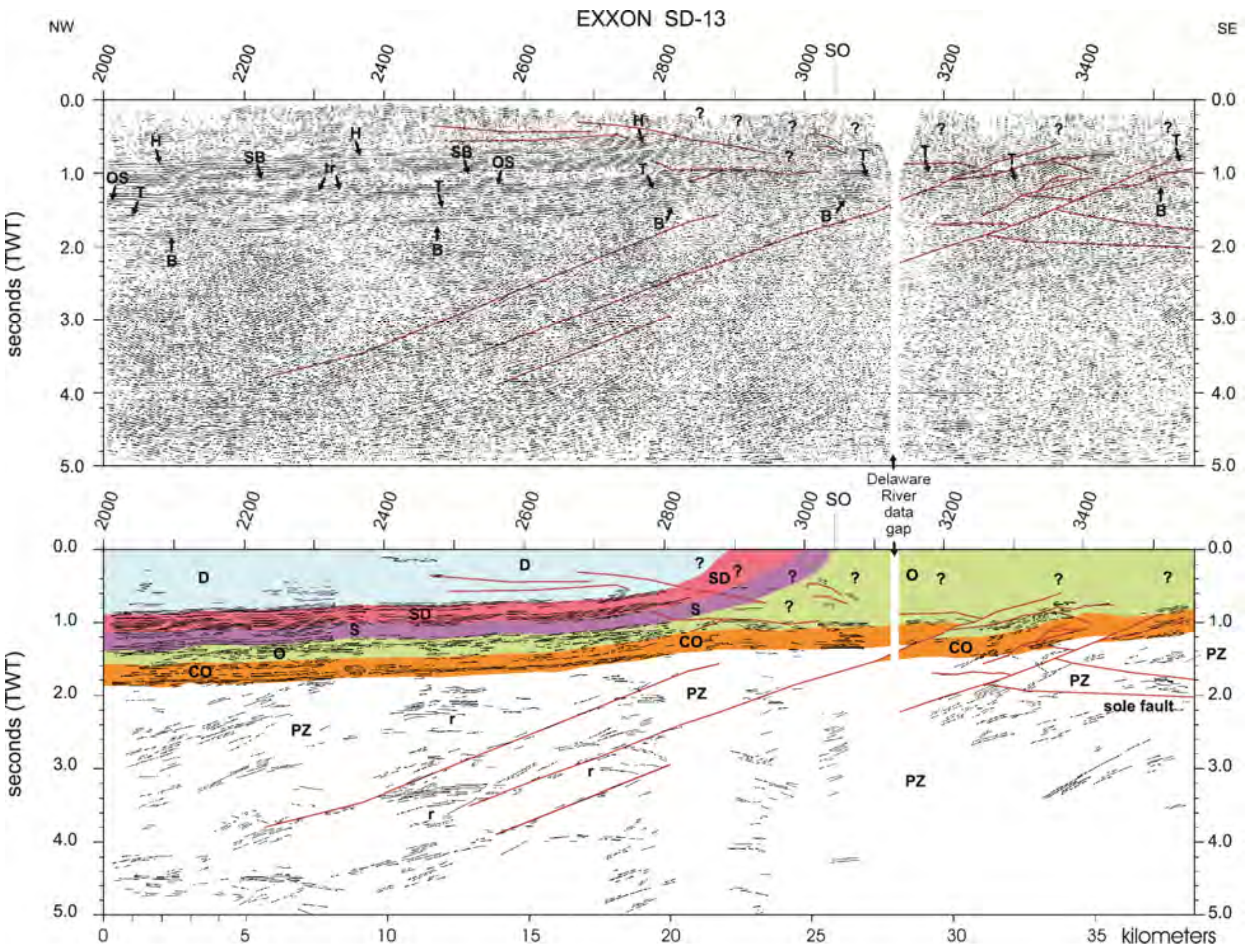

Figure 11. Exxon seismic-reflection profile SD-13. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing (bottom). PZ – Proterozoic, B – upper boundary of PZ unit, CO – Cambrian and Ordovician carbonates, T – upper boundary of CO unit, O – Ordovician Martinsburg flysch, OS – upper boundary of O unit, S – Silurian molasse, SB – upper boundary of S unit, SD – Silurian and Devonian, undivided, H – upper boundary of SD unit, D – Devonian undivided, r – rollover, ol – onlap, po – pinch out. SO on map is location of the Taconic unconformity. Heavy red lines are faults. (modified from Herman et al., 1997).

Local Surficial Geologic History

High Point State Park lies entirely within the limit of the last glaciation and only glacial deposits (Figure 12) and erosional features associated with the Late Wisconsinan ice sheet are preserved here. Older glacial deposits and features were buried beneath younger glacial sediment or were eroded during the last glaciation. The Late Wisconsinan advance of ice into northwestern New Jersey consisted of ice lobes initially moving southwestward down Minisink and Kittatinny Valleys. In time, the ice became thick enough to flow over Kittatinny Mountain, cutting across the region's southwesterly topographic grain. The terminal moraine, which lies 30 mi (48 km) south of the park (Figure 12), generally marks the farthest advance of the ice sheet. However, in a few valleys, sublobes of the glacier extended as much as 1 mi (1.6 km) south of the moraine. Thickness of ice above High Point during the Late Wisconsinan Maximum (LGM) is estimated at 500 to 2,500 ft (152 to 762 m) depending on one's advocacy of "thin ice" or "thick ice" models near the terminus of the Laurentide ice sheet. A thick-ice model for this part of the Laurentide ice sheet seems a better fit for the following reasons: 1) tracing moraines indicates an average terminal ice sheet profile of 225 ft/mi (43 m/km); 2) regional ice flow during the LWM was directed southward across Kittatinny Mountain's strongly-developed southwesterly topographic grain; and 3) ice was thick enough to mold drumlins on the western flank of Kittatinny Mountain.

During deglaciation, the edge of the ice sheet thinned and its flow became more controlled by the southwesterly trend of the larger valleys. The Kittatinny and Minisink Valley ice lobes retreated gradually to the northeast. However, at times the edge of the ice lobes remained stationary, and in a few instances readvanced southward a few miles (kilometers). During periods when the glacier margin remained stationary, sand and gravel laid down by meltwater streams built up at and beyond the glacier margin in stream valleys and glacial lakes in Minisink, Wallpack, and Kittatinny Valleys (Figure 13). Additionally, end moraines were deposited at the glacier's terminus.

Both the ice-marginal parts of meltwater deposits and end moraines mark the former edge of the ice sheet. These ice-recessional features were used to reconstruct the geometry and retreat history of the ice sheet. The Augusta margin, which runs through High Point (Figure 13), is delineated by the Augusta and Montague moraines. The continuity of the moraines, and

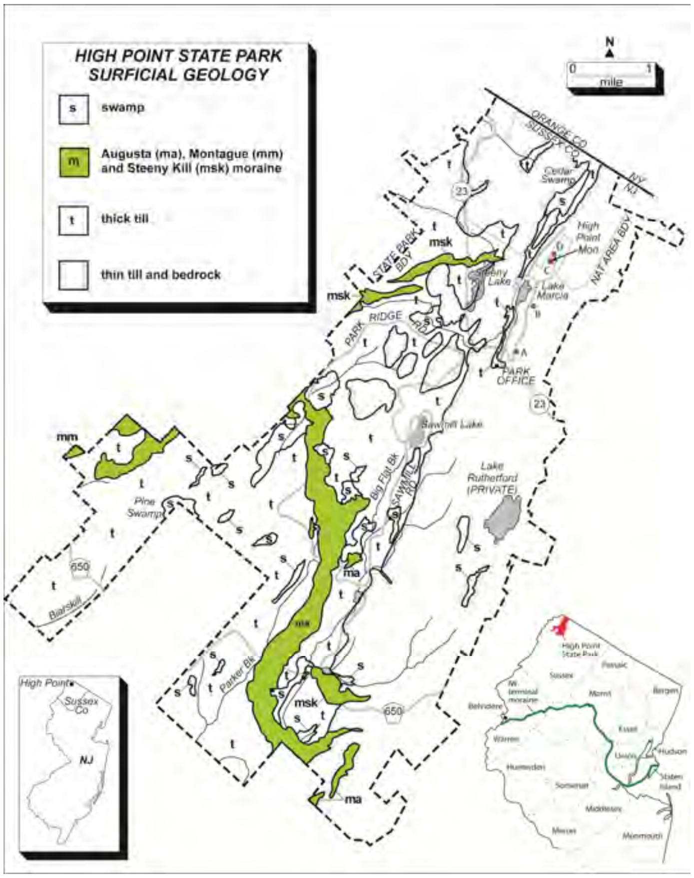

Figure 12. Surficial geologic map of High Point State Park and location of features named in text.

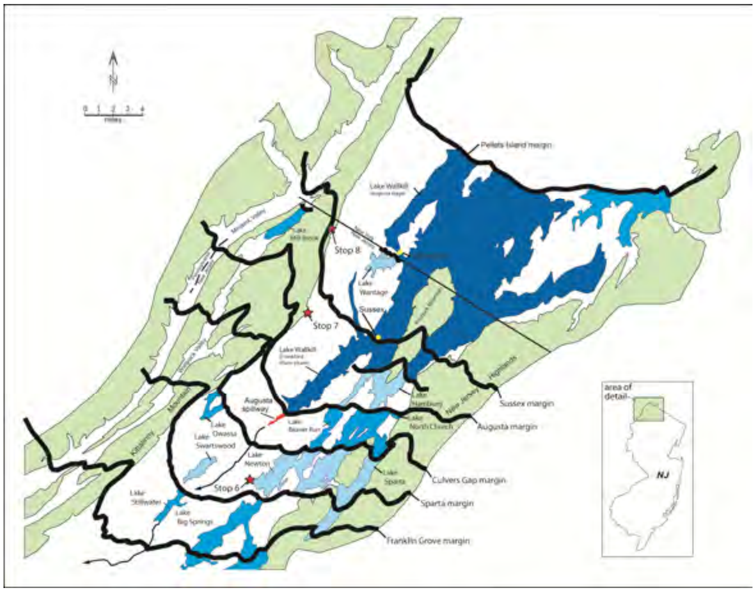

Figure 13. Ice margins of Late Wisconsinan age showing successive positions of the Kittatinny and Minisink Valley ice lobes as they retreated northeastward, and location of large glacial lakes in northwestern New Jersey (modified from Witte, 1997).

the size and extent of contemporaneous meltwater deposits in valleys south of the Augusta margin show that the glacier's terminus maintained a nearly constant position for probably more than a hundred years.

Erosion by Ice

Features carved in bedrock by moving glacial ice are numerous in the park. They include striations, crescentic marks, polished bedrock, and plucked outcrops. Striations and crescentic marks in the park show that the glacier flowed S70°W to due west. These features were made near the edge of the Kittatinny Valley ice lobe during the late stages of deglaciation and they indicate strongly-developed lobation and dispersal flow at the ice lobe's terminus. The more southerly-oriented striations, made earlier when the ice was much thicker and its margin far south of High Point, were subsequently removed by glacial erosion. In a few places on Kittatinny Mountain, cross-cutting striae (Figure 14) record these changes in ice flow.

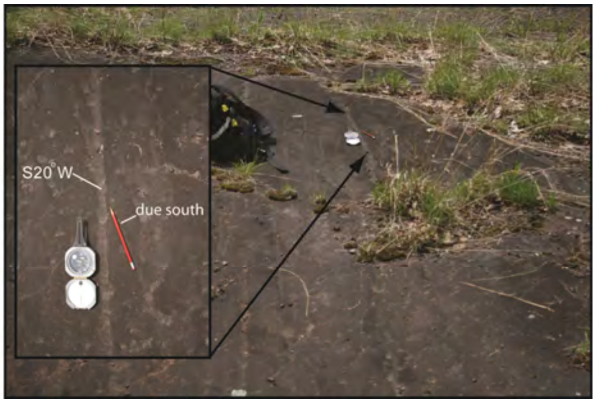

Figure 14. Cross-cutting striations on the Bloomsburg Red Beds near Blue Mountain Lake parking area, Kittatinny Mountain.

Other forms of glacial erosion include polishing and plucking. Many outcrops show evidence of glacial scour, which is reflected by their polished surfaces and streamlined forms. Elsewhere, weathering has roughened the rock surface, removing evidence of glacial scour. Plucking occurred where rock fragments, fractured and loosened from pressure exerted by the weight of the overriding glacier, were broken off. Generally, the fragments, many boulder-sized, were removed from the lee side of the outcrop. In extreme cases, the processes of abrasion and plucking formed roche moutonnées.

Glacial Deposits

Till covers the bedrock surface in most places, except the rocky crest of Kittatinny Mountain and a few steep hillslopes. Where it is thin, the underlying bedrock topography shows through. Thicker till subdues and buries this irregular surface, and in many places completely hides it. Till in the park is typically a compact, yellowish-brown to light olive brown, or reddish-brown silty sand consisting of a mixture of quartz sand, rock fragments, feldspar, silt, and clay. Subangular to subrounded clasts of quartz-pebble conglomerate, quartzite, red sandstone, gray sandstone, and red shale may make up as much as 20 percent of the deposit by volume. Many of these are striated. This material is probably lodgement till and color and clast provenance is dependent on direction of ice flow over the local bedrock. Ice flow over the Bloomsburg Red Beds produced reddish till and flow over the Shawangunk Conglomerate produced brown till. The two-till exposure along Clove Brook, 1.5 mi (2.4 km) northwest of High Point (see Day 2 Road Log, mileage 71.4 and fig. 11) represents multiple directions of ice flow.

Overlying this lower compact till is a thin, discontinuous, loose, poorly sorted silty sand and sand containing as much as 35 percent pebbles, cobbles, boulders, and lenses of sorted sand, gravel, and silt. Overall, stones are typically more angular than those in the underlying till. This material is ablation till, flow till, and basal-meltout till, debris that was released from the glacier by melting. Frost heaving, burrowing animals and insects, and root growth have also altered the upper few feet (about 1 meter) of till making it less compact, and reorienting its stones.

Glacial erratics are ubiquitous in the park and most are locally derived. Boulders of Martinsburg (Om) sandstone were glacially-transported out of Kittatinny Valley to Kittatinny Mountain, where they rest as much as 900 ft (274 m) above their source area. They along with local striae provide a clear indication that there existed a dispersal pattern of ice flow along the margin of the Kittatinny Valley lobe.

Glacial Landforms

Landforms in the park include drumlins, end moraines, and kettles. Most drumlins are in the western part of the park in places where till is thick. They trend due south to south 13° west, a more southerly direction than shown by nearby striations. This suggests that the drumlins formed when ice was much thicker, and its flow not as controlled by topography as it was when the striations were made.

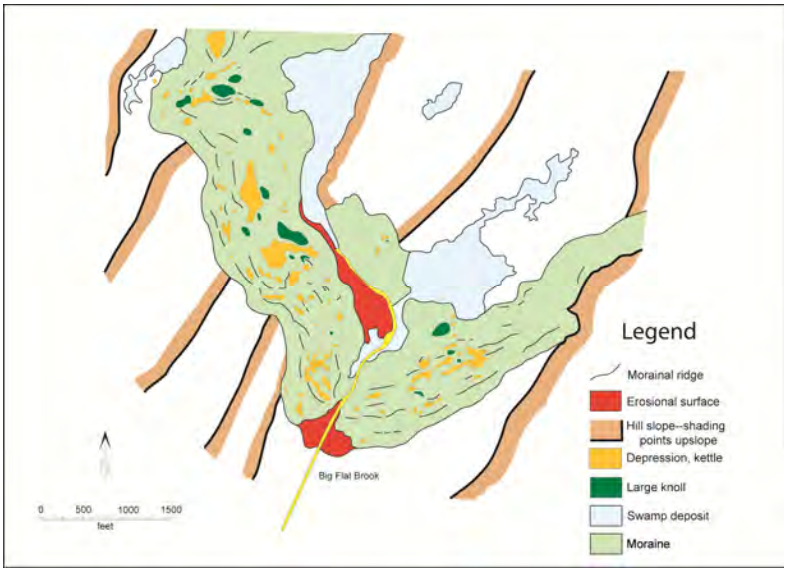

Figure 15. Morphologic features of the Augusta moraine (modified from Witte, 2008).

The Augusta, Montague, and Steeny Kill Lake moraines (Figure 12) are bouldery, segmented to nearly-continuous ridges that mark the former lobate edge of the ice sheet. They consist of stony till with lenses of silt, sand, and gravel. Ridge-and-kettle and knob-and-kettle topography is generally well developed (Figure 15). Their lobate course, morphology, a few outcrops, and evidence of glacial readvance suggest they were formed by, 1) the pushing or transport of debris and debris-rich ice by the glacier at its margin, and 2) penecontemporaneous and postdepositional sorting and mixing of material by mass movement, chiefly resulting from slope failure caused by melting ice, and collapse of saturated sediment. The source and mechanism of sediment transport are unclear. Most of the morainal material appears to be of local origin, but it is not known whether the glacier was simply reworking drift at its margin or was transporting sediment to the margin along shear planes (Koteff and Pessl, 1981). Inwash is not a viable mechanism because the larger more continuous morainal segements lie on mountains and ridges and adjacent to thick till.

Postglacial History

Ice retreated from New Jersey about 17,000 yrs. BP. During the few thousand years following deglaciation, the harsh climate and sparse vegetation enhanced erosion of the land. Unconsolidated, water-saturated surficial materials were easily moved downhill by the constant pull of gravity. Disintegration of rock outcrops by frost shattering formed extensive accumulations of talus at the base of cliffs on Kittatinny Mountain. Boulder fields formed at the base of slopes where rocks, transported by soil creep, came to rest. Other fields were formed where meltwater winnowed the finer-grained material from till leaving behind the heavier stones. A few others may have been deposited directly by the glacier. In places boulders stand upright appearing as tombstones, while others form crude stone circles. These features were probably made by frost heave, and possibly tree growth. Stream deposits consist of channel sand and gravel and boulder lags, with finer sediment forming very on narrow flood plains. Many streams in High Point State Park flow in deep ravines cut by glacial meltwater.

Swamps and bogs are numerous, forming over glacially-made shallow lakes and ponds. Several nearby studies (Neiring, 1953; Sirkin and Minard, 1972; Cotter, 1983) have established a dated pollen stratigraphy that nearly goes back to the onset of deglaciation. Changes in pollen taxa record the transition from tundra with sparse vegetation, to open parkland of sedge and grass with scattered stands of spruce and fir. From about 14,000 to 11,000 yrs. BP, a dense closed boreal forest developed that consisted largely of spruce and fir blanketing the uplands. This was followed by a period (11, 000 to 9,700 yrs. BP) when pine became dominant. About 9,400 yrs. BP, oak became dominant and displaced the conifers, signaling the change from boreal to temperate climate. Figure 16, derived from a pollen study of nearby Cedar Swamp (Figure 12) by Nering (1953), illustrates forest succession in the High Point area over the last 10,000 years.

Mastodon remains, excavated from Shotwell Pond in Stokes State Forest (~ 11 mi [18 km] southwest of High Point) show the presence of these large mammals on Kittatinny Mountain during the close of the Ice Age. They disappeared from this area about 12,000 yrs. BP, presumably because of a rapid change in climate and food source rather than overhunting by Paleo-Indians.

Selected Surfical Geologic Features near High Point

The following descriptions of locations A to D (Figure 12) are modified from Witte and Monteverde (2005).

A. Location - Port Jervis South quadrangle, main ridge of Kittatinny Mountain, 1,500 ft (457 m) north of Route 23, east side of Scenic Drive (Figure 1). Glacially eroded and weathered Shawangunk Formation (Figure 17).

Explanation - The overall streamlined and smoothed rock surface, faint striations, and crescentic marks are products of glacial erosion. The scratches and crescent-shaped marks on the outcrop east of Scenic Drive show that the ice sheet (Kittatinny Valley lobe) flowed S70^{o}W. Several angular to subangular boulders of conglomerate, glacially transported from nearby locations, lie on the scoured rock surface. The polygonal pattern outlined by vegetation on the rock surface follows joints and fractures in the bedrock. These features gradually widen over

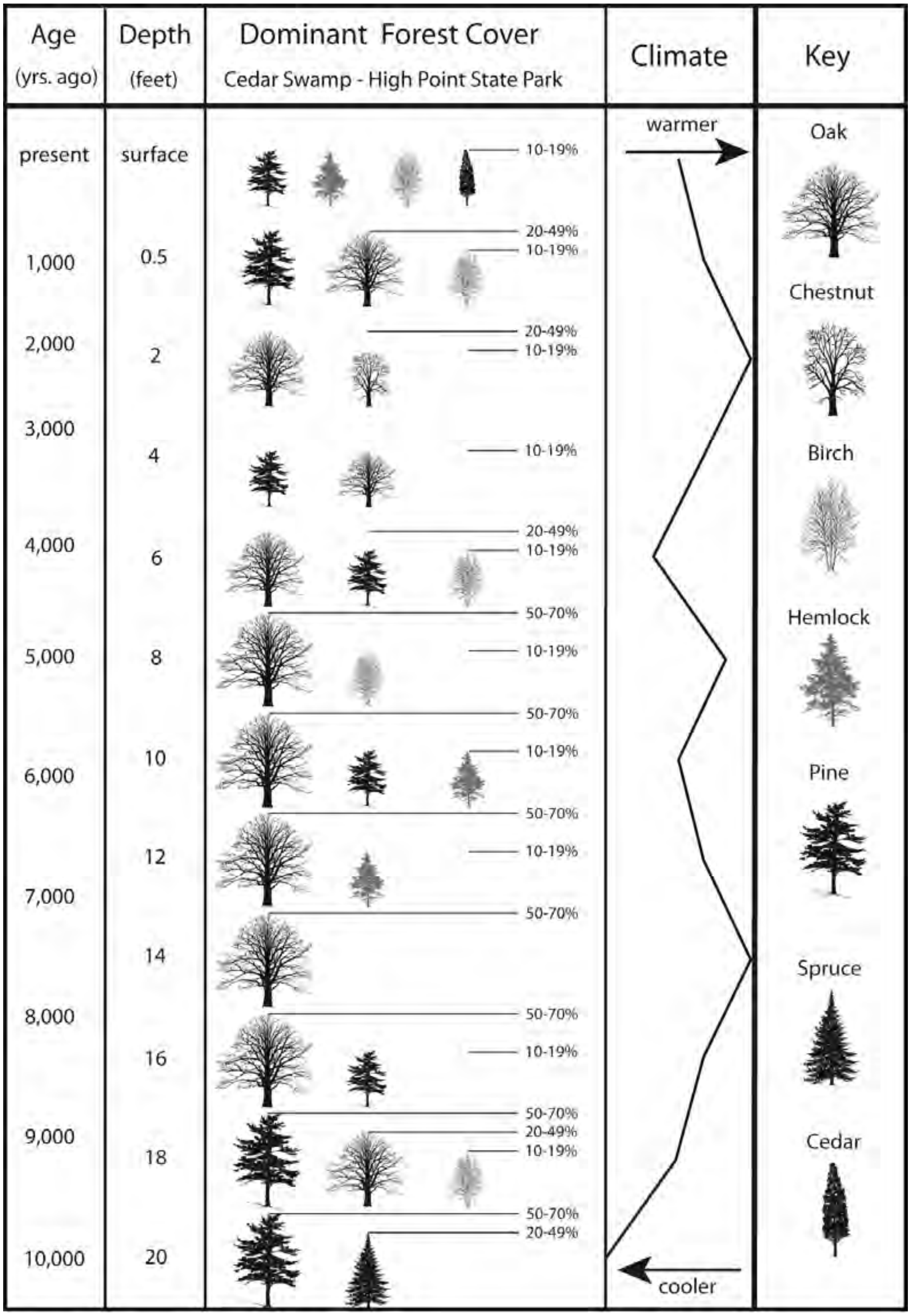

Figure 16. Forest succession around Cedar Swamp, High Point State Park, during the last 10,000 years. Dominant trees and percentages are based on a percent-pollen diagram constructed by Neiring (1953). Relative temperature change is based on the percentage of cold- vs. temperate-tolerant species.

Figure 17. Glacially scoured and weathered Shawangunk Formation showing joint blocks formed by frost heave. Scale at photo's center is in 1-ft (0.3-m) gradations.

time by the action of freezing water, and root growth, eventually filling in with rock fragments that form a thin soil. The expansion of ice also breaks the rock apart along bedding surfaces as shown by the elevated position some joint blocks.

B. Location - Port Jervis South quadrangle, main ridge of Kittatinny Mountain, 4,000 ft (1,219 m) north of Route 23, east side of Scenic Drive (Figure 12). Small oval-shaped boulder field (Figure 18).

Explanation - Most of the boulders were dislodged from adjacent outcrops of the Shawangunk Formation. Over time they accumulated at the base of the slope and a small boulder field formed. Parts of the boulder field are collapsed. This shows that some of the boulders may have fallen onto a small block of remnant glacial ice or postglacial ground ice. The effects of frost heave and root growth have fractured numerous boulders, moved some into crude stone circles, and reoriented many to tombstone positions.

Figure 18. Accumulation of Shawangunk joint blocks forming a small boulder field. Scale near photo's center is in 1-ft (0.3-m) gradations.

Boulder fields are found throughout the park in three settings. These are: 1) in hollows, swales, and saddles along the main outcrop belt of the Shawangunk Formation. Here they typically lie below large outcrops or above bedrock that lies very close to the surface. Boulders in this setting are generally angular in shape, and may be as much as 25 ft (8 m) long; 2) in areas of thick till, boulders form massive, oval-shaped accumulations that lie near the base of hillslopes, and more rarely they occur on broad uplands where they may have been deposited by the glacier. Boulders in this setting generally have a subrounded shape, their corners worn down during glacial transport. Sorting is common and many boulders form crude stone circles; and 3) bouldery accumulations in small upland valleys and elongated fields along hillslopes formed in places where meltwater winnowed the fines from till, leaving a bouldery lag.

C. Location - Port Jervis South quadrangle, Kittatinny Mountain, High Point Monument (Figure 12).

Geology - Panoramic view of New Jersey Highlands, Kittatinny Valley, Kittatinny Mountain, Shawangunk Mountains, Catskill Mountains, Minisink Valley, Pocono Plateau.

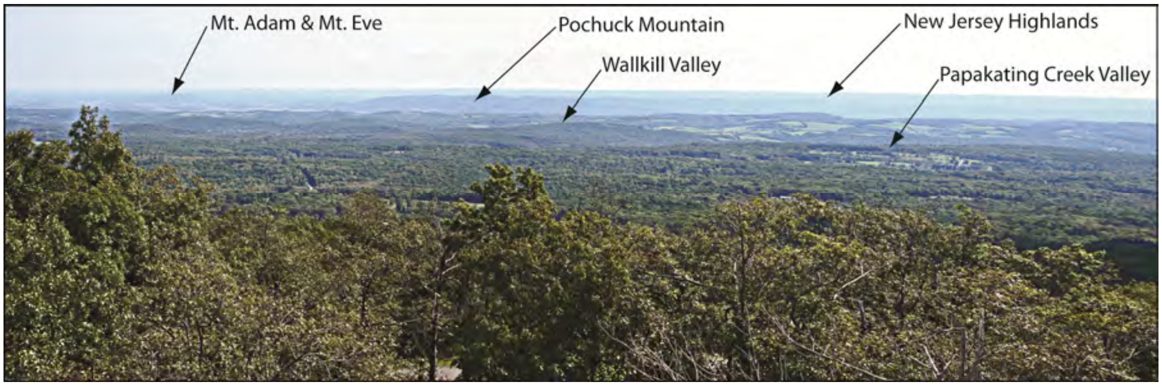

Figure 19. Vista from High Point Monument looking southeastward across Kittatinny Valley to the New Jersey Highlands.

View to the southeast across Kittatinny Valley (Figure 19): Kittatinny Valley forms the broad lowland between the New Jersey Highlands and Kittatinny Mountain. Its upper part is drained by the Wallkill River, which flows northward and empties into the Hudson River just south of Kingston, NY. Papakating Creek is a tributary of the Wallkill River. Kittatinny Valley is underlain by northeast-trending belts of slate and sandstone of the Martinsburg Formation and limestone and dolomite of the Kittatinny Supergroup and Jacksonburg Formation; all of Lower Paleozoic age. The higher ridges and hills in the valley are typically underlain by slate and sandstone, whereas most of the larger river valleys are underlain by carbonate rock. In most places, these valley floors are covered by thick glaciodeltaic and glaciolacustrine sediment laid down in the many glacial lakes that formed during Late Wisconsinan deglaciation. The extensive, rich, black, agricultural soil found in the Wallkill Valley consists of peat and humus that filled in the shallow parts of a large postglacial lake, the successor to glacial Lake Wallkill.

The uplands visible across Kittatinny Valley include the far distant ridges and hills of the New Jersey Highlands, and the Pochuck Mountain, Mount Adam, and Mount Eve outliers. These areas are all chiefly underlain by Pre-Cambrian granite and gneiss.

View to the southwest along the curving ridge line of Kittatinny Mountain (Figure 20): The large, high ridge that forms the spine of Kittatinny Mountain is underlain by tough quartzite and conglomerate of the Shawangunk Formation. The lower area west of the ridge is underlain by less resistant red shale and sandstone of the Bloomsburg Red Beds, and several of the smaller hills in this area are drumlins. Because the Shawangunk Formation is highly resistant to weathering and erosion, it stands out in greater relief than the area on its flanks. The small notch near the ridge's midpoint is Culvers Gap, which was cut by an ancestral stream of the Raritan or Delaware Rivers.

View northwest across Minisink Valley to the Pocono Plateau (Figure 21): The uneven upland in the distance is the Pocono Plateau, an area underlain by gently-northwest-dipping, Middle-Paleozoic sandstone and shale. Extensive erosion of these rocks over millions of years has created a rugged landscape that remains largely uncultivated. The Delaware River drains southeastward from the Pocono Plateau to the towns of Matamoras, PA, and Port Jervis, NY. Here the river enters Minisink Valley, makes a right-angle turn and continues its course southwest to Wallpack Bend following the Onondaga Limestone and Marcellus Shale.

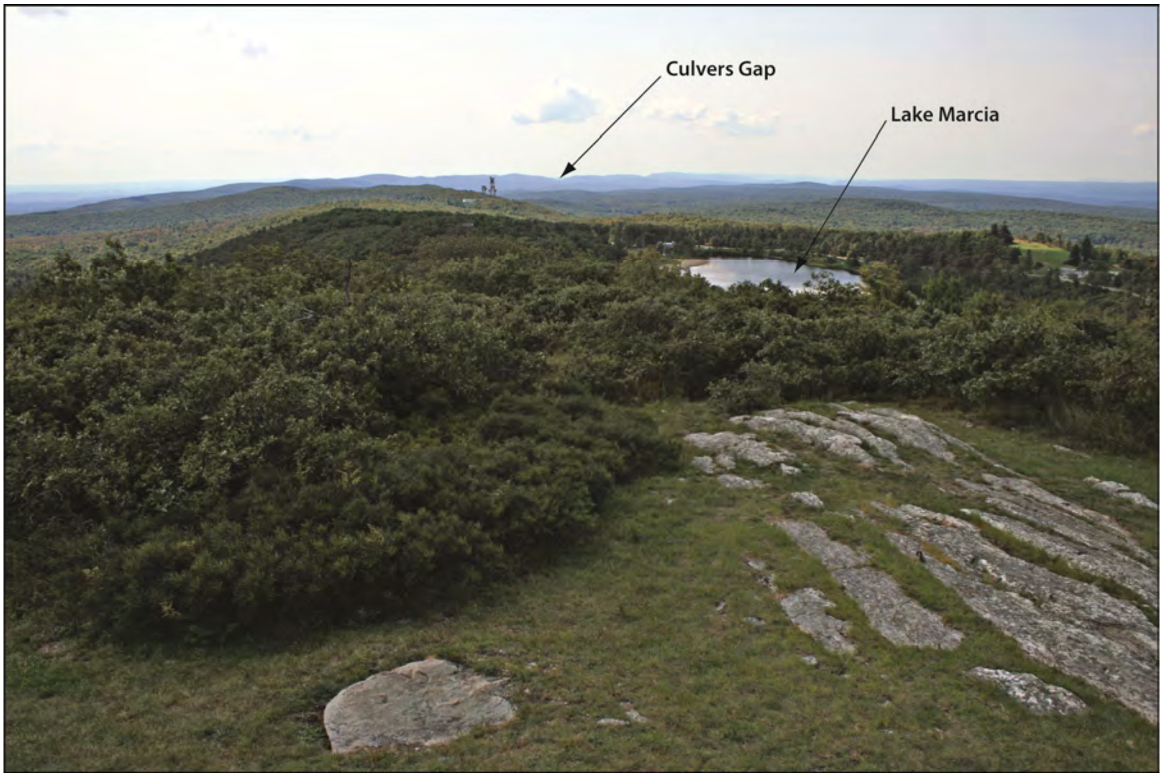

Figure 20. Vista from High Point Monument looking southwestward along the curving ridgeline of Kittatinny Mountain. The small notch along the ridge's midline is Culvers Gap, a wind gap cut by the ancestral Raritan or Delaware Rivers millions of years ago and prior to the onset of glaciation in North America.

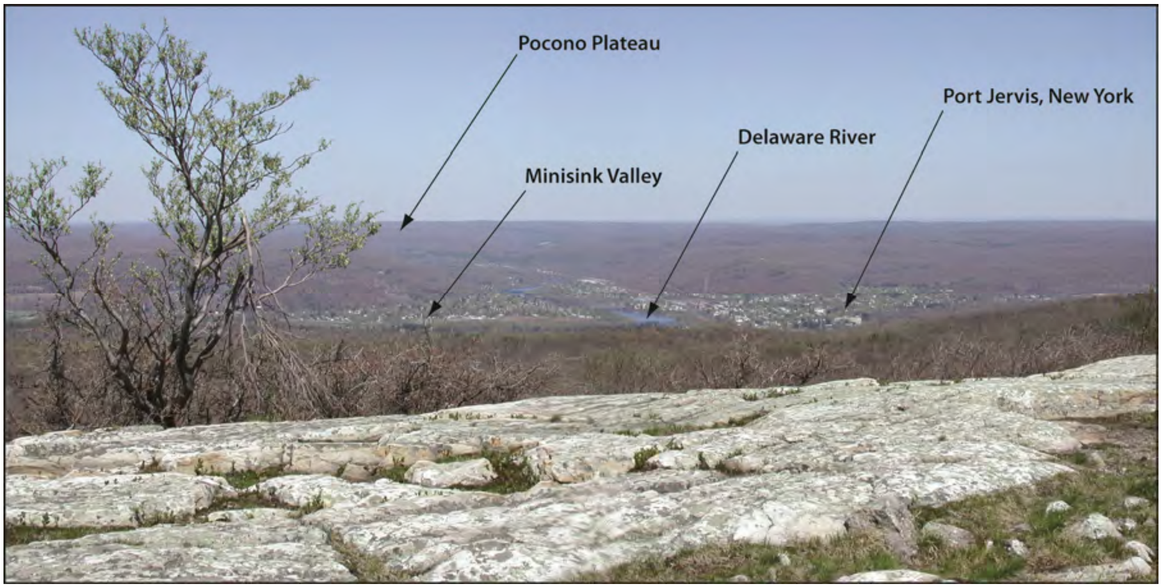

Figure 21. Vista from High Point Monument looking northwest across Minisink Valley to the Pocono Plateau.

Figure 22. Vista from High Point Monument looking northeast along the ridgeline of Kittatinny Mountain. If you see this man, pay him no attention; especially if he wants to tell you a tale about an Indian princess.

View to the northeast along the ridge line of Kittatinny Mountain (Figure 22): The broad upland at northeast end of ridge is the Shawangunk Mountains. The Catskill Mountains, which can be seen only on a very clear day, form a high, jagged upland west of the Gunks. The Dalai Epstein has much to say about the geology along this view. We submit to his far greater knowledge and await his rambling oratory.

D. Location - Port Jervis South quadrangle, Kittatinny Mountain, northeast side of High Point Monument (Figure 12).

Excellent examples of striations can be seen on the glacially polished rock surface (Figure 23) northeast of the monument. They consist of straight scratches and larger grooves that show the glacier flowed south 85^{o} west to due west. Crescentic marks (Figure 24) are also well developed and they show a similar direction of ice flow.

In places weathering has removed the striations and roughened the glacially-polished rock surface. This suggests that these features were once covered by thin soil, which greatly lessened the effects of weathering. When viewed from a distance the rock outcrops have a streamlined and asymmetrical, smoothed shape. On the downstream side (west and southwest), rock has been removed by glacial plucking and quarrying. On the upstream side (east and northeast), rock has been removed by abrasion. This gives the outcrop a characteristic shape called a roche montonnée.

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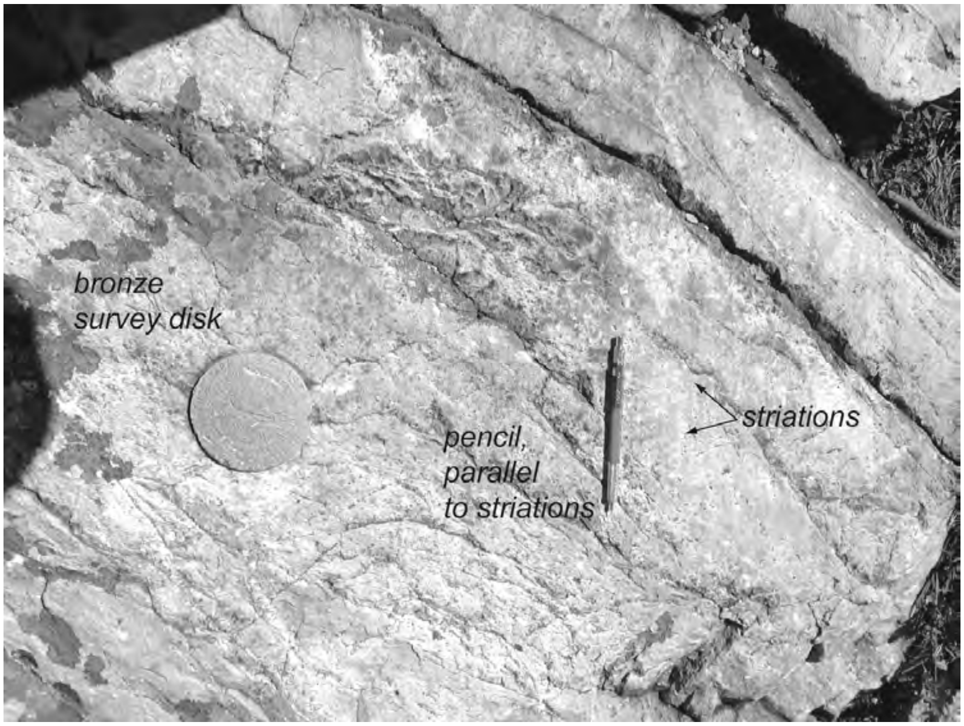

Figure 23. Striations on the Shawangunk Formation just north of the monument. They indicate, with supporting evidence (erratic dispersal, ice-margin geometry, retreat history) that ice of the Kittainny Valley lobe flowed west across Kittainny Mountain.

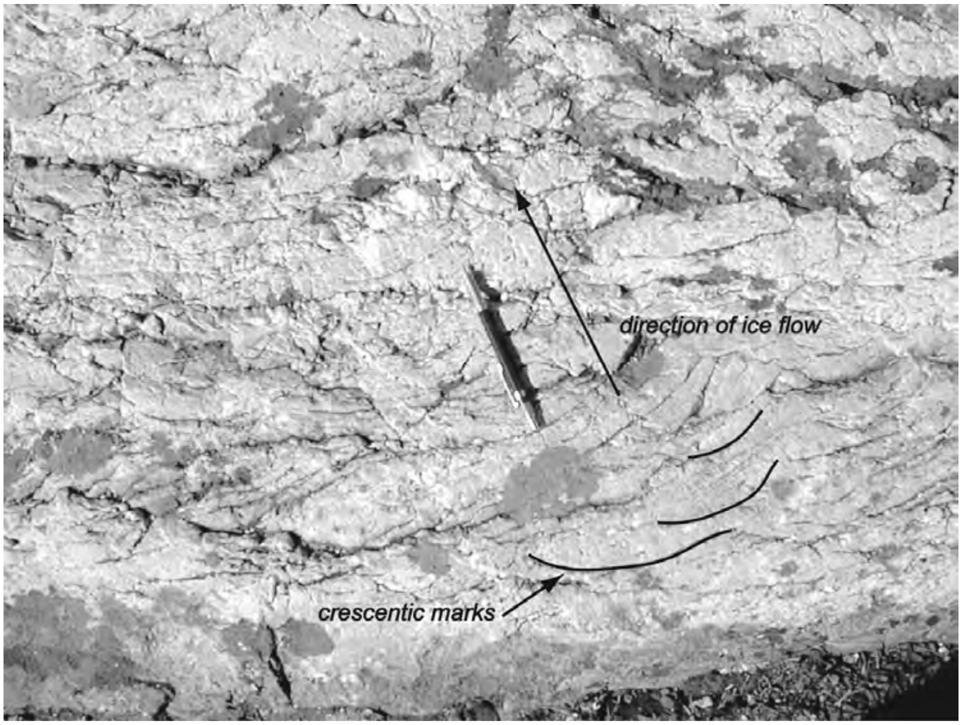

Figure 24. Cresentic marks (a few highlighted on photo) on the Shawangunk Formation just north of the monument. They show a similar direction of ice flow as nearby striations.

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STOP 9: OTISVILLE RAILROAD CUT
An Enigmatic Diamictite; A Tale of Two Unconformities
Leader: Jack Epstein

Note: This mysterious exposure is hiding deep underneath a Shawangunk bedding plane. A camera with a good flash and possibly a strong flashlight would help at this stop. The ground could be soggy after a heavy rain—wear footwear accordingly.

Figure 1. The angular unconformity between Silurian and Ordovician rocks exposed near Otisville, New York. Conglomerate and sandstone of the Shawangunk Formation overlies shales of the Martinsburg with an angular discordance of eight degrees. Photo taken in 1986.

The contact exposed between the Martinsburg formation of Ordovician age and the Shawangunk Formation of Silurian age along the abandoned Erie Railroad at Otisville, NY, is one of the classic angular unconformities in the Appalachian Mountains (Figure 1). This is a classic exposure, discussed by many geologists in the past (Clarke, 1907, Schuchert, 1916, and others) (Figure 2) and visited by the 34th Meeting of the New York Geological Association (Fink et al., 1962). All have recognized the angular discordance in bedding between the Martinsburg (N16°E, 44°NW) and Shawangunk (N36°E, 28°NW). In this area we are in the broad open-fold

Figure 2. Photographs of the angular Unconformity at Otisville, NY, showing stages of erosion at the contact (compare with Figure 1). Left photo from Schuchert (1916, pl. 21; *Contact between the Hudson River Sandy Shales and the Shawangunk…*). Willard (1938, fig. 4) and friends are wondering about the contact in the right photograph, although no comments about what they may seen appear in print. That

Epstein, Jack, 2012, Stop 9: Otisville railroad cut, *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. 354-361.

zone of Taconic deformation (discussed at Stop 10), although these gentle structures are interrupted locally by a faulted overturned fold (see Inners et al., this guidebook).

The uppermost rocks of the Martinsburg Formation are near the Middle and Late Ordovician boundary in age, and the lowest rocks in the Shawangunk Formation are probably Middle Silurian in age (The Shawangunk pinches out about 35 mi (56 km) to the northeast along the unconformity, where Upper Silurian rocks appear above the Ordovician units (Figure3). Thus, the Taconic hiatus in southeastern New York may be 20 to 30 million years, nearly as long as the entire Silurian Period itself. An interesting question is – *what went on during that long period of time?*

Figure 3. Angular unconformity between the south-dipping Rondout Formation (Upper Silurian) and the near-vertical Austin Glen Formation (Ordovician), located on the on-ramp to NY 23 in the northwest corner of Catskill, NY. The angular difference is about 48°.

The Shawangunk is mostly conglomeratic, with quartz pebbles as much as 2 in (5 cm) long. No pebbles from the underlying Martinsburg were seen. The lowest few inches is pyritized. The Martinsburg comprises shale with minor thin graywacke siltstones and contains no obvious secondary cleavage. Between the two formations there is an interval, generally less than 1 ft (0.3 m) thick, of diamictite (a nongenetic term referring to a poorly sorted sedimentary rock with a wide range of particle sizes), clay, and a collection of various rock type, many of which are not like those of the overlying and underlying formations. The clay with its slickensided quartz veins is believed to be tectonic (fault gouge).

Between the solid Martinsburg bedrock and the Shawangunk there is an unusual zone, as much as 1 ft (0.3 m) thick (Figure 4A), containing a poorly sorted and vaguely bedded diamictite. The unit contains angular to rounded pebbles of several different lithologies, as well as clasts from the Martinsburg, in a clay-silt matrix (Figures 4B to D). Bedding is generally poor, but some samples collected from the northeast side of the cut show reasonably decent bedding. There is a sharp contact with the Shawangunk above and also a sharp contact with the Martinsburg below; both are unconformable.

The diamictite is dark yellowish orange and consists of a variety of clasts in a sand-silt matrix. The clasts consist of fragments of the underlying Martinsburg, quartz pebbles (similar to those found in the overlying Shawangunk), and exotic rounded to subangular pebbles (dissimilar to rock types immediately above or below the unconformity). Sorting is poor. In some places it appears that parts of the Martinsburg have been bodily lifted from the underlying bedrock and incorporated in this diamictite.

The pebbles include types foreign to the immediately underlying bedrock. They are composed of fairly clean quartzite, some of which are pyritic, fine-grained protoquartzite and subgraywacke, red siltstone, medium-gray siliceous siltstone, laminated micaceous siltstone, medium dark-gray shale, graywacke, and vein quartz. Many are rounded, some have a thin weathering rind, and others have surfaces that are weathered in relief. The rounded cobbles may have been exposed to the air at one time, weathered, transported, and incorporated in the

Figure 4. A—Diamictite between the overhanging conglomerate of the Shawangunk Formation and shales of the Martinsburg Formation; B, C, and D—Chuncks excavated for the diamictite showing light-colored sandstones, red beds, and dark shales; E—Variety of shapes of the pebbles; F—Some pebbles are rounded, others are angular, such as the slickensided white quartz vein material on the left; G—Sandstones, siltstone, and slickensided vein quartz in a variety of shapes.

diamictite. As a working hypothesis, the origin of the diamictite is a zone of tectonic movement, and/or a poorly sorted sedimentary deposit, i.e., colluviums.

The source for the pebbles are a bit enigmatic. The graywacke pebbles could have been derived from the Martinsburg. The pebbles of quartzite are similar to quartzites fairly high up in the Shawangunk, but obviously the Shawangunk could not have been the source of the pebbles. The dirtier sandstones, red sandstone and siltstone, as well as the quartzite pebbles, may have come from the Quassaic Formation of Waines (1986) of the Marlboro Mountains, presently 5 to 15 mi (8 to 24 km) east of the Taconic unconformity. The age of the Quassaic is somewhat speculative, but it probably ranges from lower Martinsburg through the Upper Ordovician (Waines, 1986), so some of it, at least, could have supplied the pebbles and cobbles to the deposit. Similar rocks are found in Little Mountain in the Friedensburg quadrangle of eastern Pennsylvania, between the Susquehanna and Lehigh Rivers, as well as possibly at the Spitzenberg a bit farther northeast. Some possible problems remain: (1) the shape of the pebbles suggests short transport, but similar rocks are not presently found in the Martinsburg immediately below; (2) the possible source terrane for these pebbles was probably not similar to the one which supplied the graywacke sandstone presently in the Martinsburg; and (3) few (if any) of the pebbles like those described are found in the conglomerates of the immediately overlying Shawangunk Formation.

Evidence for shearing in the diamictite, suggesting some fault movement is plentiful (Figure 5). The occurrence of angular slickensided vein quartz fragments that are oriented in all directions within the diamictite presents a problem in interpretation. The fact that the gouge and quartz veins are found uniquely between the Martinsburg-Shawangunk contact suggests that the movement is post-Taconic, probably Alleghanian, in age. The exotic rounded pebbles unconformably overlie the Martinsburg and unconformably underlie the Shawangunk. It is therefore post-Martinsburg and pre-Shawangunk in age, a product of Taconic uplift. The problem is that angular fragments of vein quartz (Alleghanian?) could be incorporated within the diamictite if it were of Taconic age. The resolution to this dilema may be that there has been multiple movement along the fault at the Shawangunk-Martinsburg contact, and that these weird rocks are a composite deposit, made up of both Taconic colluvium and fault breccia. Therefore, the angular fragments of vein quartz were incorporated in the colluvium during later fault movement. Alternatively, the fragments of vein quartz could have been derived from vein quartz produced during Taconic faulting and incorporated in the colluvium as sedimentary clasts.

Another puzzlement is that the colluvium, if that is what it is, contains many disoriented clasts of slickensided vein quartz. This indicates fault movement prior to incorporation in the colluvium. Possibly the Martinsburg nearby was faulted and slickensided during Taconic deformation and the slickensided fragments were later incorporated in the colluvium. Another possibility is that the diamictite is a fault gouge and not a colluvium, and there has been several periods of movement, the latest one of which fractured earlier slickensided rocks. The problem with this interpretation is that it does not account for the exotic pebbles nor does it explain the lack of foliation in the diamictite.

The area around Otisville in the Late Ordovician was not glaciated as was North Africa during the well-known Hirnantian Gondwanaland glaciations. However, sea level was undoubtedly lowered, which somehow may come into the picture of the occurrence of the diamictite. Maybe not. What do you think?

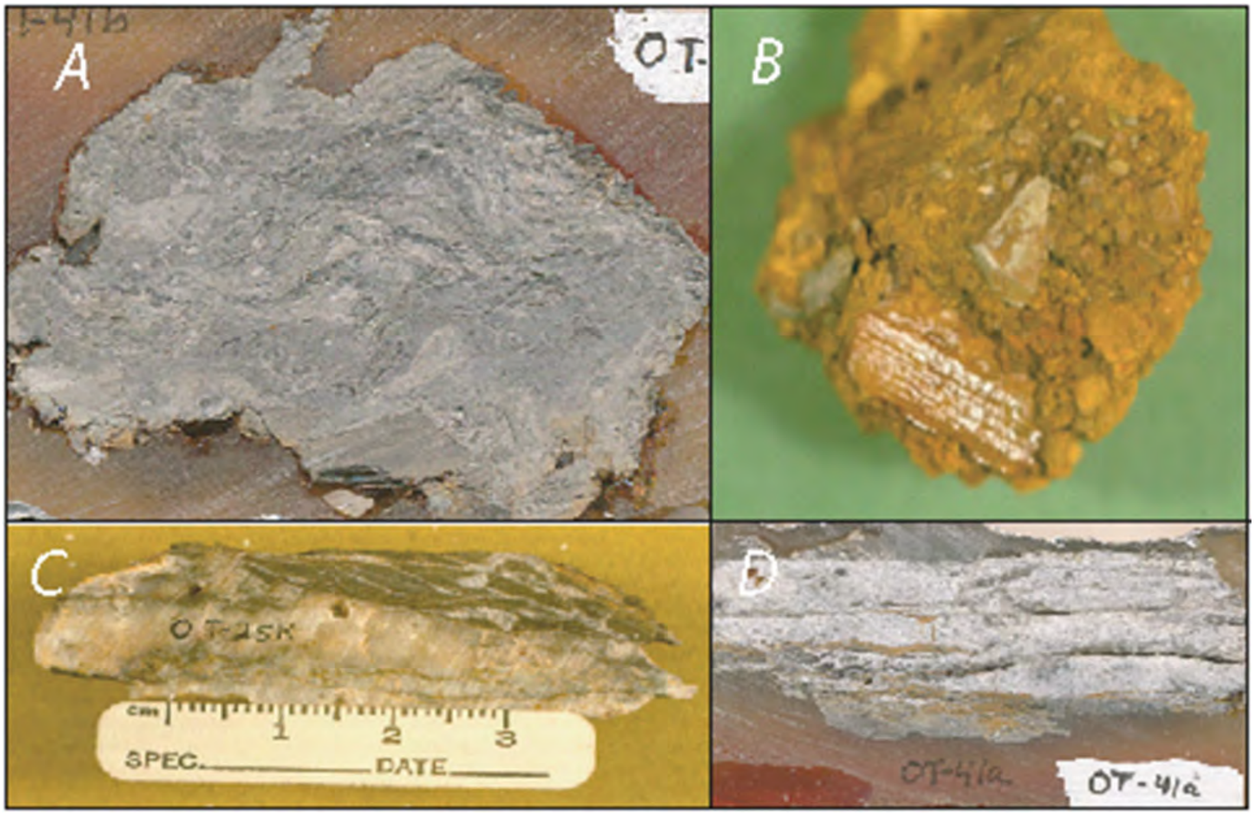

Figure 5. Many rocks in the diamictite contain evidence for shearing within the unit. A—Convoluted clay gouge scattered through the unit; B—Slickensided rock fragment; C—Sheared quartz vein and shale (Martinsburg-derived?); D—Sheared quartz and shale.

The clay within the zone between the Martinsburg and Shawangunk occurs as discontinuous light bluish-gray layers that have been weathered to moderate red and grayish orange. The clay is internally folded and contains both continuous and disrupted quartz veins. In places, closely spaced fractures extend down from the clay into the underlying bedrock. In other places the lowest few millimeters of the Shawangunk is sheared (see Figure 6D). At the inconformity exposed along NY 17 south of Wurtsboro, NY, (south of mileage 102.7, Day 2 Road Log). the upper few inches (centimeters) of the Martinsburg is rotated. The clay is clearly a fault gouge. The vein fragments are slickensided, indicating repeated movement along the zone. Angular Martinsburg fragments are also found in the gouge, presumably incorporated during fault movement.

One question that needs to be asked is why the clay in the fault gouge has remained a sticky clay, whereas surrounding rocks have been lithified? The answer may be that the contact is a zone of alteration. This area of the Shawangunk Mountains contains several abandoned lead-zinc mines and there are many prospects and mineralized localities throughout the area. The lower few inches (centimeters) of the Shawangunk here at Otisville is similarly altered.

I do not believe that this total deposit is a fault breccia, because there does not appear to be a foliation in it, although it may have been affected by movement to some degree. It looks more like a product of mass wasting, that is, a colluvium. Moreover, it contains a large variety of pebbles, which could have only been brought in as a sedimentary deposit.

These data add an interesting hitherto unrecognized chapter to Late Ordovician paleogeography in the central Appalachians. It seems likely that following the deposition of the marine Martinsburg shales and graywackes, the Martinsburg was uplifted during the Taconic orogeny. But later as the Martinsburg surface was subaerially exposed, diamictic colluvium was spread out on the exposed surfaces, and exotic pebbles and cobbles were incorporated in the diamictite. Much of this material was subsequently removed during pre-Shawangunk erosion and only scattered occurrences remain. The clasts were derived from a source that is no longer exposed nearby. The only evidence for that source is from the few pebbles that we have found. It might be suggested that thrusts brought these exotic rocks close to the site of deposition, and that thrusts sheets were subsequently eroded. If this is true, these thrusts must have been Taconic in age. These deposits were later covered by conglomerates and sandstones of the Shawangunk Formation during Middle Silurian time. These "weird rocks" indicate a fairly complex geologic history that has not been previously considered. WHAT DO YOU THINK?

Mullions at the Base of the Shawangunk

"Mullion" is an architectural term borrowed by structural geologists to describe elongate fold-like or prism-like forms developed at the boundary between rocks of different mechanical properties. They may be very regular in spacing and geometry and extend for considerable distances, or they may be irregular and short. They may originate by differential folding of rocks of contrasting properties or by disruption of competent rocks along foliation that is well developed in surrounding less competent rocks. They may be either parallel or perpendicular to the structural transport direction. These characteristics are discussed in many structural geology texts.

The basal surface of the Shawangunk at Otisville is irregular, with downward-projecting mullions with a general wave-like form. They have a relief of about 2 in (5 cm) and are about 3 in (8 cm) to 2 ft (0.6 m) apart (Figure 6). These have a general trend of N32^{o}E, about parallel to the strike of the beds and perpendicular to the regional transport direction. In a few places faint slickenlines trend about perpendicular to the trend of the mullions. Note that these mullions are found only at the Martinsburg-Shawangunk contact and are not found on any surface higher up in the section. The basal 1 in (2.5 cm) of the Shawangunk is sheared parallel to bedding (Figure 6D).

Alternative interpretations have been made of these features. Waines and Sanders (1968) believed that the clay at the contact is a paleosol. Lukas et al. (1977) and Waines et al. (1983) interpreted the clay as a hydrothermally altered Silurian shale and certain structures at the base of the Shawangunk as runnels produced by backflow on a beach. I do not believe that they formed on a beach face because they are found only at the Martinsburg-Shawangunk contact, a boundary of extreme mechanical disharmony (they are not seen at the bases of beds elsewhere in the Shawangunk) and their trend is not parallel to current directions indicated by trough crossbedding . I interpret the Shawangunk as a fluvial (braided stream) deposit, not a beach deposit (Epstein, 1993). In eastern Pennsylvania, Lehigh Gap, Stop 3, a similar clay layer to the one here is found between the Ordovician shales and graywackes and the Silurian quartzites and conglomerates (Stops 1, 3, and 5). Liebling and Scherp (1982) believe that this layer in Pennsylvania is a separate stratigraphic unit, in contradiction to the fault gouge hypothesis of Epstein et al. (1974).

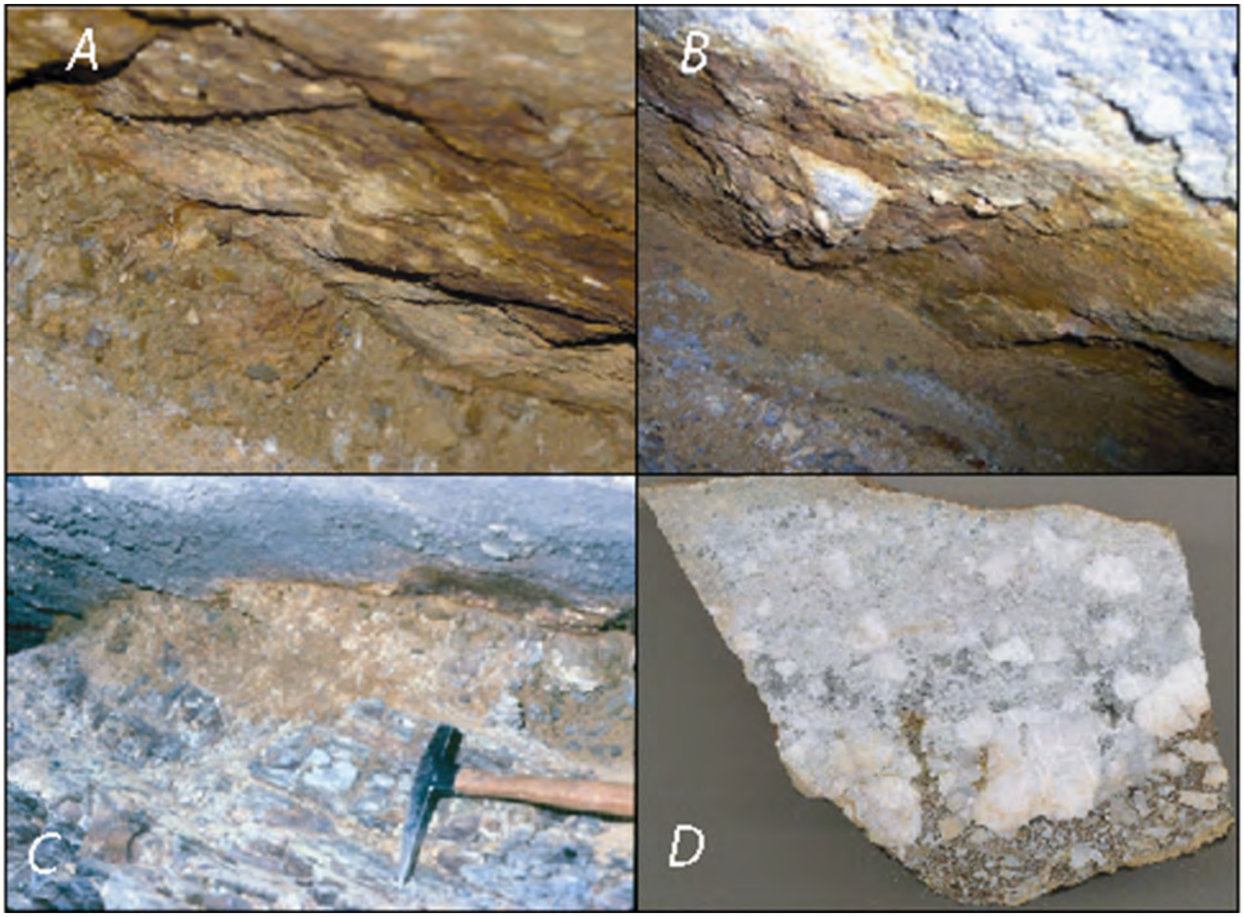

Figure 6. Downward-projecting structures at the base of the Shawangunk at Otisville New York. A—Downward "bumps" on the lowest bed of the Shawangunk Formation. These have a relief of a couple of inches (centimeters); B—Faint slickensides at right angles to the trend of the mullions. Some of the shales of the Martinsburg at the bottom appear to have been bodily lifted into the diamictite; C—The trend of the mullions heading to the upper left is apparent; D—Sawn sample of a mullion (50 mm wide) showing fractured and brecciated quartz pebbles in the lower 30 mm. Clearly, the base of the Shawangunk has been faulted.

Mullions were seen at the base of Shawangunk Formation at seven localities in southeastern New York, not only at Otisville. These are: I-84 south of Port Jervis; in a prospect near Guymard, NY; along NY 17 south of Wurtsboro; in the abandoned railroad tunnel just south of NY 17; along the gully just east of the prison at Naponoch; and a few hundred feet (meters) south of NY 55/US 46 (the "Trapps" of Waines et al., 1983). They were also seen in New Jersey (mileage 54.5, Day 2 Road Log). Between the solid Martinsburg bedrock and the Shawangunk there is an unusual zone, as much as 1 ft (0.3 m) thick, containing light-gray to light-bluish gray clay gouge with slickensided quartz veins. This gouge, and the associated mullions in the overlying conglomerates, are typical of most Martinsburg--Shawangunk contacts exposed in southeastern New York and shows that the unconformity is also a plane of movement, the displacement along which is not known.

The Holocene Angular Unconformity

What about that other unconformity at this location? While facing the Shawangunk-Martinsburg unconformity, look behind you and you will see the Shawangunk (dipping to the left) in an obducted unconformity with a flat-lying, blocky Holocene formation, probably deposited about 1846 when the Erie Railroad came to Otisville (Figure 7).

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STOP 10: ELLENVILLE ARCH
Taconic Deformation Zones
Leader – Jack Epstein

This stop will demonstrate: (1) zones of Taconic deformation; (2) more severe post-Taconic deformation than Taconic deformation in Ordovician rocks west of "Ruedemann's Line Ruedemann (1930; see Figure 5 on p. 13 of this guidebook); (3) the age of the later deformation is Alleghanian; (4) Alleghanian deformation along the Taconic unconformity decreases in intensity from Pennsylvania into southeastern New York; 5) the regional slaty cleavage in this area, where present, is Alleghanian in age; (6) the strike of Taconic structures is more northerly (by as much as 20^{o}) than Alleghanian structures; and (7) more intense, later, Alleghanian deformation overlaps the earlier Alleghanian deformation in the eastern part of the area. The following discussion is from Epstein and Lyttle (1987). I wish to acknowledge the work that Peter Lyttle added to this effort in the understanding of Ordovician structures in southeastern New York.

Taconic Tectonic Zones

Compilation of the subsurface geology in the Delaware aqueduct tunnel (Figure 1), and comparison with surface exposures in southeastern New York, allows us to identify tectonic deformation zones of Taconic age (Figure 2). These zones strike about N10-20^{o}E and progressively emerge to the southwest along the contact with the overlying Shawangunk Formation. The structure is more complex to the east. The zones are, from west to east: (1) zone 1 which has broad open folds in slight angular unconformity with the overlying Shawangunk Formation; (2) zone 2 that is a belt of less severe folds and faults with bedding in

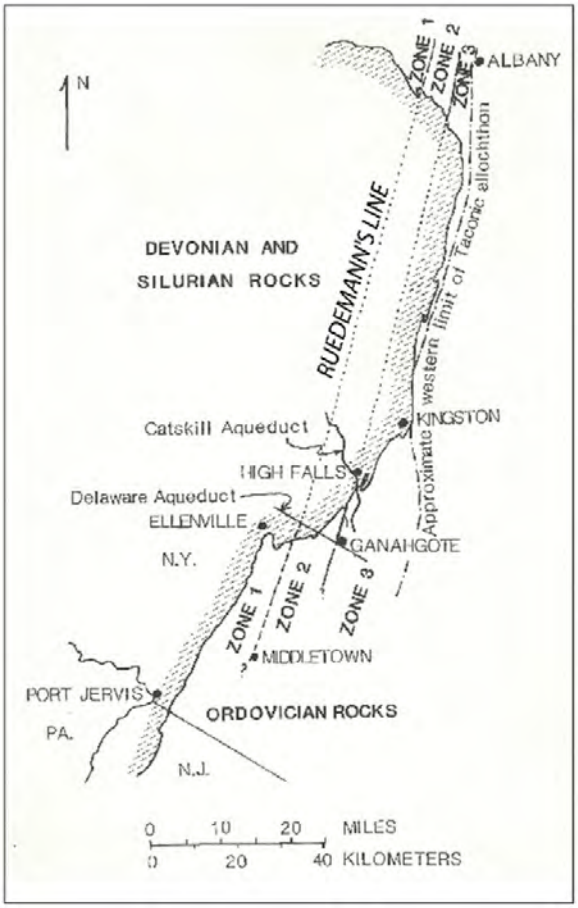

Figure 1. Map of southeastern New York showing the Taconic tectonic zones within the parautochthonous flysch, the boundary of overlapping Devonian and Silurian rocks, and the approximate western limit of allochthonous rocks of the Taconic allochthon. The zone boundaries are dotted beneath the Devonian and Silurian rocks. ZONE 1—Broad open folds; ZONE 2—Tight folds and thrust faults; ZONE 3—Overturned folds, thrust faults, and melanges. Faults and some overturned folds are found in zone 1, and some areas of open folds are found in zone 3. Zones in the Albany area are from Vollmer (1981) and Bosworth and Vollmer (1981).

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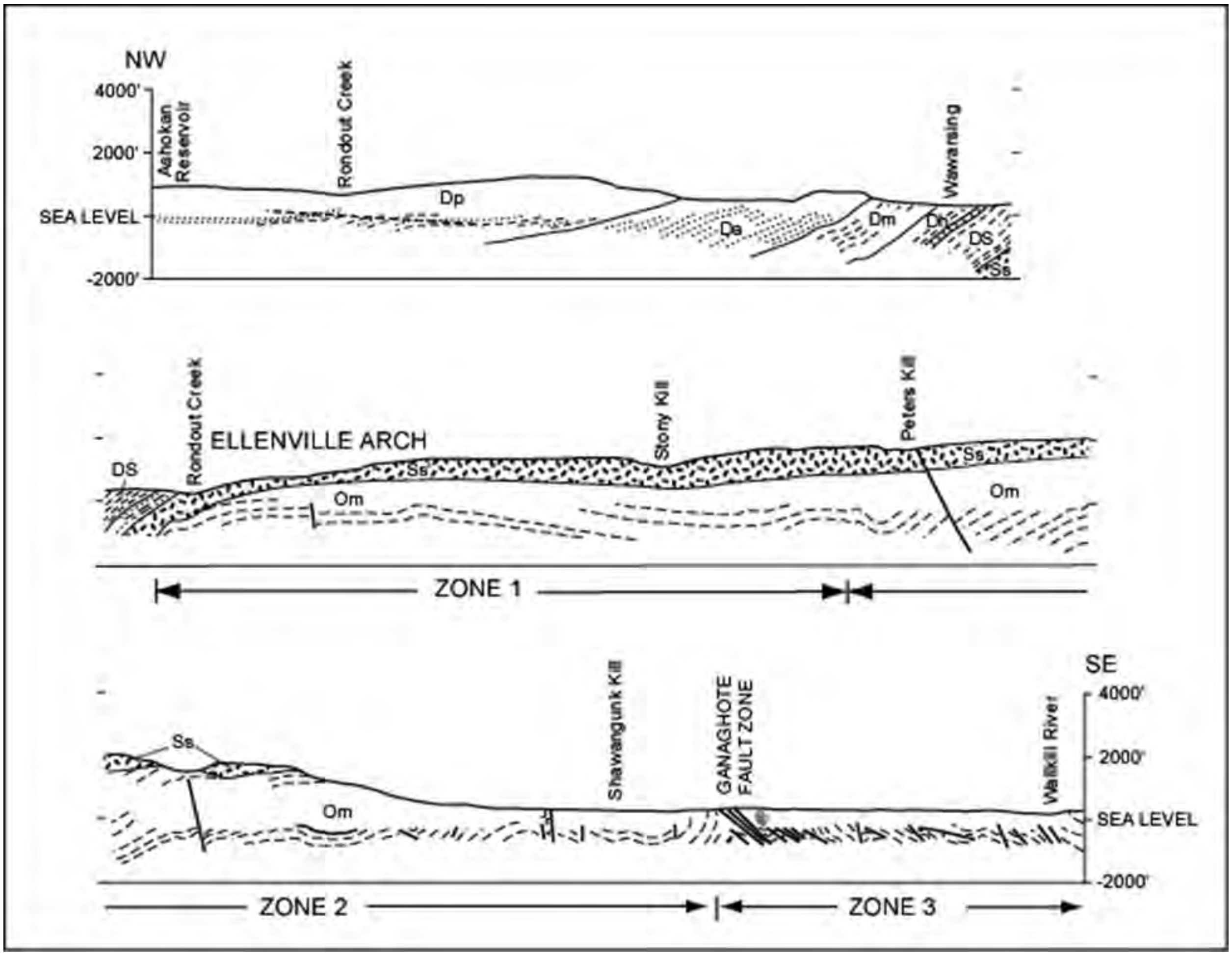

Figure 2. Cross section along the Delaware Aqeduct from the Ashokan Reservoir, through Wawarsing, to the Wallkill River (see Figure 1 for location), showing location of the Taconic tectonic zones and the Ellenville arch. Dp—Plattekill Formation; Da—Ashokan Formation; Dm—Mount Marion Formation; Dh—shales and siltstones of the Hamilton Group; DS—Onondaga Limestone through the Binnewater Sandstone; Sm—High Falls Shale, Shawangunk Formation, and tongues of the Shawangunk Formation and Bloomsburg Red Beds; Om—Martinsburg Formation. From surface mapping and underground data modified from the Delaware Aqueduct (New York City Water Board, unpub. data, 1945).

high angularity with overlying Silurian rocks; and (3) zone 3 with thrusts, steep dips, overturned folds, and melange.

Many melanges have been mapped in the Ordovician rocks of the Hudson Valley. These structures are definitely Taconic because in places the Silurian rocks truncate the scaly cleavage in them. The Taconic thrust faults that produced these melanges are abundant to the southeast of the unconformity and appear to become rarer as the unconformity is approached. The contact between zones 1 and 2 may be the extension of Ruedemann's Line which trends southerly and is overlapped by Silurian rocks southwest of Albany (Bosworth and Vollmer, 1981). This line passes under the Catskill Plateau and emerges from beneath the Shawangunk Mountains about 5 mi (8 km) east of Ellenville (Figure 1). To the east of zone 1 lie the complex structural terrane of the Taconic klippen. To the west of zone 3, such as in central Pennsylvania, angular unconformity gives way to a conformable Ordovician-Silurian sequence, and orogenic uplift is reflected only by the Taconic clastic wedge.

Ignoring for the moment all faults and folds of Taconic age, the structure of the Martinsburg belt in eastern Pennsylvania can be characterized as a northwest-dipping sequence. The oldest member is always on the south side of the Great Valley and the youngest on the north side. Lyttle and Epstein (1987) show that this monoclinal sequence is actually the north limb of a very broad anticline that involves rocks as far south as the Pennsylvania Piedmont and that this structure is probably Alleghanian in age. Going northeastward into New Jersey the middle member of the Martinsburg is found in the trough of several smaller scale synclines, but still the very broad and general structure is one of a northwestward-dipping monocline. In southern New York State, the Wallkill Valley has long been recognized as a very broad open anticline (e.g., Offield, 1967; Kalaka and Waines, 1986). Many of these faults cut Silurian rocks and we interpret them to be Alleghanian in age.

Post-Taconic Structures: Relative Effects of Alleghanian and Taconic Deformation

The tectonic effects in rocks above and below the Taconic unconformity in the central Appalachians has been the subject of considerable discussion and debate ever since the unconformity was recognized by H. D. Rogers (1838). Peter Lyttle and I have been mapping selected areas along 120 mi (193 km) of the unconformity from eastern Pennsylvania through New Jersey, and into southeastern New York, such as at many of the Stops in this guidebook. We have chosen areas where exposures are abundant enough to be able to determine structural relations in rocks on both sides of the contact.

In general, going from Pennsylvania to New York, structures become simpler, from highly faulted and folded at Hawk Mountain, just east of Stop 1, where the Tuscarora Formation rests on both the Martinsburg Formation and rocks of the Hamburg klippe, to overturned and faulted rocks at Lehigh Gap (Stop 3), to oversteepened folds at Delaware Water Gap (Stop 4), and upright to slightly overturned folds at High Point, NJ (Stop 8), and finally into a fairly simple arch at Ellenville, NY. Slaty cleavage in both Ordovician and younger rocks is common, particularly in the southwestern part of the study area.

The geology of the area near Ellenville, where Alleghanian and Taconic structures are relatively simple, is an excellent place to distinguish the effects of Taconic and later deformations. The Ellenville arch is a northeast-plunging fold with a half wavelength of about 4.2 mi (6.8 km). Folded rocks include the Martinsburg in the Great Valley, the Shawangunk in the Shawangunk Mountains, and rocks of Silurian and Devonian age in the Rondout Valley and Catskill Plateau (see Appendix 2 on p. 32 of this guidebook). The broad arch is prominent in exposed cliffs of the Shawangunk Formation in the Ellenville area (Figure 3). The shales and

Figure 3. Google image showing the fold outlined by cliffs in the Shawangunk Formation. The fold plunges to the northeast, where in about 30 mi (48 km) the formation pinches out. The conglomerates and the sandstone of the Shawangunk form dip slopes so that the topographic maps are essentially structure contour maps.

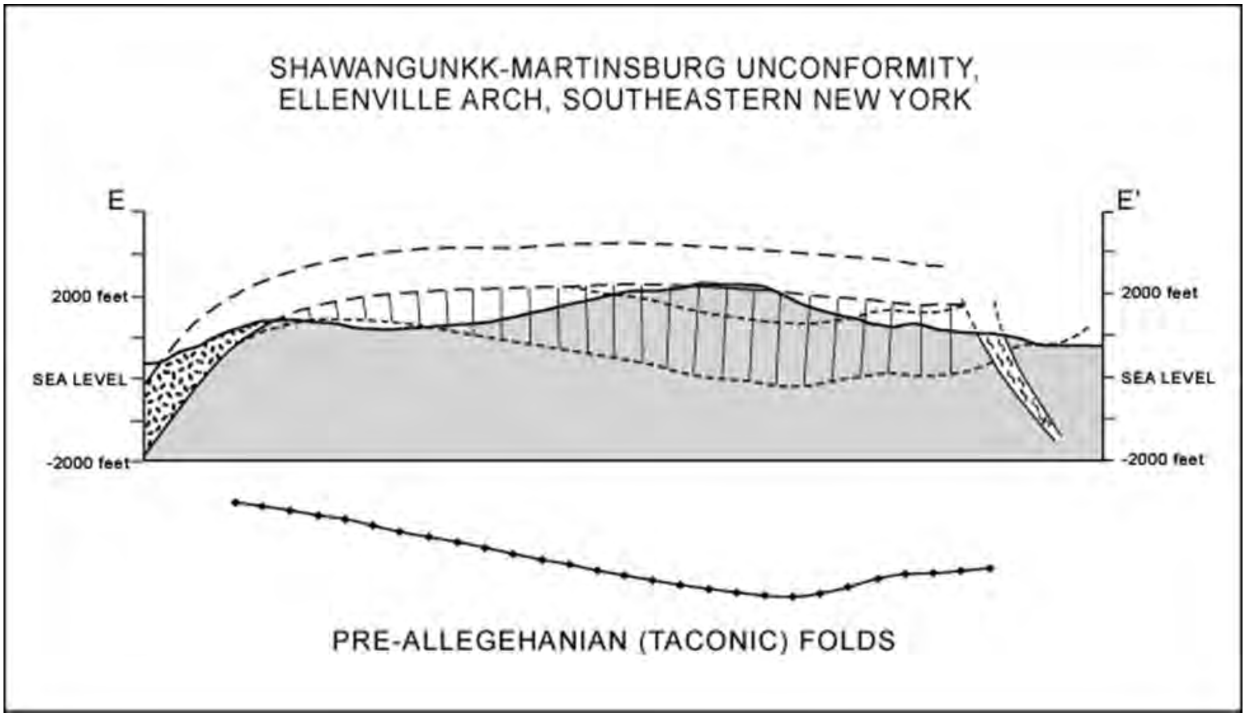

Figure 4. Cross section through the Ellenville arch east of Ellenville, showing the angular unconformity between the Shawangunk Formation (dotted) and the Martinsburg Formation (shaded), and the different position of the fold crest in the two units. By measuring the orthogonal distance between the base of the Shawangunk and a marker bed in the Martinsburg (near vertical lines), we can reconstruct the configuration of Taconic folds In the Martinsburg, shown on the lower part of diagram. See Figure 5 for location of cross section.

graywackes of the Martinsburg are fairly well exposed, and they rarely exhibit slaty cleavage in this area. We are therefore able to draw an accurate cross section which shows that the crest of the arch differs in position in the Martinsburg and in the Shawangunk (Figure 4). It is clear that this geometry is the result of the folding of an unconformable sequence. If we unfold the folds in the Shawangunk, we can reconstruct the pre-Alleghanian folds in the Martinsburg on the bottom of the diagram. Note that the Ellenville arch has been eliminated and we are left with only a broad syncline, Taconic in age.

A second type of reconstruction was prepared by rotating bedding in the Shawangunk back to horizontal using a stereo net and determining the retrodeformed Taconic attitudes in the Martinsburg. Figure 5 shows the position of the Alleghanian Ellenville arch. The heavy lines are isogons showing angles of dip and dip directions in the Shawangunk. These isogons were used to determine the amount of rotation necessary for the Martinsburg structural readings. The dips shown in the Martinsburg are these retrodeformed dips, that is, the Alleghanian folding has been eliminated. Therefore, this is a composite map, showing Alleghanian structure in the Shawangunk and Taconic structure in the Martinsburg. Note that the rotated beds in the Martinsburg dip consistently and gently to the southeast in the western part of the area and that the Ellenville arch has disappeared. The fold axes in the Martinsburg are thus Taconic in age. Also note that east of the Lake Awosting deformed zone, beds in the Shawangunk, shown by the isogons, strike ENE (average N76°E), but that the Martinsburg underneath strikes more northerly by about 16° (averages N60°E).

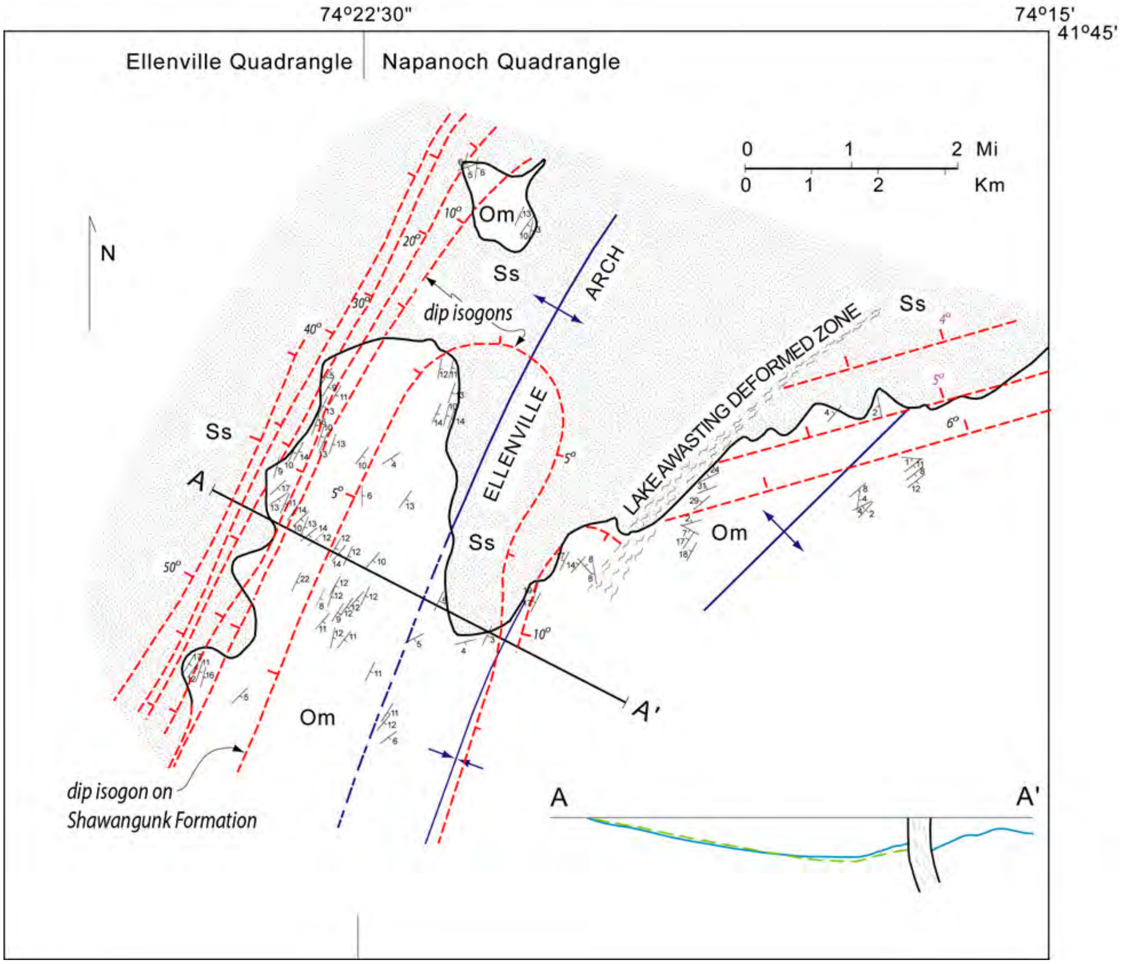

Figure 5. Geologic map of parts of the Ellenville and Naponoch 7.5-minute quadrangles (from Epstein and Lyttle, 1990) showing the unconformable contact between the Shawangunk Formation (Ss) and the Martinsburg Formation (Om), and lines of equal dip (dip isogons, red) in the Shawangunbk (solid lines on present bedding surfaces and dashed lines where the Shawangunk has been removed by erosion). In the cross section A-A' the solid blue line shows dips in the Martinsburg rotated to eliminate the Alleghanian folding shown by the dip isogons and the dashed green line shows retrodeformed Taconic structures derived from the construction of pre-Silurian folds from the exercise in Figure 4.

Using the data shown in the map, a cross section that is similar to the one shown in Figure 4 was constructed (section A-A', Figure 5). The solid line is a cross section showing bedding derived from our stereographically rotated Martinsburg. Note that it agrees almost perfectly with the pattern derived from the simple unfolding of the cross section shown in Figure 4, the dashed line. It seems clear that Taconic folds in this area are broad and open, and the Ellenville arch is a later structure superimposed on the Taconic folds.

Figure 6 shows equal area plots of bedding in the Shawangunk, in the Martinsburg, and in the stereographically rotated Martinsburg. The girdle in the Shawangunk defines a fold whose axis plunges 5°, N32°E. The Martinsburg trends, as we see them now, are more northerly, by about 10°, than trends in the Shawangunk. Interestingly, when the retrodeformed Martinsburg bedding is plotted, the Taconic folds plunge to the southwest. Therefore, we conclude that Taconic folds trend more northerly than Alleghanian folds in this area, and plunge in the

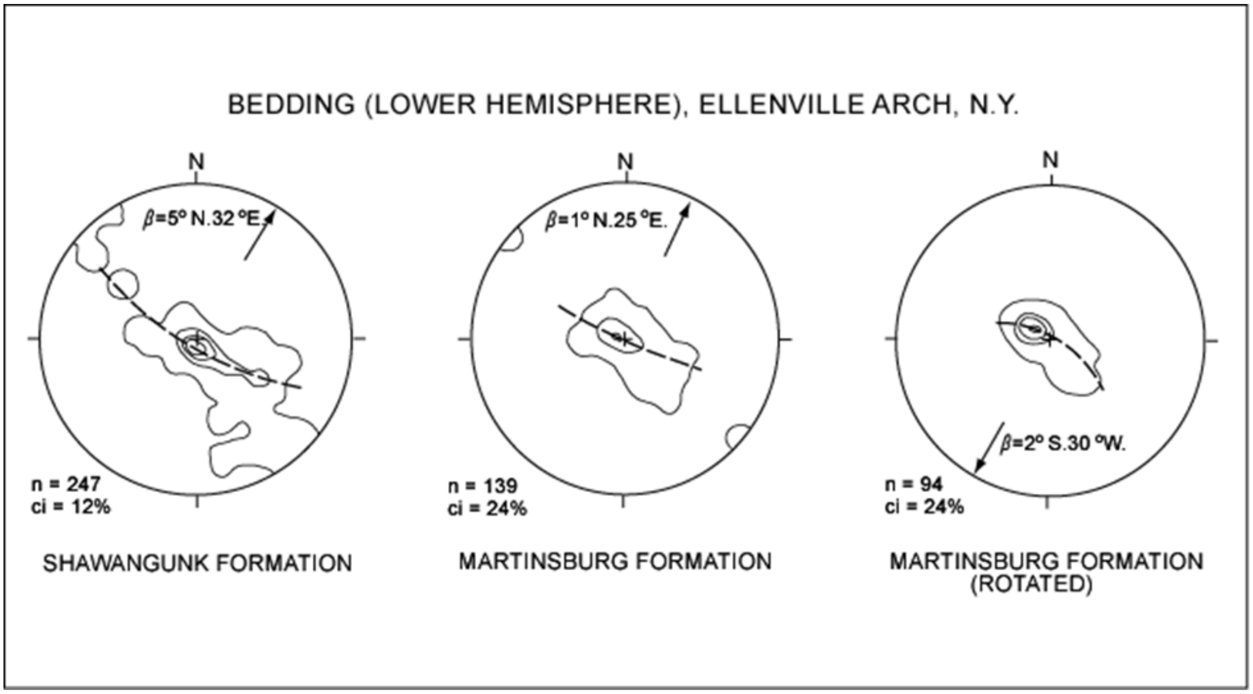

Figure 6. Equal-area projections (lower hemisphere) of the present attitudes of bedding in the Shawangunk and Martinsburg Formations in the area shown in Figure xx, and the bedding in the Martinsburg that has been rotated so as to eliminate the effects of the Ellenville arch.

opposite direction. Thus, in the Ellenville area, we have been able to distinguish Taconic from Alleghanian folds, both in amplitude and trend.

From the data presented above, and from other considerations (Epstein and Lyttle, 1986, 1987), we draw the following conclusions for the area from Ellenville to northeastern Pennsylvania near the Taconic unconformity:

1) With only a few exceptions, the Shawangunk and equivalent Tuscarora Formation east pof the Schuylkill River (Stop 1) overlie the Martinsburg Formation with an angular unconformity that ranges between an angle that is barely discernible, to about 15^{o}.
2) The dominant regional folding in all rocks along the contact is Alleghanian in age.
3) The regional slaty cleavage is Alleghanian in age.
4) Taconic folds in the Martinsburg Formation below the unconformity are mostly broad and open along the entire 120 mi (193 km) length of the contact that we have studied southwest of Ellenville. To the north in zones 2 and 3 the structures become more intense and the angular disparity between beds above and below the unconformity is greater.
5) The strike of Taconic structures trend a bit more northerly (by about 3^{o} to 20^{o}) than later structures.

Age of Post-Taconic Deformation

The following are thoughts that Peter Lyttle (mostly him) and I had about Acadian vs Alleghanian deformation in the Shawangunk Mountains where we mapped (Epstein and Lyttle, 1987). We haven't thought about it since then and the information may be a bit outdated, but here it is for whatever it is worth.

Was the entire sequence of rocks exposed in the field trip area affected by Acadian or Alleghanian deformation, or both? Marshak (1986, p. 366) gives a succinct summary of the controversy. An Acadian age was favored by Woodward (1957), Ratcliffe et al. (1975), and Murphy et al. (1980), based on the age of the youngest rock that has been deformed.

Structures in Early Devonian and Upper Silurian rocks were believed to be Acadian in age by Chadwick (1908) and Woodward (1957) because these structures were thought to be different in style and trend from structures known to be Alleghanian in age in Pennsylvania. On the other hand Sanders (1969), and Geiser and Engelder (1983) argued that secondary structures could be traced from Pennsylvania into New York, and the structures in the Hudson Valley area are Alleghanian in age. An Acadian age was inferred by Ratcliffe et al. (1975) and Sutter et al. (1985) from dating of cleavages east of the Hudson River. We favor an Alleghanian age for the following reasons:

1) The Ellenville arch is a structure at the northeast end of a series of structures that extend from tight folds with abundant faults in east-central Pennsylvania, through tight folds with less-abundant faults in easternmost Pennsylvania, through upright folds in New Jersey, and into simple folds and monoclinal dips in southeastern New York. Since these folds in Pennsylvania involve rocks of Pennsylvanian age, the Ellenville arch is therefore believed to be Alleghanian in age. In New York rocks at least as young as the Plattekill Formation of Middle Devonian age are affected by the arch. Possibly even younger rocks, now eroded away, were involved in the folding. To the east in New England the age of Acadian intrusion and deformation is generally believed to be Middle Devonian in age (Naylor, 1971). Clearly the Ellenville arch is a post-Acadian structure.
2) The structures of the Hudson Valley trend in the Silurian and Devonian rocks in the Kingston area (Marshak, 1986) may extend southwest into structures that we have mapped in the Shawangunk Mountains of the field trip area. We believe that these structures cross cut and post-date the Alleghanian Ellenville arch, and therefore formed during a later Alleghanian event. A possible example of one of these later structures in the field trip area is the Bonticou thrust.
3) Many workers have suggested that the youngest rocks that have been folded or faulted are in the Hamilton Group, thus limiting the time of deformation to Middle Devonian (the Acadian orogeny). Two such fault zones are discussed by Epstein and Lytlle (1987, road log mileage 0.3). One is in the Bakoven Shale on NY 28 just northwest of Kingston, NY, noted by Pedersen et al. (1976, p. B-4-21). The fault zone is more than 5 ft (1.5 m) thick and consists of crumpled and slickensided black shale with abundant quartz veins. The slickenlines and verging of the folds indicate that the overriding beds moved to the northwest. At 2.1 mi (3.4 km) northeast of that fault is a fault duplex about 5 ft (1.5 m) thick, slightly higher in the section in the Mount Marion Formation. Slickensides in the duplex indicate that the overriding beds moved N70^{o}W. Pedersen et al. (1976, p. B-4-6, 7, 22, 23) consider these structures to be soft-rock "pull aparts". However, a 1-ft (0.3-m) thick sandstone bed is deformed into mullions and is surrounded by slickensided surfaces and sheared shale. Tectonic shortening is estimated to be 50 to 60 percent, judging from the overlapping of the mullions.

   Similar faults have been reported in equivalent rocks in central New York as much as 100 mi (161 km) west of Albany (Schneider, 1905; Long, 1922, Rickard, 1952, Bosworth, 1984a, b). Thus, there is evidence for detachment within Middle Devonian shales under the rocks of the Catskill Plateau. Bosworth (1984b) suggested that this movement may be linked to detachment in Salina salt under the Appalachian Plateau of central New York and Pennsylvania, described earlier by Prucha (1968) and Frey (1973). Bosworth placed no age constraints on the age of this movement, except to say that it is post-Middle Devonian, and could be Acadian or Alleghanian. If it is linked to the Salina horizon, and all the rocks of the Catskill Plateau have moved on this decollement, then an Alleghanian age would be indicated.

Similar fault horizons are found in rocks even higher than the Middle Devonian shale interval. For example, one such fault was discussed by Pedersen et al. (1976, p. B-4-16). It is in the Plattekill Formation, located in the Woodstock 7.5-minute quadrangle, along NY 28, 7 mi (11 km) west of Kingston. The fault zone is a duplex about 2 ft (0.6 m) thick in which slickenlines, the verging of folds, and overlapping of structural blocks indicates translation of the overlying beds towards N23^{o}W. Well-developed cleavage is found just below the fault. All these data suggest that there has been movement of rocks of the Catskill Plateau above the Hamilton shale horizon as well as within younger rocks. Perhaps many more similar faults zones are waiting to be discovered. If the structures within the Hamilton shales really mark the limit of Acadian deformation, as a number of geologists have suggested, then younger rocks should lie on the Hamilton with angular unconformity. So far as we know, no evidence for such an unconformity has ever been presented. If one recognizes structures such as small thrust zones or detachment horizons within the Hamilton shales, and does not see this sort of structure in any overlying unit, it is meaningless to say that the Hamilton is the youngest unit affected by these structures. There is plenty of evidence to suggest that these structures formed when the rocks were at least partially lithified. Therefore, some rocks younger than the affected beds must have been present and were transported to the west in the overlying block or thrust sheet. Thn important generalizations about the ages of regional deformations are being made.

4) Lineaments, which have a trend of about N.20^{o}E. are very apparent on radar imagery and topographic maps. They extend northward into rocks as young as the Plattekill Formation of Middle Devonian age and probably extend into the Oneonta Formation of Late Devonian age. They also parallel faults that we have mapped in the Shawangunk Mountains to the south. In the Catskill Plateau, they are aligned along valleys, which preliminary investigations suggest are controlled by minor faulting and very closely spaced joints. The structures that cause these lineaments are post-Acadian in age, since they cut Upper Devonian rocks. The parallelism with the faults in the Shawangunk Mountains suggests, but does not proves an age equivalence.
5) Finally, the Acadian orogeny in New England involved deformation, metamorphism, pluton emplacement, and uplift. Dating of the late orogenic plutons places a minimum date of 380 million years (middle Middle Devonian) for the orogeny (Naylor, 1971). Therefore, Acadian deformation ceased by at least the time that the basal part of the Hamilton Group (Bakoven Shale) was being deposited, if not sooner. Thus, the response in the field trip area to Acadian deformation going on to the east was subsidence to form a basin in which Hamilton sediments were deposited. This was followed by shoaling and finally terrestrial deposition ("Catskill Formation") as the Acadian mountains to the east were uplifted. Acadian folding may never have extended as far west as the field trip area! Faill (1985)

likewise suggested that evidence for Acadian deformation of rocks in the Catskill depositional basin are either absent or ambiguous, at best. Catskill sediments are the result of Acadian orogenic uplift, and were not deformed during Acadian tectonism. Faulting in the Plattekill and Hamilton must therefore be the result of later (Alleghanian) deformation. This suggests that the flat-lying and gently dipping rocks of the Catskill Plateau may lie with fault contact on the highly deformed Upper Silurian and lower Middle Devonian rocks of the Hudson Valley. Alternatively, the severe deformation of these Silurian and Devonian rocks may not have extended as far west as the present Catskill front (Marshak, 1986, p. 366).

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Y'know, with all the stuff that's going on in the world, including the length and complexity of this guidebook, I'm inclined to believe him!