

# Geology of the Delaware Water Gap Area

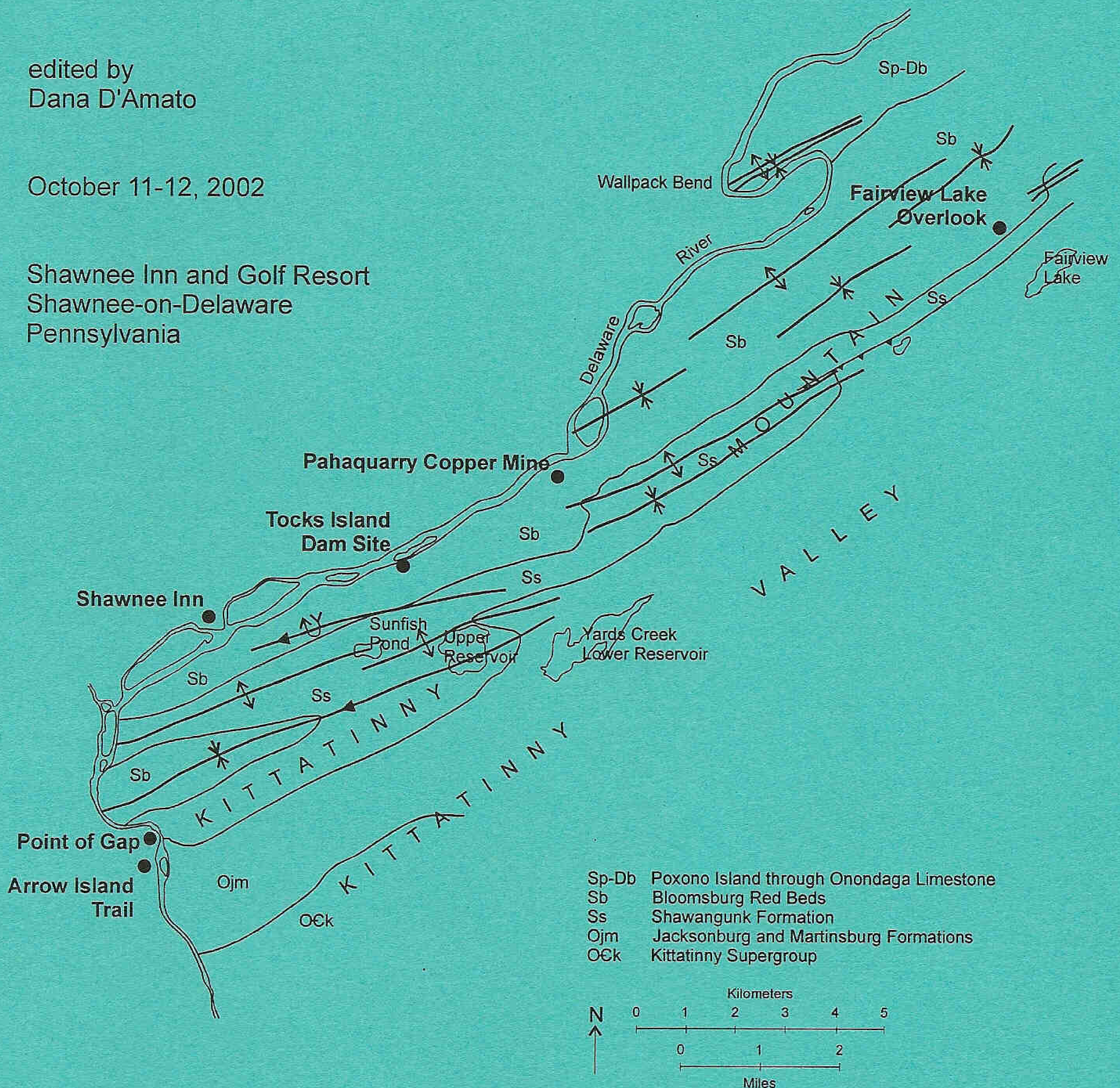
## Field Guide and Proceedings

### 19th Annual Meeting of the Geological Association of New Jersey

edited by  
Dana D'Amato

October 11-12, 2002

Shawnee Inn and Golf Resort  
Shawnee-on-Delaware  
Pennsylvania





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# STRATIGRAPHY IN THE REGION OF DELAWARE WATER GAP NATIONAL RECREATION AREA

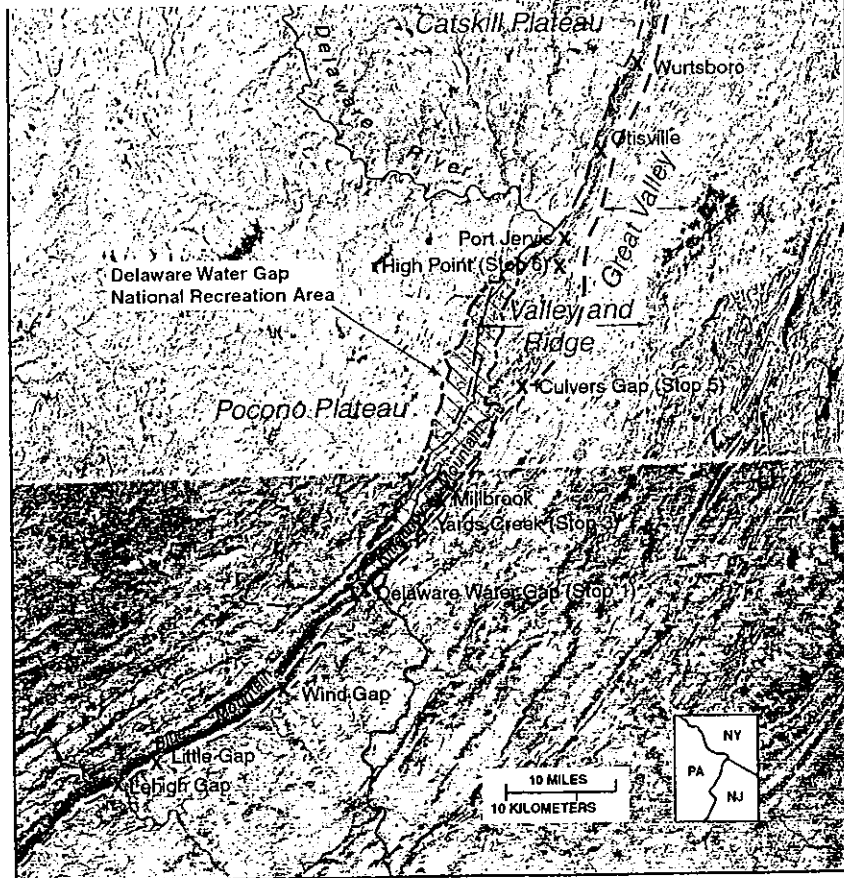
by  
Jack B. Epstein

## INTRODUCTION

Field mapping in the folded Appalachian Mountain and Great Valley sections of the Valley and Ridge physiographic province of eastern Pennsylvania and northern New Jersey by the U.S. Geological Survey, New Jersey Geological Survey, and Pennsylvania Geological Survey has led to a better understanding of all aspects of Appalachian geology. Disagreements have been common since H. D.

Rogers first described the geology of the area in 1858. Many differing opinions still exist regarding the stratigraphy, structural geology, geomorphology, and glacial geology. The rocks in the area range from Middle Ordovician to Late Devonian in age. This diversified group of sedimentary rocks was deposited in many different environments, ranging from deep sea, through neritic and tidal, to alluvial. In general, the Middle Ordovician through Lower Devonian strata are a sedimentary cycle related to the waxing and waning of Taconic tectonism. The sequence began with a graywacke-argillite suite (Martinsburg Formation) representing synorogenic basin deepening. This was followed by basin filling and pro-gradation of a sandstone-shale clastic wedge (Shawangunk Formation and Bloomsburg Red Beds) derived from the erosion of the mountains that were uplifted during the Taconic orogeny. The sequence ended with deposition of many thin units of carbonate, sandstone, and shale on a

Figure 1. Satellite image showing wind and water gaps in Shawangunk, Kittatinny, and Blue Mountains in New York, New Jersey, and Pennsylvania, and the physiographic provinces traversed in the field trip.



shelf marginal to a land area of low relief. Another tectonic-sedimentary cycle, related to the Acadian orogeny, began with deposition of Middle Devonian rocks. Deep-water shales (Marcellus Shale)

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preceded shoaling (Mahantango Formation) and turbidite sedimentation (Trimmers Rock Formation) followed by another molasse (Catskill Formation).

## STRATIGRAPHY

The Ordovician, Silurian, and Devonian rocks, and overlying surficial deposits that will be seen on this Field Conference, lie mainly within the Valley and Ridge physiographic province and partly within the Great Valley of northeastern Pennsylvania and northwestern New Jersey (Figure 1). The first significant geologic study of the area was the magnificent treatise of H. D. Rogers (1858), although other less comprehensive reports appeared before. Since that time, abundant studies have resulted in an understanding of many stratigraphic details, but they have also spawned many controversies that appear to become more numerous as years go by. What follows is a terse summary of results of stratigraphic investigations and remaining problems that provide interesting research potential.

The stratigraphic sequence from the Martinsburg Formation of Ordovician age through the Catskill Formation of Devonian age comprises more than 25,000 feet (7600 m) of shale, siltstone, sandstone, conglomerate, limestone, and dolomite. The salient lithic types and the thickness of the stratigraphic units, other than the Catskill, are given in Table 1. Correlation charts are given for Lower through Upper Silurian clastic rocks (Figure 2) and for complex Upper Silurian and Lower Devonian rocks (Figure 3A). Our understanding of the physical stratigraphy has been increased by reports and dissertations on the Catskill Formation (Glaeser, 1963; Epstein et al., 1974; Berg et al., 1977), Onesquethawan rocks (Inners, 1975; Epstein, 1984; Ver Straeten, 1996a, 1996b), Upper Silurian and Lower Devonian rocks (Epstein et al., 1967), the Shawangunk Formation (Epstein and Epstein, 1972; Epstein, 1993), and the Martinsburg Formation (Drake and Epstein, 1967; Lash et al., 1984), to name a few.

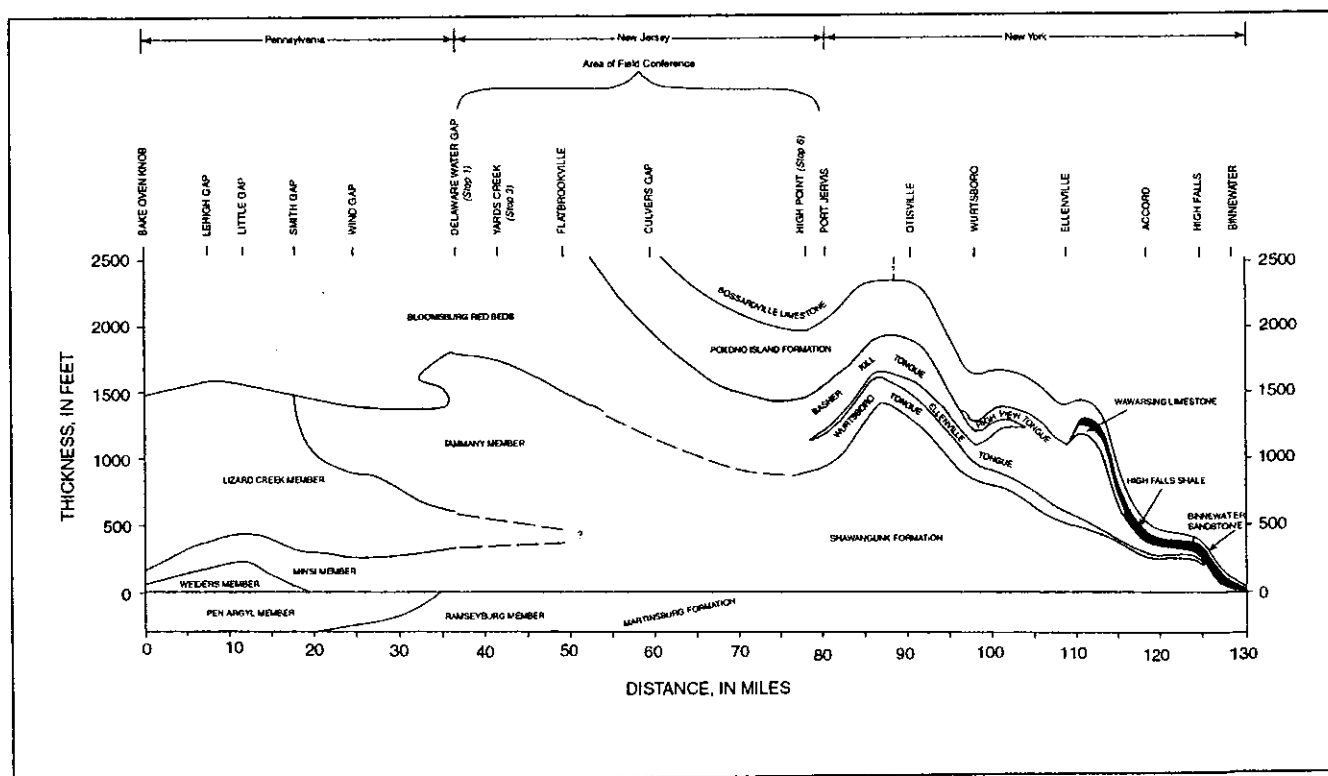


Figure 2. Correlation chart of Silurian rocks from southeastern New York, through New Jersey, and into eastern Pennsylvania. Modified from Epstein (1972, 1993). See Figure 1 for location of most of the sections.



Table 1. Description of rock units in the Field Conference area

System	Series	Formation		Member	Description	Thickness (feet)	
	Upper	Trimmers Rock		Millrift	Dark-gray to medium-dark gray siltstone, shale, and very fine-grained sandstone, coarsening upwards. Fossiliferous (brachiopods).	720-1,825	
				Sloat Brook			
	Middle	Mahantango			Medium-dark-gray siltstone and silty shale. Fossiliferous, biostromes (corals, brachiopods, pelecypods, bryozoans).	1,300-2,450	
	Middle	Marcellus	Brodhead Creek	Dark-gray, laminated to poorly bedded silty shale; depauperate brachiopods. Medium-dark gray shaly limestone.	800-950		
			Stony Hollow	Medium-dark-gray to medium-gray, laminated to thin-bedded, shaly limestone, fossiliferous (brachiopods).	150		
			Union Springs	Medium-dark-gray to dark-gray laminated shale; sheared along detachment.	50		
		Onondaga (Buttermilk Falls)	Seneca	Fossiliferous cherty limestone. Contains TIOGA ash bed.	15		
			Moorehouse (Stroudsburg)	Medium-gray limestone and argillaceous limestone with beds, pods and lenses of dark-gray chert. Fossiliferous (brachiopods, ostracodes), burrowed.	135		
			Nedrow (McMichal)	Medium-dark-gray calcareous argillite with lenses of light-medium gray fossiliferous limestone.	40		
			Edgecliff (Foxtown)	Medium-dark-gray calcareous siltstone and argillaceous limestone containing lenses of dark-gray chert. Fossiliferous, one-inch diameter crinoid "columnals" in lower half.	80		
		Lower	Schoharie			Medium- to medium-dark gray argillaceous calcareous siltstone. Fossiliferous (brachiopods, <i>Taonurus</i> burrows in lower half, vertical burrows in upper half).	100-150
Esopus				Medium- to dark-gray silty shale and shaly to finely arenaceous siltstone. Poorly fossiliferous. Burrowed ( <i>Taonurus</i> ).	180-300		
Oriskany Group			Ridgeley		Light- to medium-gray, fine- to coarse-grained calcareous sandstone and quartz-pebble conglomerate with minor siltstone, arenaceous limestone, and dark-gray chert. Fossiliferous (brachiopods).	0-16	
			Shriver Chert		Medium-dark-gray siliceous calcareous shale and siltstone and beds, lenses, and pods of dark-gray chert and minor calcareous sandstone. Fossiliferous (brachiopods), burrowed.	50-85	
Helderberg Group			Port Ewen Shale		Medium-dark-gray poorly fossiliferous, irregularly laminated calcareous shale and siltstone grading up to fossiliferous, burrowed, irregularly bedded calcareous siltstone and shale.	150	
			Minisink Limestone		Dark- to medium-gray argillaceous fossiliferous limestone.	11-14	
			New Scotland	Maskenozha	Dark-gray silty calcareous laminated fossiliferous shale with lenticular argillaceous fossiliferous limestone.	45	
				Flatbrookville	Medium-dark-gray silty and calcareous fossiliferous shale with lenticular medium-gray argillaceous, very fossiliferous limestone.	20-33	
			Coeymans	Stormville	Medium-gray, fine- to coarse-grained, biogenic limestone, fine- to medium-grained arenaceous limestone, fine- to coarse-grained, crossbedded and planarbedded calcareous sandstone and quartz-pebble conglomerate, with some dark-gray chert. Fossiliferous (brachiopods, crinoids).	0-20	
				Shawnee Island	Shawnee Island: Medium-gray, argillaceous and arenaceous irregularly bedded fossiliferous and burrowed limestone with chert at top. Contains bioherms of medium-light-gray very coarse grained crudely bedded biogenic limestone with corals, stromatoporoids, and shelly fauna ( <i>Gypidula</i> ). Thacher: Dark-gray, unevenly bedded limestone with yellowish-gray shale partings.	0-60 0-35	
				Thacher Mbr of Manlius Fm			
				Kalkberg Limestone	Medium-dark gray argillaceous massive fossiliferous limestone (diversified fauna) with nodules and lenses of dark-gray chert.	0-60	
	Peters Valley	Medium-gray arenaceous limestone to light-medium-gray fine- to coarse-grained pebbly calcareous sandstone. Cross bedded, fossiliferous.		0-9			
Depue Limestone		Medium- to dark-gray arenaceous and argillaceous fossiliferous Limestone.	13-29				



				Ravena	Medium-dark-gray slightly argillaceous, fossiliferous limestone.	0-30
SILURIAN AND DEVONIAN	Up. Silurian & Low. Devonian	Rondout	Mashipacong		Medium-dark- to light-gray shale, calcareous shale, and very fine- to medium-grained argillaceous limestone. Mudcracks, cut and fill.	8-15
			Whiteport Dolomite		Dark- to medium-gray mud-cracked laminated dolomite.	5-10
			Duttonville		Dark- to medium-gray calcareous shale and argillaceous limestone. Mud-cracked intervals and biostromal limestone beds.	10-20
SILURIAN	Upper	Decker	Wallpack Center	Clove Brook	Wallpack Center: Lenticular and evenly bedded quartz-pebble conglomerate, calcareous sandstone and siltstone, argillaceous and arenaceous limestone and dolomite. Cross bedded, planar bedded, flaser bedded, fossiliferous.	0-85
		Bossardville Limestone			Clove Brook: Medium-gray to medium-dark gray fossiliferous (crinoidal) limestone with light-olive-gray shale partings near top.	0-50
					Dark- to medium-gray, laminated argillaceous limestone locally containing deep mud cracks (as much as 20 feet deep) grading up to dark-gray laminated limestone. Poorly fossiliferous (ostracodes).	12-110
	Middle & Upper	Poxono Island			Light-olive-gray to green, calcareous and dolomitic, laminated, fissile to nonfissile shale, olive-green dolomite, sandstone, and siltstone.	500-800
		Bloomsburg Red Beds			Red, green, and gray siltstone, shale, sandstone, and conglomeratic sandstone in upward-fining sequences. Cross-bedded and laminated, mud cracks, cut and fill, scattered ferroan dolomite concretions. Partly burrowed. Fish scales locally.	1,500
	Lower and Middle	Shawangunk (Members lose their identity several miles northeast of Delaware Water Gap)	Tammany		Gray, fine- to coarse-grained, partly crossbedded, pyritic conglomerate, evenly bedded quartzite, and about 2% dark-gray argillite.	800
			Lizard Creek		Gray to olive-gray, fine- to coarse-grained, partly crossbedded, pyritic, thin- to thick-bedded quartzite interbedded with thin- to thick bedded, gray argillite.	275
			Minsi		Gray to olive-gray, fine- to coarse-grained, partly crossbedded, pyritic and feldspathic, thin- to thick-bedded quartzite, conglomeratic quartzite, and conglomerate. Locally contains mud-cracked argillite.	300
ORDOVICIAN	Middle and Upper Middle and Upper	Martinsburg	Pen Argyl		Dark-gray to grayish black, thick- to thin-bedded (some beds more than 20 feet thick), evenly bedded claystone slate, rhythmically interbedded with quartzose slate, subgraywacke, and carbonaceous slate. Taconic unconformity at top. Disappears under Shawangunk about one mile west of Delaware Water Gap.	3,000-6,000
			Ramseyburg		Medium- to dark-gray claystone slate alternating with light- to medium-gray, thin- to thick-bedded graywacke and graywacke siltstone.	2,800
			Bushkill		Dark- to medium-gray thin-bedded (beds do not exceed six inches thick), claystone slate with thin interbedded quartzose slate and graywacke siltstone and carbonaceous slate. Not exposed in Delaware Water Gap National Recreation Area.	4,000

Several problems remain. Whereas stratigraphic relationships of Upper Silurian through lower Middle Devonian strata are well known between Delaware Water Gap and Lehigh Gap, 29 miles southwest of Delaware Water Gap, this group of rocks is poorly understood for at least 20 miles southwest of Lehigh Gap. The entire sequence becomes thinner and more clastic, and several units disappear as an ancient low-lying positive area is approached to the southwest near Harrisburg, PA. This positive area was termed the "Harrisburg axis" by Ulrich (1911) and Willard (1941), and named the



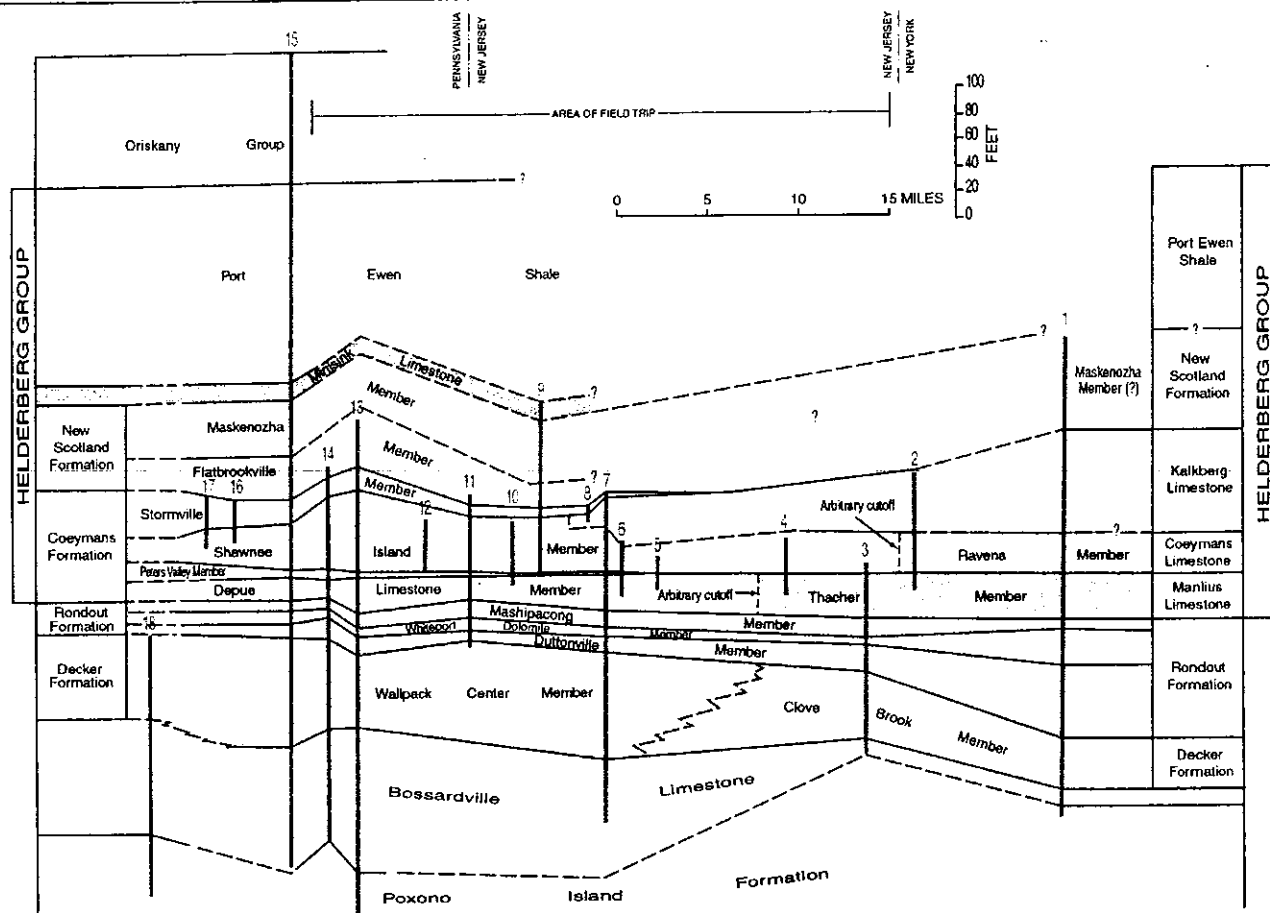


Figure 3A. Correlation chart of Upper Silurian and Lower Devonian formations in the vicinity of the Delaware Water Gap National Recreation Area, northeastern Pennsylvania, northern New Jersey, and southeasternmost New York. Modified from Epstein et al., 1967. Section locations shown on Figure 3B.

"Auburn Promontory" by Swartz (in Willard et al., 1939). Poor exposures, abrupt facies changes, and limited paleontologic data have hampered our understanding of these rocks.

The ages of the rocks in the Valley and Ridge of eastern Pennsylvania are generally well known, but the exact locations of the two systemic boundaries within the sequence are still a bit speculative. The Ordovician-Silurian boundary is generally accepted (incorrectly?) as being at the unconformable contact between the Martinsburg and Shawangunk Formations. The uppermost beds of the Martinsburg are late Middle Ordovician in age (Berry, 1970), but the basal beds of the Shawangunk have not yielded diagnostic fossils. On the basis of regional considerations, the basal Shawangunk could be uppermost Ordovician in age (Epstein and Epstein, 1972). Thus, the dating of the Taconic unconformity in eastern Pennsylvania is still open to question.

The location of the Silurian-Devonian boundary is a somewhat lesser, but nonetheless important, problem. The lowest Coeymans Formation is definitely known to be Devonian, on the basis of conodont studies (A. G. Harris, oral communication, 1982), and the Decker Formation is possibly Silurian in age. Thus, the boundary may lie within about 30 feet (9 m) of poorly fossiliferous dolomite, shale, and limestone of the intervening Rondout Formation, or possibly within sandstone, limestone, and dolomite of the Decker Formation. Recent attempts to collect conodonts from this interval have so far

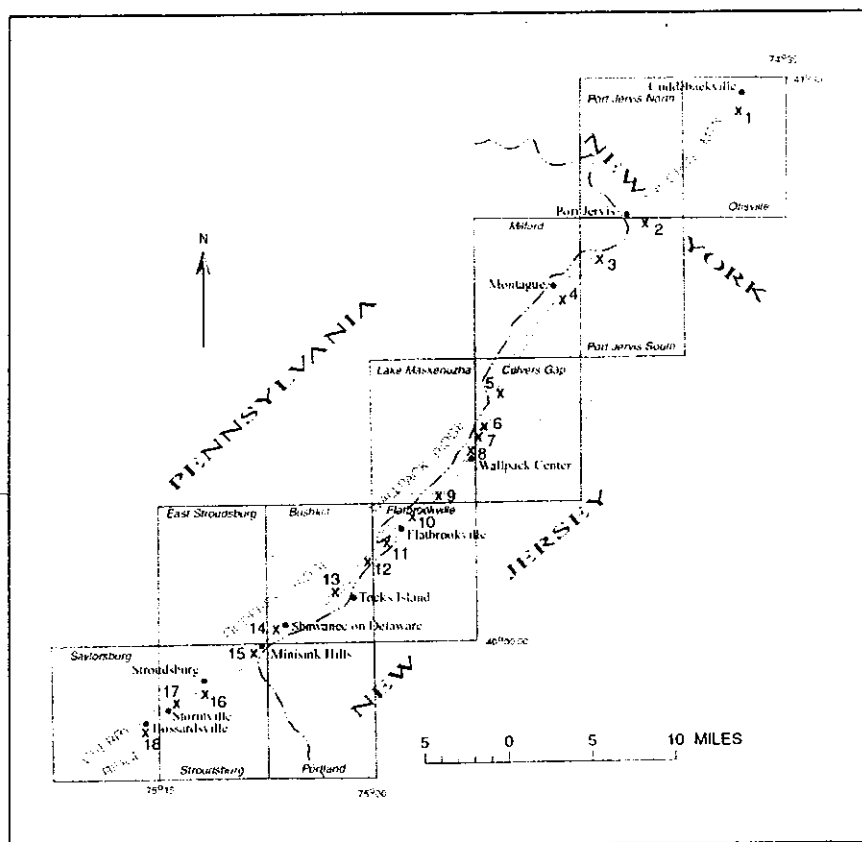


Figure 3B. Outcrop belt (yellow) of uppermost Silurian and lowermost Devonian rocks in the Delaware Water Gap National Recreation Area and location of measured sections shown in Figure 3A. Modified from Epstein et al., 1967.

source terrane in juxtaposition with Shawangunk depositional basin that was more quartz rich than the rocks presently south of the Shawangunk outcrop belt (Epstein and Epstein, 1972).

A major controversy that still exists after nearly a century of debate concerns the number of members within the Martinsburg Formation. 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 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 Table 1) in almost the same way as defined by Behre (1933). This should not be surprising because the best geologist of all, the slate quarrymen who have toiled over the Martinsburg since the first half of the 19<sup>th</sup> 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 grance (dirty sandstone) is interbedded with the slate.

failed to resolve this problem. A discussion of the long-standing debate of the position of the Silurian-Devonian boundary is given in Epstein et al. (1967).

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, 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



Differences in stratigraphic interpretation have led to various thickness estimates. Those who accept a two-fold interpretation have estimated that the Martinsburg is as thin as 3000 feet (Stose, 1930), whereas those who support the idea of three members have estimated thicknesses of more than 10,000 feet (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 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., Figure 6 in Epstein, 1980). 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 inches thick and are generally less than 2 inches thick (Figure 4A). This laminated to thin-bedded characteristic is present everywhere in the member over an outcrop width of nearly 5 miles in places and an outcrop length of more than 30 miles. The overlying Ramseyburg Member comprises about 25 percent graywacke. The slates in the graywacke are thin bedded at the base and become thicker bedded upwards. The first thousand feet 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 feet thick (Figure 4B). In 1967 the Field Conference visited a quarry in the Pen Argyl, but most of these quarries are now inactive and flooded. This is the area from which most slate for pool tables is mined. The thick-bedded material is not repeated south of the Ramseyburg outcrop belt, a fact long known to the slate quarrymen of the area. They recognized the difference between the Pen Argyl and Bushkill belts, and named them the “soft slate” and “hard slate” belts, respectively.

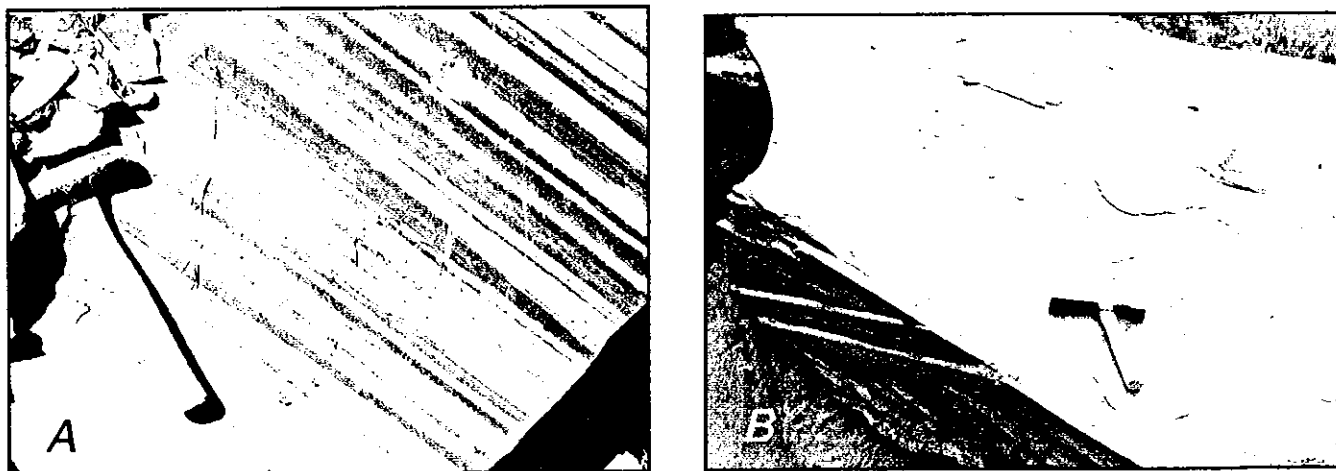


Figure 4. Typical exposures of thin-bedded "hard slate" (A, Chapman quarries, 20 miles southwest of Delaware Water Gap) and the much thicker bedded "soft slate" (B, Penn Big Bed Quarry, 19 miles WSW of Delaware Water Gap). Some of the beds in the Penn Big Bed quarry exceed 20 feet in thickness (Lash et al., 1984, Stop 9) making it appropriate for such uses as billiard table tops.

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). In any event, the final answer to the question of the number of members in the Martinsburg must await a final verdict based on additional paleontologic studies (see Finney, 1985). At present, the three-member interpretation is favored. A more recent study of

graptolites in the Delaware Water Gap area supports this interpretation (Parris and Cruikshank, 1992). 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.

### SEDIMENTOLOGICAL HISTORY

An interpretation of the depositional environments and paleogeography of the rocks in the Delaware Water Gap area may be made by study of their sedimentary structures, regional stratigraphic relations, petrographic characteristics, and faunal content, and by comparing these rocks with sediments that are being deposited today. The environments of deposition represented by the rocks in the Field Conference area and the paleogeography from Silurian through early Middle Devonian time is depicted in Figure 5.

Few modern studies have been made of the rocks in the Martinsburg Formation, but it appears that these sediments were deposited in a rapidly subsiding flysch-turbidite basin (Van Houten, 1954) formed during Middle Ordovician continental plate collision. The highland source for the Martinsburg was *Appalachia* to the southeast, and the sediments covered a foundered Cambrian and Ordovician east-facing carbonate bank. 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 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 Ramseyburg Member. Paleocurrent studies indicate that the turbidites flowed down the regional slope to the northwest and turned longitudinally in a northeast direction along the basin axis (McBride, 1962). The deepest part of the basin appears to be in northeasternmost Pennsylvania. Many thick intervals (possibly more than 100 feet thick) of lenticular packets of coarser graywacke were probably deposited in submarine channels that fed the fans. 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 and silt-shale turbidites were deposited between more widely spaced, coarser grained turbidites. The Martinsburg of eastern Pennsylvania and New Jersey lies begging for a detailed petrologic study to decipher the intricacies of its sedimentological history. The contact between the Pen Argyl and Ramseyburg Members disappears under the Shawangunk just within the confines of Delaware Water Gap National Recreation Area (DEWA) one mile west of Delaware Water Gap (Epstein, 1973). The Pen Argyl does not reappear in New Jersey. Several small slate quarries and prospects in the Ramseyburg Member, all long since abandoned, are found within the DEWA boundaries (Epstein, 1974).

Rapid shallowing of the Ordovician basin was accomplished by deposition of the thick Martinsburg detritus and 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 the area of the Field Conference.

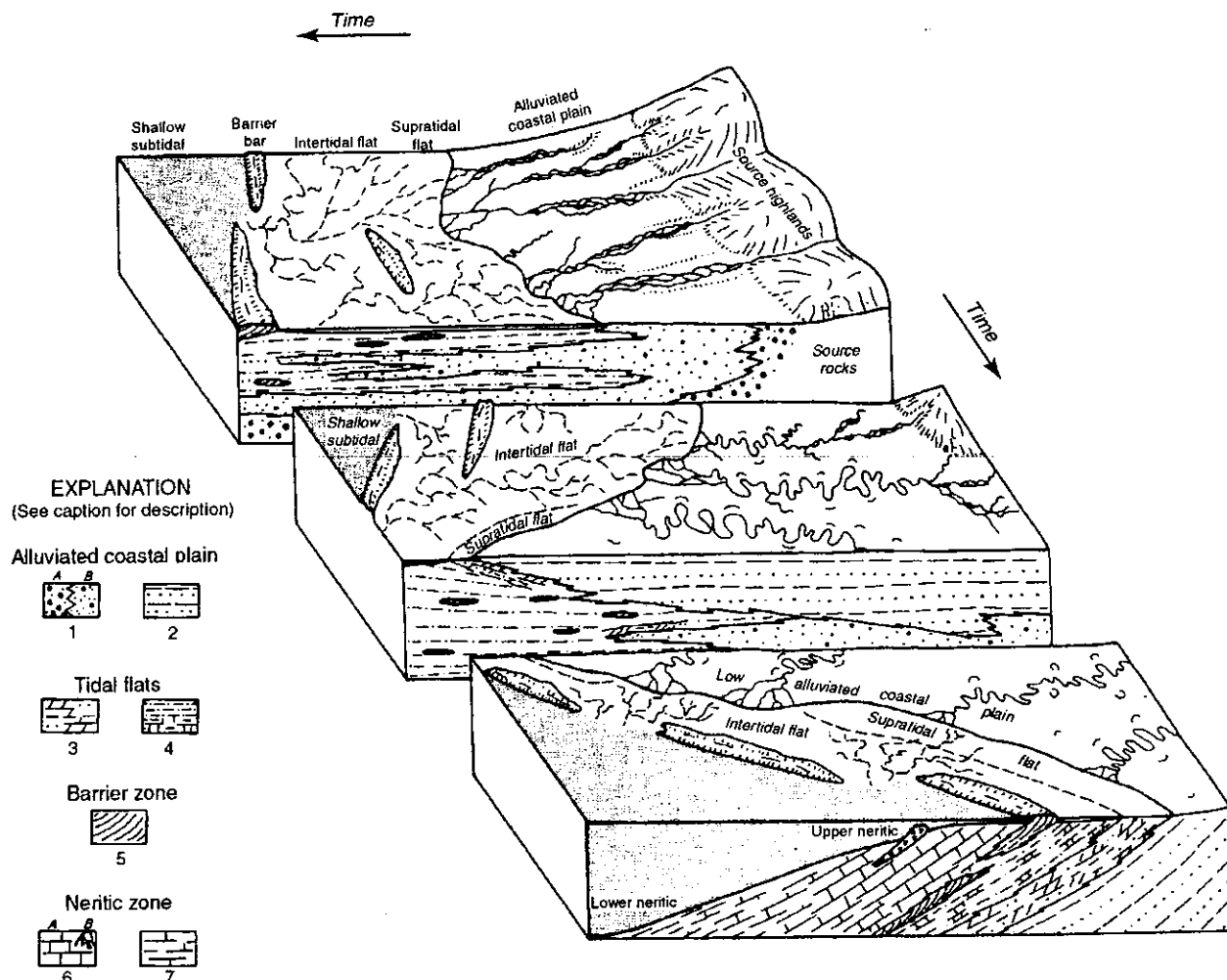
The conglomeratic sandstone members of the Shawangunk Formation, the Weiders, Minsi, and Tammany (Figure 2) are believed to be fluvial in origin and are interposed by a transitional



marine-continental facies (the Lizard Creek Member). The fluvial sediments are characterized by rapid alternations of polymictic conglomerate with quartz pebbles more than 6 inches long, conglomeratic sandstone, and sandstone (cemented with silica to form quartzite), and subordinate siltstone and shale. The bedforms (planar beds, crossbedding, and possibly antidunes) indicate rapid flow conditions. Crossbed trends are generally unidirectional to the northwest. The minor shales and siltstones are thin, and at least one is mudcracked, indicating subaerial exposure. These mudcracks may be seen at the south entrance to Delaware Water Gap on the New Jersey side by looking up about 60 feet at an overhanging ledge (Figure 6). These 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 present are mere 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 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, estuaries, and shallow neritic shelves. These are generally highly agitated 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 interpretation (Epstein et al., 1974). The occurrence of collophane, siderite, and chlorite nodules, and *Lingula* fragments indicate nearshore marine deposition. 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 linear source to the southeast and a marine basin to the northwest (Figure 5). 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 (Epstein and Epstein, 1972). 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 braided streams of the Shawangunk gave way to gentler 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 (Allen, 1965). The cycles are as much as 13 feet thick and ideally consist of a basal crossbedded 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 inches long were derived from caving of surrounding mud banks. These 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 suggest possible minor marine transgressions onto the low-lying fluvial plains (Epstein, 1971). The source for the Bloomsburg differed from that of the Shawangunk because the red beds required the presence of iron-rich minerals (Miller and Folk, 1955), suggesting an igneous or metamorphic source. Evidently, the source area was eroded down into deeper Precambrian rocks.



**Figure 5. Generalized block diagram showing sedimentary environments and major lithofacies in northeasternmost Pennsylvania from Silurian through Early Devonian time. Modified from Epstein and Epstein (1969).**

In general, the environments and facies are younger towards the bottom and to the left of the diagram as indicated by the arrows showing time. For example, the upward succession of deposits and environments during Shawangunk time are represented in the uppermost block going from right to left. Taconic orogenesis uplifted the highlands shown on the right, which were the source for the coarse braided stream sediments of the Weiders Member of the Shawangunk Formation. As we go to the left, the slightly finer clastic sediments of the Minsi Member are shown on the alluviated coastal plain. The Minsi overlies the Weiders in eastern Pennsylvania, and the diagram demonstrates the stratigraphic axiom that a vertical rock succession at one place indicates lateral variations over an area. Continuing to the left (and upwards in the stratigraphic succession into younger rocks), we see a variety of transitional deposits typical of the Lizard Creek Member of the Shawangunk Formation (shallow subtidal to supratidal flat). In a similar way, the diagram depicts the changing environments from terrestrial fluvial of the Shawangunk in the upper block, through various tidal and neritic environments of the Silurian and Devonian rocks in the lower block.

*Alluviated coastal plain:*

1. Streams of high gradient, coarse load, low sinuosity (braided).
  - A. Bedforms in upper flow regime (planar beds, possible antidunes) and lower flow regime (dunes). Chiefly conglomerate and sandstone. Weiders Member of the Shawangunk Formation.
  - B. Bedforms in lower upper flow regime (planar beds) and upper lower flow regime (dunes). Chiefly conglomeratic quartzite and quartzite. Minsi Member of the Shawangunk Formation, Lizard Creek Member of the Shawangunk Fm.



2. Streams of low gradient, medium load, and fine floodplain deposits, high sinuosity (meandering). Bedforms in lower flow regime (dunes and ripples). Sandstone, siltstone, and shale. Bloomsburg Red Beds and possibly Decker Formation and Andreas Red Beds in Lehigh Gap area.

*Tidal flats:*

3. Supratidal flat, may include tidal creeks. Dolomite, limestone, shale, sandstone. Laminated (algal), massive, mud cracked, intraclasts, sparse fauna. Lizard Creek Member of the Shawangunk Formation, Poxono Island Formation, Decker Formation, Rondout Formation.
4. Intertidal flat, may include tidal channel and gully, estuary, lagoon, beach. Shale, siltstone, sandstone, and limestone in areas of low terrigenous influx, minor nodules and oolites of collophane, siderite, and chlorite. Irregularly bedded and laminated, graded, rippled, flaser-bedded, cut-and-fill, ball-and-pillow structure, burrowed, restricted fauna (abundant leperditiid ostracodes in carbonates; Lingula and eurypterids in noncarbonates). Lizard Creek Member of the Shawangunk Formation, Poxono Island Formation, Bossardville Limestone, Decker Formation.

*Barrier zone:*

5. Offshore bar and beach. Sandstone, siltstone, and conglomerate. Foreshore laminations, cross-bedding, some burrowing, scouring, wave-tossed shell debris, some textural maturity. Lizard Creek Member of the Shawangunk Formation, Decker Formation, Stormville Member of the Coeymans Formation, Ridgeley Sandstone, Palmerton Sandstone.

*Neritic zone:*

6. Cherty calcareous shale and siltstone, laminated to unevenly bedded, partly burrowed, diverse fauna. Decker Formation, Stormville Member of the Coeymans Formation, New Scotland Formation, Minisink Limestone, Port Ewen Shale, Shriver Chert, Esopus Formation, Schoharie Formation, Buttermilk Falls Limestone.

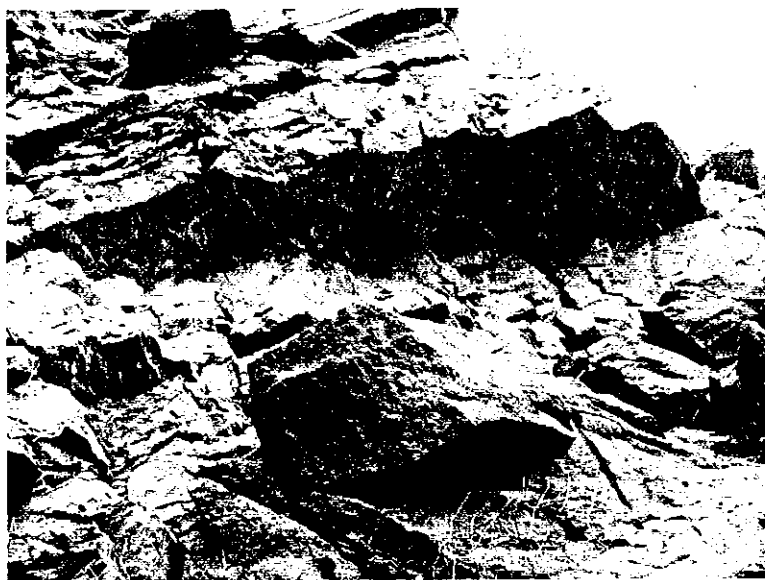


Figure 6. Mudcrack casts at the base of a sandstone bed in the Minsi Member of the Shawangunk Formation, New Jersey side of the Delaware Water Gap. Mudcrack polygons are about 1 foot across.

From Poxono Island time through Oriskany time, the fluvial deposits of the Bloomsburg gave way to transgression of a shallow marine shelf. The area was maintained near sea level and a complex of alternating supratidal and intertidal flats, barrier bars, and subtidal zones was maintained (Figure 5). Sediments indicative of supratidal flats contain laminations of probable algal origin, fine-grained laminated to very thin-bedded massive dolomite and limestone, very restricted fauna (mainly leperditiid ostracodes) or no fossils at all, and mudcracks (Figure 7). Supratidal sediments are found in the Poxono Island Formation, Bossardville Limestone, Decker Formation, and Rondout Formation. Intertidal flat sediments are characterized by graded, laminated, and

thin-bedded partly quartzose limestone, cut-and-fill structures, small-scale crossbedding, intraclasts (edgewise conglomerates), abundant leperditiid ostracodes, storm-tossed shell debris, and some mudcracks. Intertidal flat sediments are found in the Poxono Island Formation, Bossardville Limestone, Decker Formation, and Rondout Formation. Barrier-bar and beach deposits are distinguished by calcareous sandstone, conglomerate, and quartzose limestone with foreshore laminations and crossbedding, cut-and-fill structures, intraclasts, skeletal debris of a variety of marine organisms, and scattered burrows. These deposits are common in the Decker Formation, Ridgeley Sandstone of the



Figure 7. Mudcrack columns, about 13 feet deep, in the Bossardville Limestone along creek in Shawnee-on-Delaware.

Oriskany Group, and Coeymans Formation. Neritic deposits consist predominantly of calcareous shale and limestone that may contain abundant chert. Fauna are diverse and abundant, and burrowing may be extensive. Reefs developed locally in the Shawnee Island Member (and equivalent strata) of the Coeymans Formation in both Pennsylvania and New Jersey. Neritic units include the Decker Formation, Coeymans Formation, New Scotland Formation, Minisink Limestone, Port Ewen Shale, and Shriver Chert of the Oriskany Group.

The wandering shoreline during deposition of the Poxono Island through the Oriskany migrated northwestward and the area became emergent following Oriskany deposition. Next came a rapid change to moderate to deep neritic conditions during deposition of the Esopus and lower Schoharie Formations. These

rocks are characterized by persistence over a wide geographic area (eastern Pennsylvania to east-central New York), lack of abundant skeletal debris, abundant hexactinellid sponge spicules, and abundant *Taonurus*, a trace fossil typical of the *Zoophycus* facies of Seilacher (1967). A regressive phase followed from Schoharie into Onondaga (Buttermilk Falls) time as indicated by an upward transition from horizontal to vertical burrows, an increase in marine fauna (including corals), and an increase in limestone (Ver Straeten, 2001, p. 35). These features indicate water depths within the photic zone and warm, well-oxygenated, and gently circulating water. The Palmerton Sandstone, found about 10 miles southwest of DEWA, lying between the Schoharie Formation and Onondaga Limestone, was most likely a marginal marine (bar or beach) linear sand body. It is massive and generally lacks distinctive internal structures, making a precise interpretation of its depositional environment a bit uncertain.

The black pyritic shales of the Marcellus Shale, with its depauperate fauna, reflects development of an anoxic basin below wave base in the deeper part of a prodelta plain, heralding the arrival of the regressive deposits of the Catskill delta. The Tioga ash-bed zone, a series of altered volcanic tuffs (Dennison, 1969; Smith and Way, 1983) occurs in the upper Onondaga of this area (and extends up into the Marcellus Shale to the west). The Tioga B bed at the base of the Seneca Member of the Onondaga marks the top of the Onesquethaw Stage. The ash beds record a period of volcanism that presages the onset of the Acadian orogeny later in the Devonian (see Ver Straeten, 2001, p. 35).

The overlying Mahantango Formation, which contains coarser siltstones than the Marcellus, and very diverse fauna (brachiopods, corals, bivalves, bryozoans, trilobites, etc.), indicates a shallower marine environment with better circulation.

Local biostromes containing abundant corals attest to the return of more "normal" marine conditions. One of these biostromes, the so-called "Centerfield coral reef" (actually a coral biostrome), is well exposed in several places outside the DEWA, providing excellent fossil collecting for amateur paleontologists. These localities are along PA 191, about 2.7 miles north of Stroudsburg in the East Stroudsburg quadrangle (Wilt, 2001, p. 72); along PA 115, 0.5 miles northwest of Saylorsburg in the Saylorsburg quadrangle (Hoskins et al., 1983); and along I-80, about 2.5 miles west of Stroudsburg in the Stroudsburg quadrangle. The first two localities have a wide shoulder



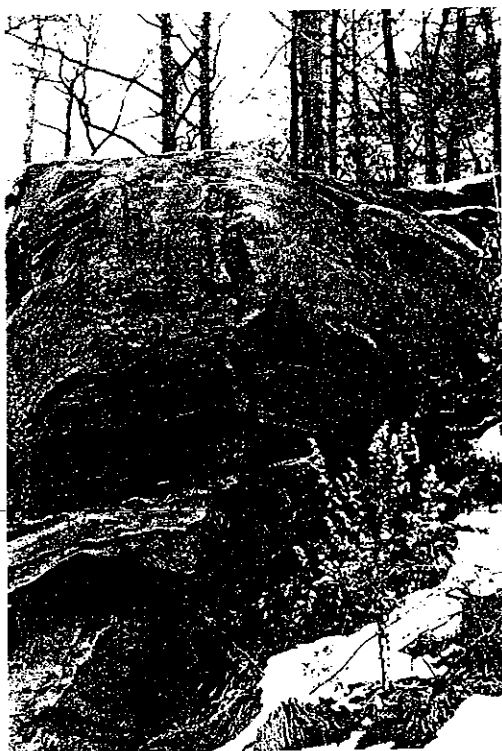


Figure 8. Burrow of *Archanodon catskillensis* (Vanuxem) in the lower part of the Towamensing Member of the Catskill Formation at Hawks Nest on NY 97, 1.3 miles north-northwest of Sparrow Bush, Orange Co., NY.

along the road for parking. The I-80 locality—though spectacular—is unsafe for collecting because of high-speed traffic.

The Trimmers Rock Formation contains many features suggesting deposition from turbidity currents, including graded sequences, scoured bases, transported fossil hash, and sole marks. These pro-delta slope deposits are transitional up into sediments of the Catskill Formation, and were probably deposited in the pro-deltaic apron in front of the advancing Catskill delta.

The Catskill delta advanced northwestward and the shoreline shifted in response to tectonic uplift and sinking, and to fluctuating loci of deposition. Fine sandstones of the Towamensing Member of the Catskill Formation (lowest member) are rippled, partly burrowed, and contain plant fragments, as well as burrows of the clam *Archanodon* (Figure 8; Sevon et al., 1989). These sediments grade up from the Trimmers Rock Formation and are shallower delta front sandstones of the advancing delta, reworked by ocean currents after being transported to the site of deposition along distributary channels. They may also be partly fluvial in origin.

The overlying Walcksville Member contains red beds that have features similar to the older Bloomsburg Red Beds—crossbedded sandstones with scoured bases, mudcracks, carbonate concretions, and upward-fining cycles, as well as roots—suggesting that a low-lying subaerial fluvial plain of the

Catskill delta prograded over the underlying transitional sediments. Subsidence and marine incursion followed with deposition of fossil-bearing siltstones, shales, and sandstones of the superjacent Beaverdam Run Member. Conditions similar to those of the Walcksville returned during Long Run time, followed by a thick and coarser sequence of sandstones and conglomerates, suggesting that during upper Catskill time the area was overwhelmed by braided stream deposits as Acadian orogenic uplift to the southeast raised a linear mountain chain similar to the source area that supplied earlier sediments during Shawangunk time.

More sediments were deposited during the later Paleozoic, but the younger rocks formed from these sediments have been eroded away from the Delaware Water Gap area and the nearby Pocono Plateau. The sedimentological record begins again with the deposition of glacial deposits and alluvium during the Pleistocene and Holocene—but that's a wholly different story.

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# STRUCTURAL GEOLOGY OF THE DELAWARE WATER GAP NATIONAL RECREATION AREA

by  
Jack B. Epstein

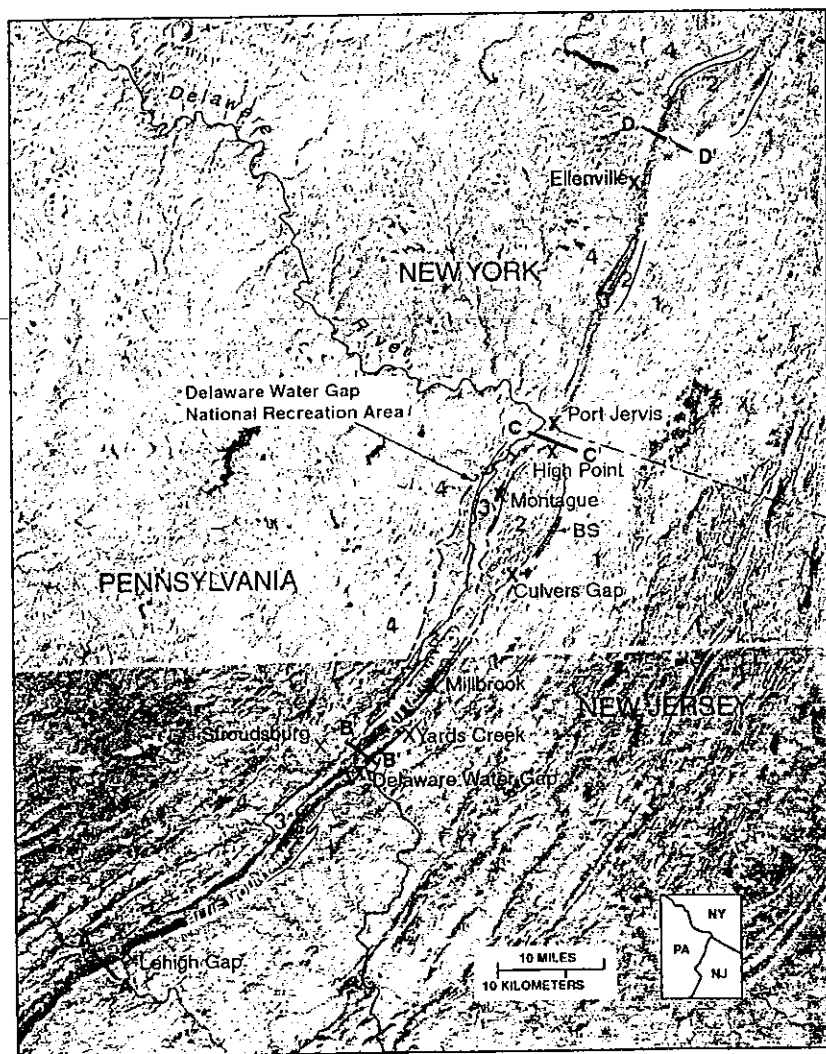


Figure 9. Satellite image of the Delaware Water Gap National Recreation Area showing lithotectonic units (in red) and locations of cross sections shown in Figure 10. BS is the nepheline syenite intrusion near Beemerville, NJ. The exposed syenite is exposed at the north end; the remainder is buried. Its significance is discussed at STOP 6, High Point, NJ.

cleavage is refracted to steeper angles. Cleavage tends to die out within hundreds of feet of the contact with the overlying Shawangunk Formation. The angular discordance at the Martinsburg-Shawangunk contact within the area of the Field Conference is less than  $15^\circ$ . Bedding and fold patterns in the Martinsburg within several thousand feet of the Shawangunk mimic those in the

Field mapping in rocks of Ordovician to Devonian age in the Valley and Ridge province of eastern Pennsylvania and northwesternmost New Jersey indicates that rocks of differing lithology and competency have different styles of deformation. Folding is thus disharmonic. Four rock sequences, lithotectonic units, have been recognized. Each sequence is presumably set off from those above and below by decollements (detachments along a basal shearing plane or zone). 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, Table 3) and their distribution is shown in Figure 9. In general the intensity of folding diminishes to the northeast, from overturned and faulted folds in the southwest to northwest-dipping monoclines with superimposed gentle folds in the northeast (Figure 10).

Lithotectonic unit 1 comprises the Martinsburg Formation. Slaty cleavage is generally well developed in its pelitic rocks. In the interbedded graywackes, a coarser fracture

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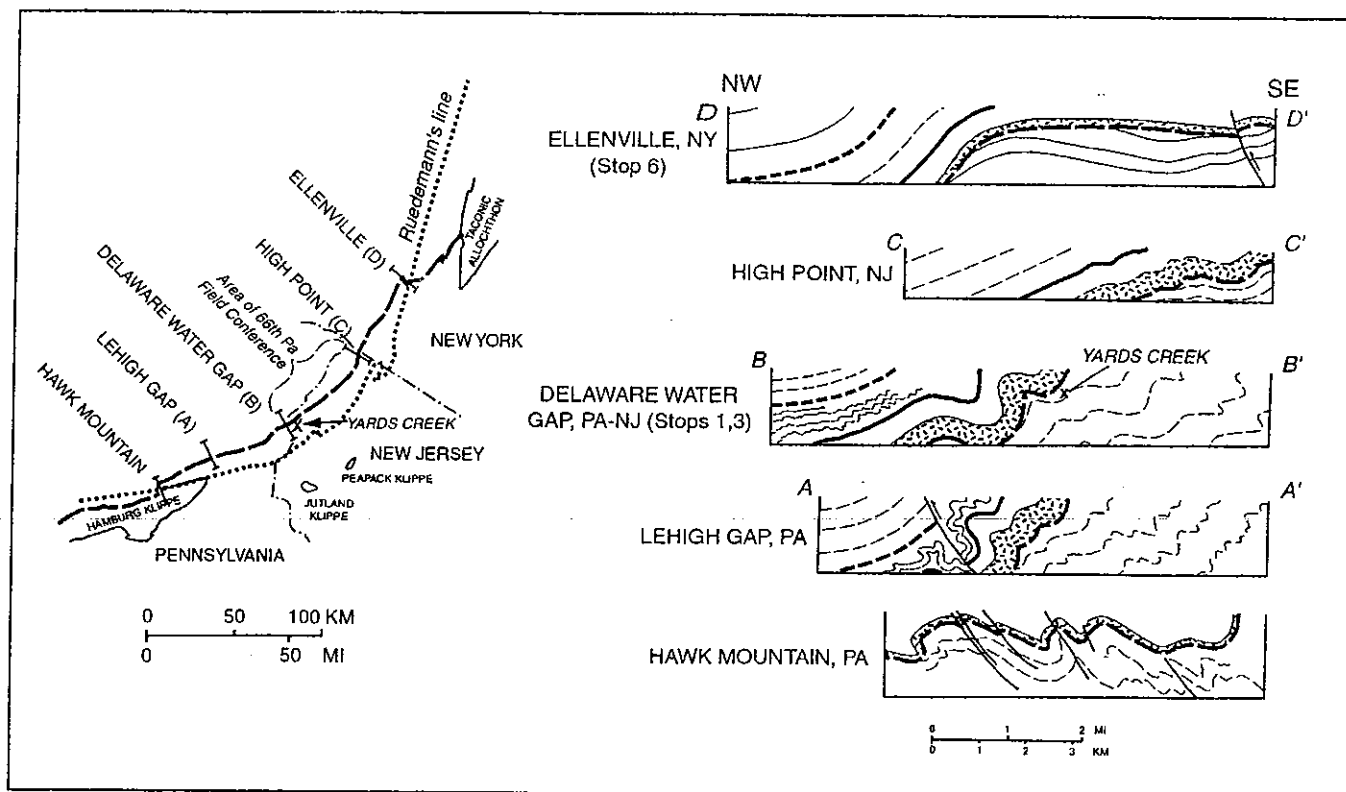


Figure 10. Generalized tectonic map and cross sections along the Taconic unconformity, northeastern Pennsylvania, New Jersey, and New York. Dashed heavy line is the Taconic (Ordovician) unconformity separating the Silurian clastics of lithotectonic unit 2 from the underlying Martinsburg Formation (unit 1). Solid heavy line separates lithotectonic units 2 and 3. Short-dashed heavy line separates lithotectonic units 3 and 4. Dotted heavy line, including Ruedemann's line, separates broad open Taconic folds to the north and west from more intense structures to the south and east. Dotted unit in the cross sections is the Tuscarora Sandstone – Shawangunk Formation. Lettered cross sections also shown in Figure 9. Modified from Epstein and Lytle, 1987.

younger rocks, suggesting that the folding is Alleghanian in age. The angular discordance in strike is more than  $7^\circ$ , the Martinsburg beds striking more northerly those in the Shawangunk, so that the contact between the upper Pen Argyl and middle Ramseyburg Members of the Martinsburg heads under the Shawangunk slightly more than one mile southwest of the Water Gap (Epstein, 1973).

Lithotectonic unit 2 is made up of resistant, competent quartzites and conglomerates of the Shawangunk Formation overlain by finer clastics of the Bloomsburg Red Beds. These underlie Blue and Kittatinny Mountains in Pennsylvania and New Jersey, and Shawangunk Mountain in New York. Concentric folding by slippage along bedding planes is common. Cleavage is found within the shales and siltstones of this unit, but it is not so well developed as in the Martinsburg where slates have been commercially extracted. The reason for this is not because of different time of formation (e.g., Taconic or Alleghanian), but because of slight lithologic differences—the Martinsburg shales were more uniform and of finer grain than those in the Silurian clastic rocks. Folds are generally open and upright (Figure 11), but some limbs are overturned. In the Water Gap, the Bloomsburg is thrown into many small folds in the core of the Dunnfield Creek syncline.

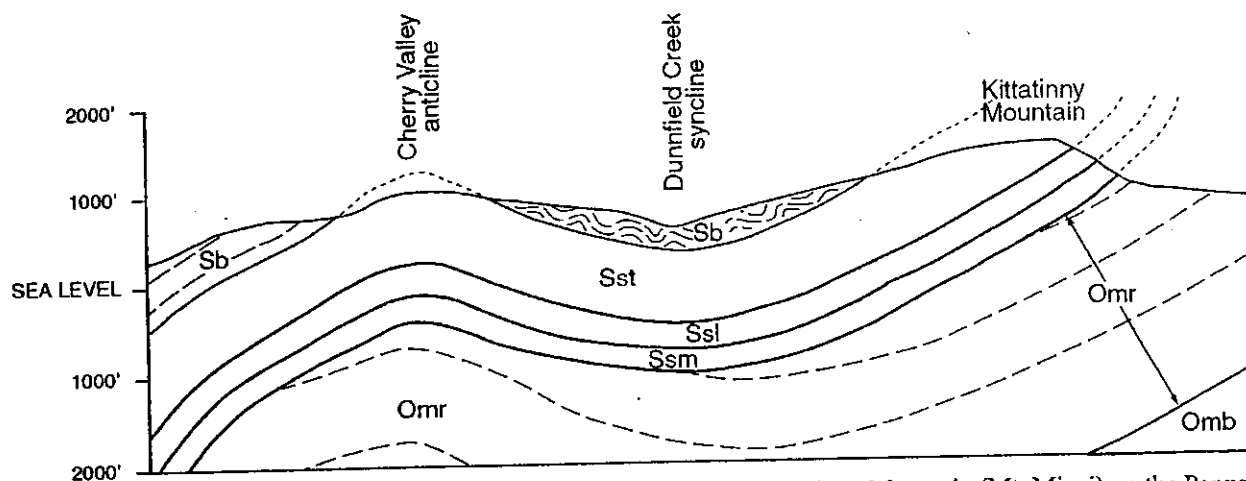
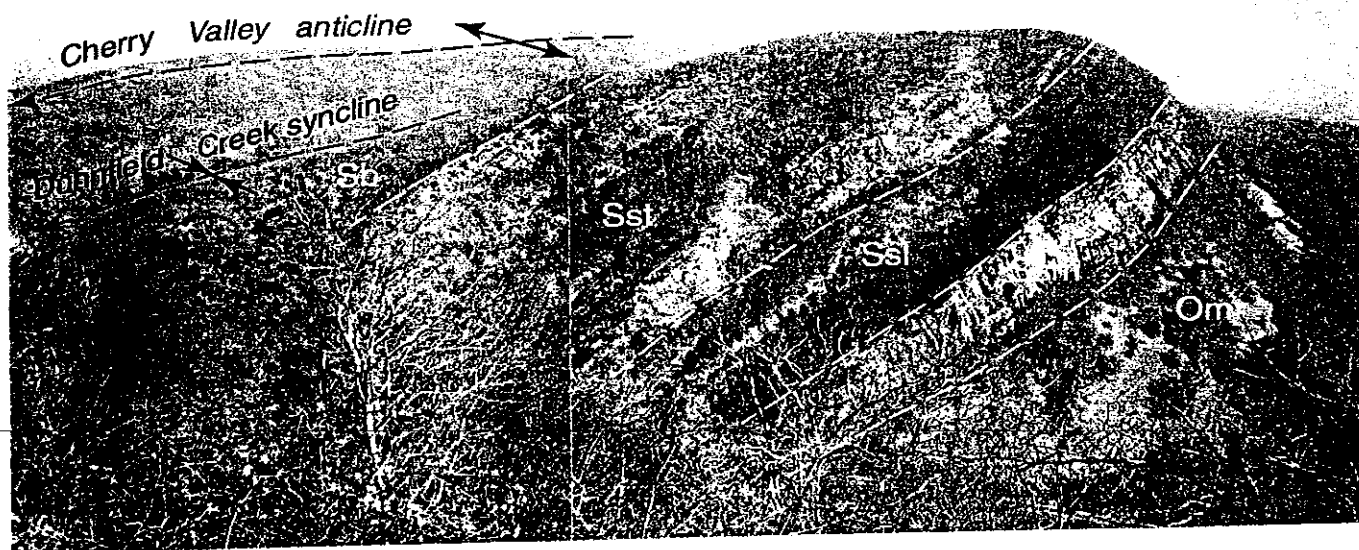


Figure 11. Delaware Water Gap in New Jersey as viewed from atop Kittatinny Mountain (Mt. Minsi) on the Pennsylvania side. Omb, Bushkill Member of the Martinsburg Formation; Omr, Ramseyburg Member of the Martinsburg Formation; Ssm, Minsi Member of the Shawangunk Formation; Ssl, Lizard Creek Member of 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 (Beerbower, 1956).

Cleavage in the Bloomsburg dips to the southeast and appears to have been rotated during later folding. Numerous bedding-plane faults (Figure 12), many with small ramps, in the Bloomsburg contain slickensides with steps that indicate northwest translation of overlying beds, regardless of position within a given fold. Dragging of cleavage along some of these faults indicate that faulting postdated cleavage development, which in turn, predated folding.

The home for rocks of lithotectonic unit 3 is in a narrow ridge (Godfrey, Wallpack) northwest of Kittatinny and Blue Mountains. Folds in this sequence in the southwestern part of the area are of smaller scale than surrounding units (Figure 13 and 14). Axes of these folds are doubly plunging and die out within short distances, making for complex outcrop patterns (Epstein, 1973, 1989). Folding

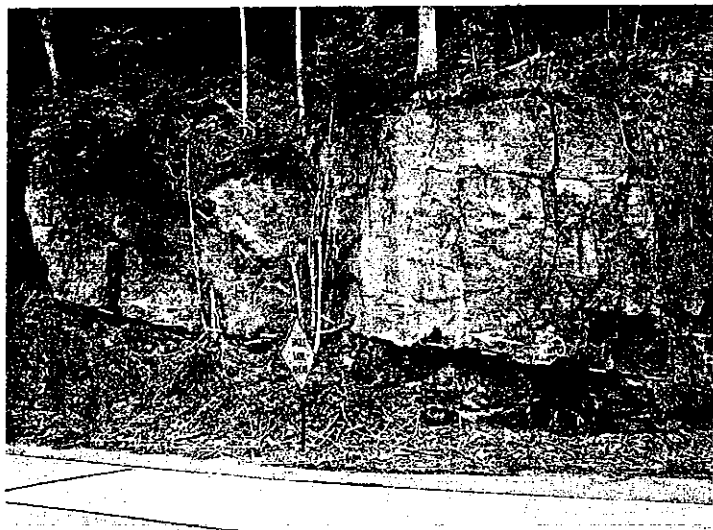


Figure 12. Bedding thrust and ramp at base of sandstone in the Bloomsburg Red Beds along Old Mine Road in New Jersey.

decollement in relatively incompetent rocks, are believed to separate the four lithotectonic units. The Martinsburg-Shawangunk contact is interpreted to be a zone of detachment between lithotectonic units 1 and 2 and can be seen at Yards Creek. Thin fault gouge and breccia, about 2 inches thick, are present at the contact. Elsewhere, such as at Lehigh Gap (Epstein and Epstein, 1967, 1969), and at exposures in southeastern New York (Epstein and Lyttle, 1987), thicker fault gouge, bedding-plane slickensides containing microcarps or steps, and drag folds indicate northwest movement of the overlying Shawangunk Conglomerate.

The change in style of deformation between lithotectonic units 2 and 3 takes place in the Poxono Island Formation, but considerable northwest movement is indicated by wedging and bedding slip in the Bloomsburg Red Beds (Figure 12).

becomes less intense and in the northeast part of the DEWA where units 2 and 3 dip uniformly to the northwest.

There is a sharp contrast between the structure of lithotectonic units 4 and 3. Unit 4 makes up rocks of the Pocono Plateau north of the Delaware River. These rocks dip gently to the northwest and are interrupted throughout the area by only sparse and gentle upright folds. Cleavage is present, but not as well developed as in underlying rocks. Southwest of the field trip area, however, cleavage in Middle Devonian shales and siltstones is so well developed that these rocks were quarried for slate in the past in the Lehigh Gap area.

Three decollements, or zones of

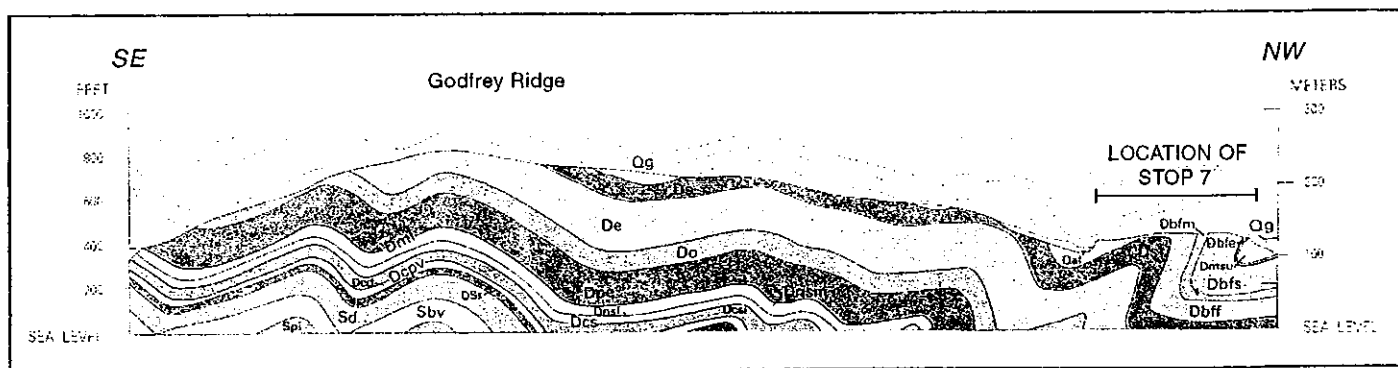


Figure 13. Cross section through Godfrey Ridge showing an overturned anticline in the railroad cut south of I-80 in East Stroudsburg, Pa. Spi, Poxono Island Formation; Sbv, Bossardville Limestone; DSr, Rondout Formation; Dcpv, Peters Valley Member of the Coeymans Formation; Dcd, Depue Limestone Member of the Coeymans Formation; Dcs, Stormville Member of the Coeymans Formation; Dcs, Shawnee Island Member of the Coeymans Formation; Dnsf, Flatbrook Member of the New Scotland Formation; Dnsm, Maskenozha Member of the New Scotland Formation; Dmi, Minisink Limestone; Dpe, Port Ewen Shale; Do, Oriskany Group; De, Esopus Formation; Ds, Schoharie Formation; Dbff, Foxtown Member of the Buttermilk Falls Limestone; Dbfm, McMichael Member of the Buttermilk Falls Limestone; Dbfs, Stroudsburg member of the Buttermilk Falls Limestone; Dbfe, Echo Lake Member of the Buttermilk Falls Limestone; Dmsu, Stony Hollow and Union Springs Members of the Marcellus Shale; Qg, Wisconsin glacial deposits; Qal, alluvium. Modified from Epstein, 1989.



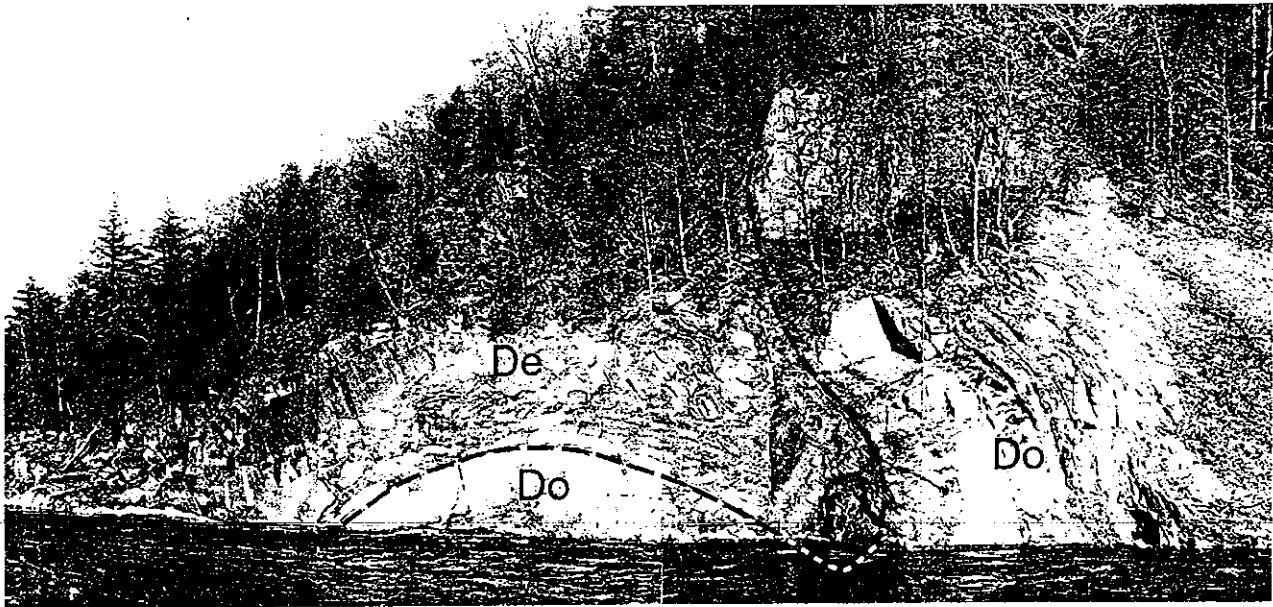


Figure 14. Typical overturned fold in lithotectonic unit 3 along Brodhead Creek, one mile west of the village of Delaware Water Gap. Do, Oriskany Group, comprising the Ridgely Sandstone at the top and Shriver Chert in slope to right; De, Esopus Shale. View looking south. Outcrop is the same structure as in the northwesternmost syncline at depth in the cross section in Figure 13.

The movement between lithotectonic units 3 and 4 occurred within the Marcellus Shale. In the Lehigh Gap area, about 30 miles southwest of the Delaware Water Gap, the Marcellus is extensively faulted (Epstein et al., 1974) in a zone several hundred feet thick.

The intensity of deformation in the Valley and Ridge in the Field Conference area decreases to the northeast from Pennsylvania, through New Jersey and into New York (Figure 10). Southwest of Delaware Water Gap, as at Lehigh Gap, many of the folds are recumbent and isoclinal, and continued tightening has produced faults in lithotectonic units 1 and 2 because of insufficient space in the cores of anticlines (Epstein et al., 1974). The amplitudes of folds are greater in this area. The Appalachian Mountain section of the Valley and Ridge province is far wider than to the northeast (40 miles wide west of Lehigh Gap compared to not more than 5 miles wide east of Delaware Water Gap), and slaty cleavage is developed to a greater degree in younger and younger rocks. For example, whereas slate has been quarried in the Martinsburg throughout eastern Pennsylvania, it has been quarried in a shaly interval in the Mahantango Formation near Lehigh Gap (Behre, 1933, p. 121).

### **A WORD OR TWO ABOUT 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 was considered a metamorphic process, occurring during elevated temperature and pressure. Slaty cleavage is well developed in pelitic rocks of the Martinsburg Formation. The Martinsburg has been quarried for slate since it was discovered about 1808.

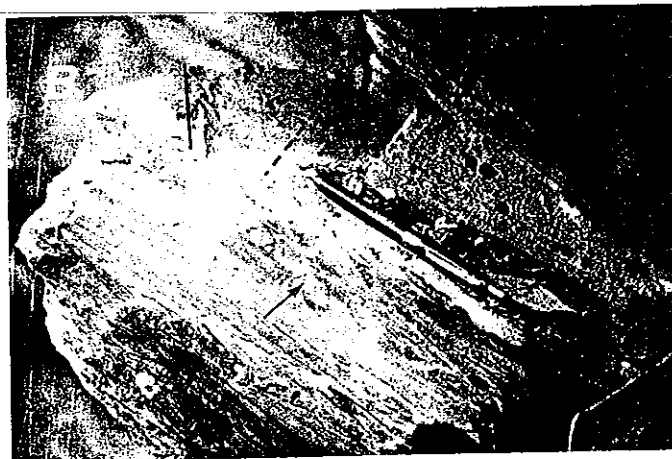


Figure 15. Sandstone dikes in the Martinsburg Formation along US Route 46 south of Delaware Water Gap. A. Dike #1 in Figure 16, same dike as shown by Maxwell (1962, Fig. 4A). Cleavage (dashed line) dips  $8^\circ$  less than the dike. Mud from the overlying bed replaced the evacuated sand and formed a mud dike in the graywacke. A poorly developed cleavage in the graywacke is about  $10^\circ$  steeper than the mud dike. B. Another sandstone dike at this locality (# 2 of Figure 16).

cleavage in the water-bearing muds. Note, however, that the dike is not parallel to the slaty cleavage in Figure 15A. There are several other dikes extending down from the parent bed (Figure 16). None of these are parallel to the cleavage. They vary considerably in dip, dip direction, and strike. In one case (dike #2, Figure 15B) 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 17. 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.

South of Columbia, NJ, the Martinsburg Formation is exposed in continuous outcrops along US 46. Here, about 5 miles south of Delaware Water Gap, is an exposure of interbedded graywacke and slate in the Ramseyburg Member of the Martinsburg. Based on interpretation of a sandstone dike intruded down from a graywacke bed and into the cleavage of the underlying slate, 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 the cleavage was the result of only slight stress on pelitic sediments with high porewater 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 ideas 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 450 hits for *slaty cleavage*).

Figure 15A is a photo of the dike that Maxwell first discovered that stimulated his interpretation of a nonmetamorphic 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

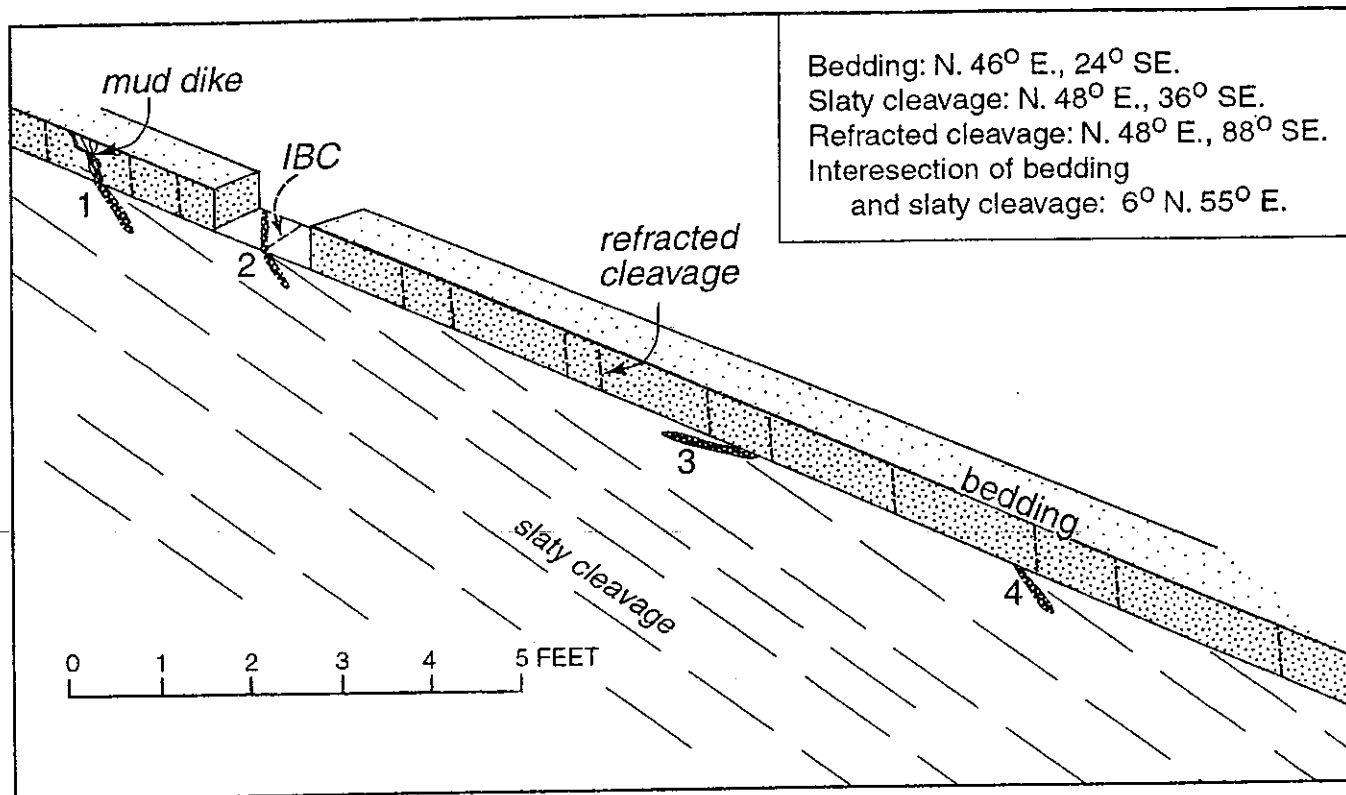


Figure 16. Sandstone dikes extending down from a graywacke bed into slate in the Ramseyburg Member of the Martinsburg Formation, along US 46, five miles south of Delaware Water Gap. North is to the left.

1. Sandstone dike shown in Figure 15A 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 15B. 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 17 shows the details.
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.

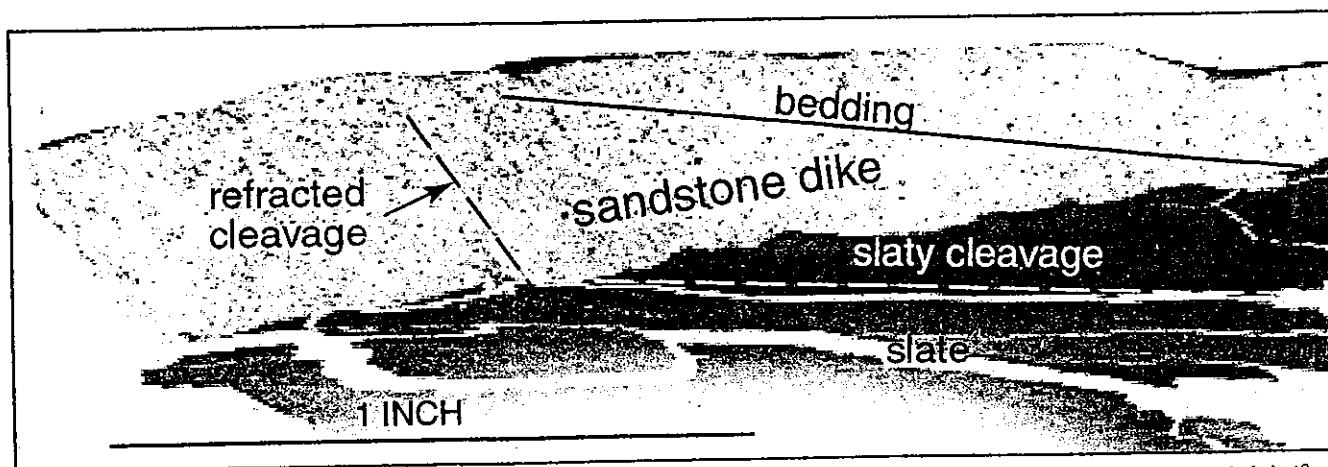


Figure 17. Scanned thin section of sandstone dike #3 shown in Figure 16. The dike dips to the southeast (to the right) 4° less than bedding and slaty cleavage dips 9° more than the dip of the dike. Irregular fracture at word "slate" is pull apart in thin section.

I have concluded (Epstein and Epstein, 1967; Epstein, 1974) 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, but we try a stab at it under *Structural relations along the Taconic unconformity between New York, New Jersey, and Pennsylvania* (Epstein and Lyttle, 2001, p. 22). Some of the thoughts and data used to reach this conclusion are listed here, without going into great detail:

- (1) An Alleghanian age for the regional slaty cleavage is supported by  $^{40}\text{Ar}/^{39}\text{Ar}$  whole-rock analysis from the Martinsburg Formation at Lehigh Gap (Wintsch et al., 1996).
- (2) The arching of cleavage in different stratigraphic levels and at different places in the Martinsburg Formation as the contact with the overlying Shawangunk is approached demonstrates a post Silurian age for the cleavage. It is not due to Alleghanian folding of a Taconic cleavage as suggested by Maxwell (1962) and Drake et al. (1960).
- (3) There are many examples of bedding-plane slickensides that are cut by cleavage in the Martinsburg as well as in younger formations. This indicates that the Martinsburg was competent enough to deform by flexural-slip prior to passive deformation and does not support the hypothesis that the cleavage was imposed upon a water-bearing pelite.
- (4) The mica in the slate is 2M muscovite as shown by X-ray analyses. This, along with chlorite porphyroblasts, 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.
- (5) 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 (1914, p. 108) and Behre (1933, p. 119).
- (6) 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).

In summary, in easternmost Pennsylvania and northern New Jersey the prominent slaty cleavage in the Martinsburg Formation is not Taconic in age, but formed during the latest Paleozoic deformation at the same time cleavage formed in post-Ordovician rocks. The folds associated with the regional cleavage are Alleghanian. However, with some difficulty, as discussed by Epstein and Lyttle (2001) folds of Taconic age can be resolved from the complex fold package in this part of the Appalachians.



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# PALEONTOLOGICAL INVESTIGATIONS OF THE NEW JERSEY STATE MUSEUM IN THE DELAWARE WATER GAP NATIONAL RECREATION AREA

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**ABSTRACT:** Geological investigation of the eastern United States began in the latter portion of the eighteenth century, culminating in the production of the first geologic map in 1809. Shortly thereafter, formalized study of the Appalachian region began. A significant portion of the resulting stratigraphic and paleontological knowledge was obtained from field work completed in the New York-New Jersey-Pennsylvania corridor. Although the Delaware Water Gap National Recreation Area was not established until 1965, several published sections and at least one stratigraphic type section are located within its boundaries. Paleontological type specimens, mostly collected before the area received National Park Service status, pepper the Paleozoic collections of major institutions.

The first comprehensive research completed on the paleontology of the region was that of Stuart Weller (1903). Additional surveys by Herpers (1949), Beerbower (1959), Epstein et al. (1967), Parris et al. (1979-1984), and others, have re-emphasized the importance of the regional fossil resources to the interpretation of its geologic history.

Geologic variation and complexity, both horizontal and vertical, characterize the Paleozoic rocks of the Appalachian belt. Significant exposures occur in the tracts now under the authority of the National Park Service. Conservation of resources in this potentially valuable research area and the realization of its educational potential are priorities in the Delaware Water Gap National Recreation Area, and the New Jersey State Museum remains a strong partner with the National Park Service in such efforts.

**INTRODUCTION:** Paleontological research in the Delaware Water Gap region has been linked historically with the stratigraphic study of the Appalachians. The early colonists and explorers must have been particularly interested in the great mountain system that impeded travel routes to the west, and seemed to stretch interminably in linear fashion from northeast to southwest. Presumably, the possibilities of resources and economic exploitation were considered from the earliest times.

Reportedly, among the first strictly geologic features to be described in the colonies was a petroleum spring, discovered by Jesuit missionaries in 1656. Just before the American Revolution, Lewis Evans denoted the Devonian strata of New York (Wells, 1963), and a great surge of investigation began into the Paleozoic rocks of the Tristates area. By 1803, C.F.C. Volney had produced the first color geologic map of the United States. This was followed in 1809 by a detailed geologic map of the eastern United States, published by Philadelphia William McClure (Chrastina and Jones, 1989). By 1830, formalized investigation of the Appalachian region began, more especially in the New York-New Jersey-Pennsylvania corridor, a center of early American population and economic development. By 1868, George H. Cook, New Jersey's first State Geologist, had published the first extensive contribution to New Jersey geology (Cook, 1868). Two years later, Brodhead completed a 276-page book on the natural

wonder known as the Delaware Water Gap (Brodhead, 1870). With such attention being drawn to the region now occupied by the Delaware Water Gap National Recreation Area, it is not surprising that paleontologists flocked to the area for even more detailed research.

Fossils are extremely valuable guides for untangling stratigraphic questions, such as relative age or the lithologic identities of discontinuous exposures of strata. It is interesting to note that serious mistakes concerning Appalachian stratigraphy were promulgated and persisted for almost fifty years before 1840 until proper attention was given to the invertebrate paleofauna of the region (Cooper, 1971). Hall and Clarke were among the first geologists to seriously address the vast resources of Paleozoic fossils. Their monographs on the Paleozoic invertebrate fauna of New York (Hall, 1843, 1857, 1862-1866; Hall and Clarke, 1888, 1893, 1894) also contained superb scientific illustrations of the fossil record known at that time, and these remain extremely valuable references for species identifications.

Although most reviews of the fossil record in the region tend to emphasize the Paleozoic record and its invertebrate fossil resources, Pleistocene (Ice Age) deposits are also widespread there, which are also of considerable paleontologic interest. Bog deposits in the vicinity of the National Recreation Area have yielded both vertebrate and invertebrate (freshwater molluscan) fossils, and occasionally cave deposits have produced mammalian fossils. With the exception of the Marshall's Creek Mastodon recovery (Hoff, 1969), little direct research has been focused upon the Pleistocene paleontology of the region during recent decades, so considerable potential exists for future investigations.

Another sector ready for re-investigation is the paleobotanical record of the region. While plant fossils are generally uncommon and fragmentary in the primarily marine Paleozoic formations, paleobotanists have made enormous strides in the interpretation of such materials. Fragmentary plant material of the Devonian formations, reported periodically in the past, is due for re-investigation. The genus *Psilophyton* was then widely distributed, but the generally poor preservation of the reported material has discouraged researchers.

It is impossible within the scope of this brief review to adequately credit all who have contributed to the understanding of paleontology in the Delaware Water Gap National Recreation Area. However, it is important to note that many of those who contributed greatly in the past include authorities who may not have worked within its boundaries (or only occasionally did). Among these, Vanuxem (1842), Mather (1843), White (1882), Schuchert (1897), Swartz (1939), Willard et al (1939), Oliver (1967), Boucot et al. (1969), and Babcock and Feldman (1986) were significant contributors. As work progresses on local paleontology, it has become apparent that the stratigraphy and paleontology of the Recreation Area, especially in New Jersey, have a significant role in our understanding of Ordovician, Silurian, and Devonian paleoecologic and stratigraphic transitions between Pennsylvania (the central expanse of the Appalachians) and New York (the northern expanse). This role was little known when the Recreation Area was established, and presumably was not a significant factor among the political considerations that led to its preservation by the National Park Service. The Recreation Area should now be considered a scientific treasure of first magnitude.

**HIGHLIGHTS OF PALEONTOLOGIC RESEARCH:** Stuart Weller was the first individual to seriously address the paleontology of the Delaware Water Gap region. His preliminary work along the Walpack Ridge (Weller, 1900) and the Kittatinny Valley (Weller, 1901) laid the groundwork for his notable monograph on the New Jersey Paleozoic faunas (Weller, 1903). The New Jersey State Museum, chartered in 1895, became the ultimate repository of Weller's collections, some of which were from sites no longer accessible. In spite of continuing taxonomic and stratigraphic reinterpretation, Weller's monograph remains a highly valuable resource for specimen comparison and identification (albeit sometimes difficult to obtain). No comparable work has appeared since then.

Considering the impetus given to paleontologic research in the area by Weller, it is perhaps not surprising that few investigations occurred in the next few years. It was not until after the Second World War that Henry Herpers followed with works on the fossils of the Esopus, Schoharie, and Rondout Formations and, most especially, the conulariids (Herpers, 1949, 1950, 1951). His specimens, including the Type of conulariid *Reticulaconularia sussexensis*, are part of the New Jersey State Museum's collections. Herper's interest in the conulariids laid the groundwork for augmenting the museum's holdings of Conulariida, an emphasis that continues today (Albright, 1995).

The Conulariida of the Delaware Water Gap National Recreation Area deserve special note. These extinct, strangely pyramidal fossils of the Paleozoic are nowhere common, but the Recreation Area has yielded a significant number of them from a variety of horizons. Although the systematics of the group have been revised by Babcock and Feldmann (1986), conulariids remain a mystery from the paleobiological standpoint. The generally well-preserved specimens from the Delaware Water Gap region are among the resources used by the international scientific community to further define evolutionary lineages of the group (Van Iten, 2000).

Among vertebrate fossils the Delaware Water Gap is known for the Paleozoic fish first discovered by Beerbower and Hait (1959) in the Silurian Bloomsburg (then called High Falls) Formation. These specimens, among the oldest known vertebrates, are of the very primitive jawless fish known as ostracoderms. Several genera of the Family Cyathaspididae are known, although most of the specimens are fragmentary shield plates or scales, making identification difficult. Close examination of the specimens reveals fine grooves, resembling fingerprint textures, thus the specimens are not so lacking in detail as they appear in superficial examination. Hoskins (1961) discussed these fossils in a more inclusive paper on the stratigraphy and paleontology of the Bloomsburg Formation in Pennsylvania. More recent surveys by Parris and Albright (1979), performed under National Park Service encouragement, have encountered a number of additional sites for such specimens. While they are still considered scarce, it now appears that these fish remains are more abundant than previously believed. The New Jersey State Museum is again the repository for many of these specimens, including virtually all of those collected during recent decades.

Eurypterid fossils are known from the Silurian Shawangunk Formation of the Delaware Water Gap region in both New Jersey and Pennsylvania (Epstein and Epstein, 1972). Specimens from sites surveyed by the New Jersey State Museum (such as those in the Yards Creek Pumped Storage Facility) were identified by the late Carol Faul (1987) as *Hughmilleria* cf. *shawangunk* Clarke and other taxa.



A successful partnership in paleontological investigation commenced in 1984 when the Eastern Parks and Monuments Association offered financial support to the New Jersey State Museum for an investigation into fossil resources of the Ordovician System in Delaware Water Gap and nearby areas. The known resources consisted primarily of graptolite fossils, an extraordinarily challenging and facies-controlled group. The few specimens found anywhere in New Jersey had practically all come from localities noted by Weller (1903), and few had been found in subsequent years. The first year of fieldwork (Parris and Cruikshank, 1984) proved so successful in relocating old localities and finding new ones that investigations have continued to the present day (Parris and Cruikshank, 1993; Parris et al., 2001). Considerable improvement of biostratigraphic and structural interpretation of Ordovician strata has taken place due, in part, to the high number of recovered, identifiable specimens – an extremely unusual situation because the fossils occur in metamorphic rather than sedimentary terrain.

Trace fossils have been reported from the Paleozoic formations since the earliest geologic investigations, but have received additional significance as a result of current work. Formed as a result of feeding, burrowing, and other movements, or as a result of other biologic activity, trace fossils may be highly characteristic of the formations in which they occur. Perhaps best known is *Arthropycus*, which is especially prominent in the Shawangunk Formation, and known to Appalachian Trail hikers. A second example, *Taonurus caudigalli*, is essentially a lithologic characteristic (as well as a fossil) in the Esopus and Schoharie Formations. Current investigations and collections by Robert Metz (1998), Kean University, have been placed in repository at the New Jersey State Museum.

Another major advance in geologic knowledge of the region occurred when Spink (1967) reinvestigated the stratigraphy of the Paleozoic formations of northwestern New Jersey, concentrating on the exposures at the William and Sanford Nearpass Quarries, now located just north of the current limits of the National Recreation Area. Here the formations most nearly resemble their New York State equivalents. Faunal inventories illustrated the relationships of the sites to New York sites. Simultaneous work by Spink in cooperation with Epstein et al. (1967) produced representative models and types for the formations and members, where reference collections of comparative fossils could be made. Within the Recreation Area, type sections were established for: Flatbrookville and Maskenozha Members of the New Scotland Formation (Lake Maskenozha Quadrangle), Peters Valley Member of the Coeymans Formation (Flatbrookville Quadrangle), and Shawnee Island and Depue Limestone Members of the Coeymans Formation (Bushkill Quadrangle).

Diminutive fauna from the Marcellus “shale” was extensively collected during the 1970’s and 1980’s by museum staff. There are two extant New Jersey localities as well as many outcrops along U.S. Route 209 in Pennsylvania. Fossils are found less often from the latter sites, and talus from the overlying Mahantango Group often obscures the exposures and may confuse collectors as to a fossil’s horizon of origin.

The Marcellus “shale” in New York was subsequently revised by C.A. Ver Straeten et al. (1994), raising the level of the Marcellus to “subgroup” status and subdividing it into two formations – a lower Union Springs Formation and an upper Mount Marion Formation. Yolton (1967) had reported occurrences of *Agoniatites vanuxemi* from Sandyston Township in northwestern New Jersey, and museum staff have recovered such specimens from two sites in Pennsylvania formerly believed to be lowermost units of the Mahantango. Since *A. vanuxemi* is now recognized to be an index fossil for the uppermost unit of the Marcellus, the Mount Marion

Formation, it would appear that the restricted black Marcellus "shale" of New Jersey is a narrow paleoenvironmental horizon within the Mount Marion.

In terms of vertical and lateral expanse, the Devonian Mahantango Group assumes an important role in the Recreation Area. Exposures are confined to Pennsylvania, but run essentially the entire length of the Recreation Area. The famed Centerfield Horizon is well known to professional and amateur collectors (Willard et al., 1939; Beerbower, 1956). As noted by Parris and Albright (1980), it is this stratigraphic unit that offers the most potential for interpretive programming by the National Park Service and other interested groups.

A number of excellent field guides and road logs exist for the area (Epstein and Epstein, 1967, 1969); Herpers, 1952; Johnson and Willard, 1957; Parris et al., 1987; Ramsdell, 1970, 1982, 1983, 1984, and Ramsdell and Luedemann, 1978. Most illustrate the paleontology of the region, but stratigraphic information and structural interpretations are included as well.

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**FUTURE RESEARCH POSSIBILITIES:** Important investigations continue in the Delaware Water Gap National Recreation Area. The fossil resources have received first magnitude priority from the National Park Service, and both protective and interpretive aspects of these resources are being adequately considered. While interpretive programming should be expanded, the non-renewable nature of the resources must be emphasized. Certainly any action that would result in eventual destruction or diminished access to a site must be viewed cautiously and with attention to the potential for information loss. At the same time, qualified research must be allowed to continue as new questions arise and new analytical technologies become available. The New Jersey state Museum, repository of many of the collections from the region, remains available to assist future research.

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# THE TOCKS ISLAND DAM AND OTHER DAMS PROPOSED FOR THE DELAWARE

by  
David P. Harper

The Delaware River (figure 1) has been described as the only major free flowing river in the United States east of the Mississippi. This is not from lack of dams on tributary streams, dam proposals for the main stem, or adequate dam sites. Also, it does not imply an absence of water management within the basin. Proposals for dams along the Delaware have been under discussion from early in the 19<sup>th</sup> century, dams have been proposed at many locations, and there are numerous dams on tributary valleys for water supply, flood control, and low flow augmentation. The main stem of the Delaware, however, originates along the New York-Pennsylvania state line at the confluence of its East and West Branches, and follows state lines all the way to Delaware Bay. Proposals were seldom seen as equally beneficial to states on both sides of the line, and were repeatedly blocked by political interests in the seemingly disadvantaged state. Many of the projects were blocked using a 1783 treaty between New Jersey and Pennsylvania which prohibited dams by declaring the Delaware to be "... a common highway, equally free and open for use, benefit, and advantage of each state...". Only wing dams (which did not extend across state boundaries), and the Lackawaxen Dam (part of the Delaware and Hudson Canal) were completed. The Lackawaxen Dam was built in 1825, increased in height in 1848, and maintained until the canal was abandoned in 1898.

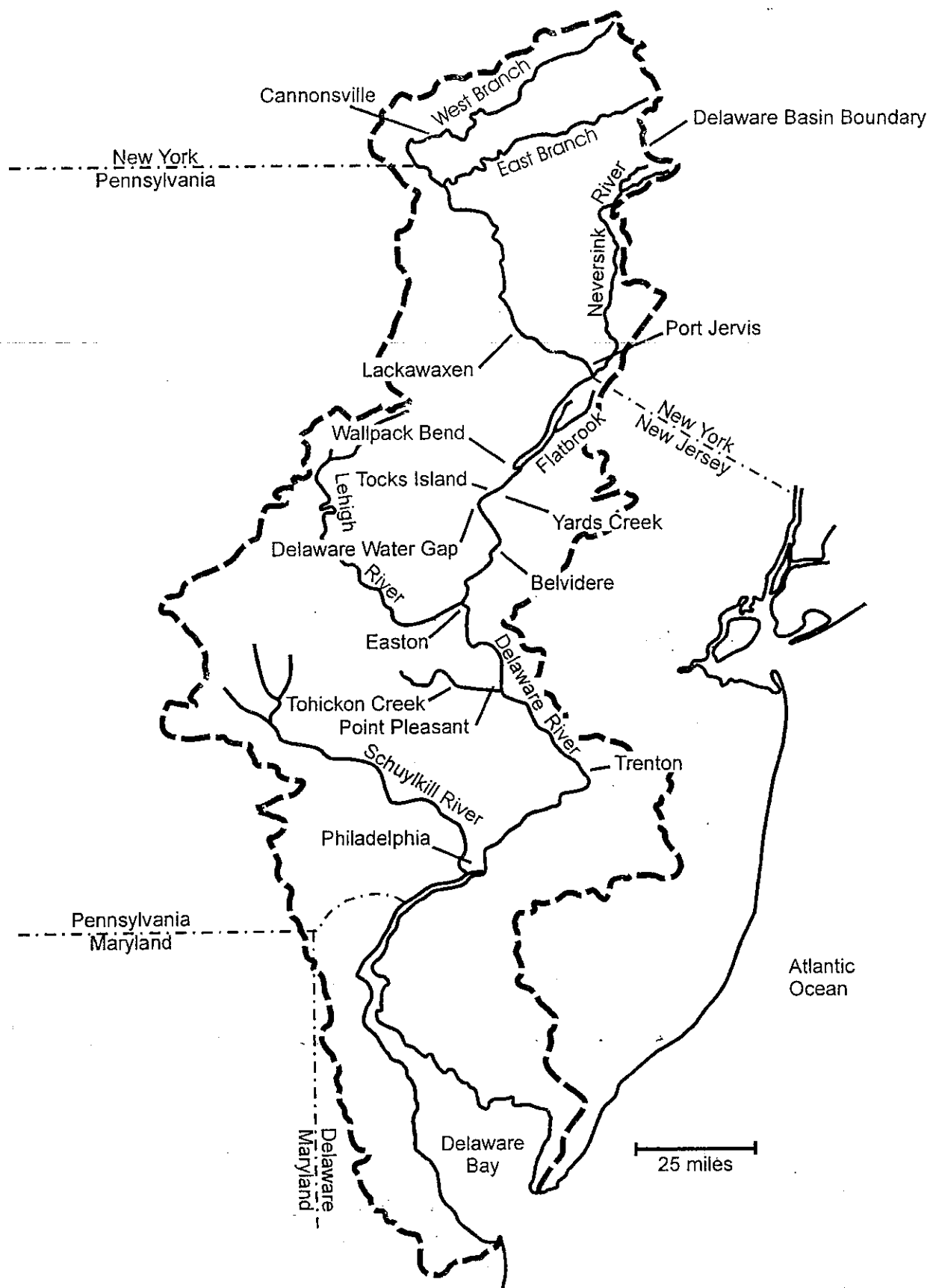
The most recent dam proposal for the main stem, authorized by Congress in 1962, was for a large multipurpose dam at Tocks Island, a short distance upriver from the Delaware Water Gap. Geologic conditions at Tocks Island were not ideal, but were amenable to engineering solutions. The project initially enjoyed wide public support, and the 1783 New Jersey – Pennsylvania treaty had been repealed by both states. Construction appeared certain. Repeated delays, however, mostly due to budget shortfalls, pushed the scheduled groundbreaking to 1975. By this time, the project had become politically untenable. Within weeks of the scheduled groundbreaking, the governors of New Jersey, New York, and Delaware went on record as opposing the dam. The project was formally deauthorized in 1992. Subsequent to rejection of the Tocks Island Dam, Delaware Basin water resources have been managed based on a "Good Faith" agreement administered by the Delaware River Basin Commission.

This history is presented in "Damming the Delaware," by Richard C. Albert. The unattributed historical material in this article is summarized from that thorough treatment. The reader is referred to Mr. Albert's book for further detail.

## Wing Dams and Canal Diversions - 1800-1840

The 1783 treaty was intended to protect navigation, primarily lumber rafting, but remained in effect long after the last lumber raft traveled the Delaware in 1923. In the early 1800s, lumber rafting grew rapidly at the same time as numerous wing dams and canals were built. Although the treaty applied to wing dams and diversions as well as larger dams, both New Jersey and Pennsylvania violated the

**Figure 1.** Map of Delaware River drainage basin showing features mentioned in text.



treaty by unilaterally permitting the construction of numerous wing dams to serve mills and divert water to canals. The dams and canals were built despite vigorous legal and physical protest.

One of the higher profile legal disputes ensued in 1815 from New Jersey's approval of a wing dam. The dispute appeared to be headed for the U. S. Supreme Court until a survey of wing dams between Trenton and Belvidere found that most were on the Pennsylvania side of the river and most interfered with navigation.

In 1823, the 72-mile long Lehigh Canal opened to transport anthracite to the Delaware at Easton, and work had begun on Delaware Canal, paralleling the Delaware River downstream from Easton. The Delaware Canal would require diversion of Delaware River water at Easton, and this diversion was strenuously contested by New Jersey. Despite the unilateral Pennsylvania diversion, the 1824 New Jersey charter for the Delaware and Raritan Canal included a provision that, because of the treaty, Pennsylvania's approval was required for water diversion. Pennsylvania set unreasonable requirements for consent, and the originally chartered company did not build the canal. In 1828, the Circuit Court for New Jersey found that Pennsylvania's consent for the water diversion was not required so long as navigation was not affected. By this time a different company had already completed the canal.

Opposition was more physical at the Lackawaxen Dam, built to allow boats on the Delaware and Hudson Canal to cross the Delaware. The dam was a major hazard for lumber rafters, and the rafters made their annoyance known by repeatedly ramming canal boats, and by fighting, beating, and sometimes shooting the boat operators. In 1829, explosives were used to destroy an 80-foot section of the dam (Dale, 1996). This opposition and persistent delays at the crossing led to the 1849 construction of the Roebling Aqueduct, safely above the lumber rafters. The dam was not decommissioned, but was instead raised from a 7-foot-high slack-water barrier to 16 feet, and equipped with a chute for the rafts (Dale, 1996). It remained in place until the abandonment of the canal in 1898.

Following completion of the canals and the ascendance of steam over water power, there was limited interest in Delaware River dams and diversion for several decades. The formerly controversial topic became dormant until hydroelectric power generation became feasible.

#### Hydroelectric Generation Proposals - 1894 – 1920

New Jersey was the first state to become involved in evaluation of the Delaware for hydroelectric generation with the publication in 1894 of a survey of the water supply and water power potential of New Jersey rivers (Vermeule, 1894). In 1897, New Jersey's legislature enacted a law allowing companies to be formed for the construction of dams for power generation. The law clearly included the Delaware as dams were limited to a height of 10 feet and were required to have chutes for lumber rafts and shad.

The first survey of the Tocks Island site for dam construction may have been for a 1902 proposal for a "Delaware Water Gap Power Company". The company appears, however, to have been the



summer project of wealthy, bored vacationers at a local resort. The proposal was not pursued further.

The New York State Water Supply Commission put forth the first serious hydropower proposal in 1907. The proposal included four dams: three hydroelectric dams across the Delaware and a larger water regulation dam and lake near Cannonsville. An even larger concurrent proposal included forty power supply dams upstream from Port Jervis. A major problem for both proposals was the lack of enough local customers. Construction was never begun on either project.

A more realistic hydropower proposal involved a dam near Belvidere. This raised the issue of the 1783 treaty. In the opinion of Pennsylvania's Attorney General, "While this agreement remains in force, the only method by which permission could be legally secured to dam the Delaware River, would be by concurrent legislative action by both states." Despite efforts over an 8-year period, legislative action was not forthcoming, and the dam was not built.

The most ambitious power generation proposal to involve the Delaware was the "super-power system" proposed in 1918 by the president of the New York, New Haven, and Hartford Railroad. This was a system of hydroelectric dams and steam generators stretching from Boston to Washington. The primary customers were to be railroads, and the power would have allowed electrification of 19 thousand miles of tracks in the region. Six flow regulating reservoirs and sixteen power supply dams were proposed for the Delaware basin. Probably because of costs exceeding one billion 1920 dollars, the system was never built.

While hydropower continued to be a consideration in dam proposals up to and including Tocks Island, it became clear through a series of proposals and controversies in the 1920s that the water supply needs of the region were more important than hydroelectric power needs. Water supply and stream flow maintenance became the primary focus of water management, with hydropower, flood control, recreation, irrigation, and navigation assuming lesser importance.

### Public Water Supply

The major public water supplies depending in whole or part on Delaware River water are Philadelphia, New York City, and northern New Jersey. Public water supply came to these areas beginning about 1800 in response to devastating fires and water born diseases that killed thousands each year. One fire in New York, for example, in 1835, burned 700 buildings and bankrupted every insurance company operating in the city. The oldest water supply system in the area is Philadelphia's, funded and built according to Benjamin Franklin's will, and opened in 1801. The system initially used water from the Schuylkill River, and later the Delaware. Eventually about half of the water was from the Delaware. Both rivers were polluted to begin with, and pollution worsened as Philadelphia and upstream cities grew, industrialized, and built sewers. Alternatives to the grossly polluted local supplies began to be investigated by the 1850's with reservoirs proposed in neighboring Bucks and Montgomery Counties. One of the Bucks County proposals, in an 1883-85 series of studies, envisioned, initially, a water powered pump station at Point Pleasant on the Delaware and, eventually, reservoirs upstream from the Delaware Water Gap. The water was to be pumped from Point Pleasant, and eventually from the Poconos, to a reservoir on Tohickon Creek,

then delivered to Philadelphia. While Philadelphia's engineering staff recommended this solution and continued to recommend upstream water sources in numerous reports at least until the 1970s, the recommendations were not supported until the 1950s in part because there continued to be influential citizens of the opinion that cheaper local water could be made fit for drinking by filtration. Sand filters were eventually installed between 1899 and 1911. They removed the threat of water-borne diseases, but did little to help the taste and odor. The water supply remained offensive and the butt of jokes until decreased contamination and improved treatment became effective in the 1950s.

Public water supply was a later development in New York City, with the first water delivered from the Croton Reservoir in 1842. The Croton system was repeatedly enlarged from then until 1906, when the massive New Croton Dam was completed. Further enlargement was prohibited after 1906 by the Smith-Dutchess County Act, which forbid additional water diversions from counties in the vicinity of New York City. This focused New York's attention first on the Hudson basin portion of the Catskills, then, by 1920 when the Catskill reservoirs proved inadequate, on the Delaware Basin.

Like New York City, northern New Jersey began looking to the Delaware Basin for water in the 1920s. A 1921 study proposed four alternatives, two of which depended on Delaware River water. The first of these proposed a reservoir in the Raritan Basin above Somerville, which would meet needs for some time. When increased needs required additional water, the system was to be augmented by pumping Delaware Basin water into the Raritan basin near Clinton. The other proposal, known as the Long Hill project, called for eight reservoirs to be built over many decades as need required. The final installation was to be a pump station on the Delaware near Wallpack Bend capable of delivering 1,500 mgd. This was twice the projected need for 1970.

A 1925 study recommended, instead, a reservoir at Chimney Rock, eventually to be fed by New Jersey's Delaware tributaries. A pump station was projected to be necessary eventually on the Delaware at Belvidere.

Following abandonment in 1934, the Delaware and Raritan Canal was proposed in 1938 for diversion of Delaware River water to the Raritan Basin. Of New Jersey's Delaware River diversion proposals, only the Delaware and Raritan Canal diversion was carried out. That diversion was not begun until the mid 1950s.

By the mid-1920s, in order to overcome numerous interstate disputes, a tri-state commission had proposed a water sharing scheme to: 1) allow each state a proportional share of Delaware River water, and 2) maintain minimum downstream flows. Objections were raised, however, that New York City would be the immediate beneficiary of approval as its plans for diversion (involving reservoirs on the East and West Branches of the Delaware and on the Neversink) were furthest along and that Pennsylvania was short-changed because the formula for water division did not recognize that a large percentage of the Delaware basin is in Pennsylvania. Additional objections to this and other plans were raised by the Lehigh Coal and Navigation Company, which had been granted diversion rights to the Lehigh River during building of the Pennsylvania Canal one hundred years earlier. This company had influential Pennsylvanians as friends and a corporate interest in seeing

that potentially competing entities did not develop water systems along the Delaware. While New York approved the proposal, New Jersey and Pennsylvania did not.

A revision which overcame some of the objections was strongly opposed by the City of Trenton, which contended that the Delaware would become a "mere brook" during the summer months. More than quantity, water quality was at issue. The Trenton water supply was experiencing severe quality problems when thunderstorms flushed industrial wastes and coal debris from the Lehigh watershed, and city officials worried that water quality under the additional diversions would force weeks of shutdown or even abandonment of the Delaware intakes. Again the compact did not pass the three legislatures as required. At this point, New York City sought and obtained legal opinions that it was entitled to a share of Delaware Basin water and, at the same time, notified New Jersey and Pennsylvania that it intended to build dams in the Delaware Basin. New Jersey initiated a lawsuit to bar the New York diversions. Pennsylvania soon entered the case, not to bar the diversions but to ensure an equitable allocation for itself.

In 1934, the Supreme Court recognized New York's right to divert water from the basin, with Justice Oliver Wendell Holmes declaring that:

"A river is more than an amenity, it is a treasure. It offers a necessity of life that must be apportioned among all those who have power over it. New York has the physical power to cut off all water within its jurisdiction. But clearly the exercise of such power to the destruction of the lower states could not be tolerated. And on the other hand, equally little could New Jersey be permitted to require New York to give up its power altogether in order that the River might come down undiminished. Both States have real and substantial interests in the River that must be reconciled as best they may be. The effort is always to secure an equitable apportionment without quibbling over formulas."

The decision went on to outline rules that would govern Delaware River diversions for decades, but New York was unable to complete the proposed reservoirs initially because of budgetary constraints during the depression, then because of World War II.

Water supply plans for New York, New Jersey, and Philadelphia continued to be proposed and debated in the following decades, particularly after 1934, when the first of a series for "308 Reports" covering the Delaware Basin was published. The 308 Reports were prepared pursuant to House Document 308, authorizing the U.S. Army Corps of Engineers to evaluate rivers where power development might be feasible in conjunction with navigation, flood control, and irrigation needs. The 308 Reports for the Delaware Basin included water supply, even though this was not specifically authorized, because this was "...the most important consideration in connection with any large-scale development of the river." (U.S. Congress, 1934). The federal government was not significantly involved in water supply projects at this time, and, due to limited navigation and lack of serious flooding prior to 1955, involvement of the Corps on the main stem above Trenton was minimal following publication of the 308 reports. The Corps had been, and continued to be, involved in navigation projects in the lower Delaware Basin (including the channel dredging, the Chesapeake and Delaware Canal, and harbor improvements) and flood control in tributary basins (including the Lehigh and Lackawaxen basins).

While proposals continued to be debated, actual work on major water supply projects in the basin was not resumed until the mid-1950s. At this time, New York was prepared to begin work on upper Delaware reservoirs redesigned from its 1920s proposal, New Jersey was prepared to begin diversions to the Raritan Basin by way of the Delaware and Raritan Canal, and Pennsylvania and New Jersey were moving towards cooperation on a dam at Wallpack Bend. Neither the New York project nor the canal diversion were in accord with the allocations approved in the 1931 Supreme Court decree, and work was delayed until Court approval in 1954 of an agreement negotiated by New York, New Jersey, and Pennsylvania.

### The Tocks Island Dam Proposal

Most major water supply proposals subsequent to 1885 for Philadelphia and 1921 for northern New Jersey called for dams or pumping stations to eventually be constructed on the upper Delaware. Tocks Island was not generally the proposed location. In a number of the studies, dams were proposed at Wallpack Bend, about 10 miles to the north. At Wallpack Bend the structure could be smaller and anchored into rock. By 1931, it was generally assumed that a dam would eventually be built at Wallpack Bend, and this assumption was embodied in provisions of the 1931 Supreme Court decision. The first serious evaluation of Tocks Island as a dam site was in the Corps of Engineers 308 Report released in 1934. The report found it to be promising. The Wallpack Bend site was more favorable for construction, but did not maximize reservoir capacity. Reservoir capacity along this section of the Delaware is limited by the expense and political impracticality of flooding Port Jervis to the north and the Water Gap to the south. Within these constraints, moving the dam downstream from Wallpack Bend to Tocks Island gained a relatively small amount of storage by increasing the length of the reservoir along the main stem Delaware valley and a substantially greater volume of storage by capturing tributary storage in the Flatbrook valley.

Further federal involvement was limited, until 1955, to test borings completed in 1942 for a navigation project. A dam at Tocks Island was under consideration as a source of fresh water to forestall contamination of aquifers by salt water along a proposed sea level canal from Bordentown to Raritan Bay. Borings to 140 feet did not reach rock, and the site was rejected as unfeasible or excessively costly.

By the early 1950s, preparatory work towards a dam at Wallpack Bend was proceeding quickly. In Pennsylvania, population and water use were expanding rapidly. In New Jersey, the Delaware and Raritan Canal diversion had not addressed northern New Jersey's water needs. By 1955, both states had repealed the anti-dam provisions of the 1783 treaty, an extensive study of the benefits of a dam at Wallpack Bend had been completed, and it had become evident that New Jersey might work in partnership with Pennsylvania on such a dam.

The project changed dramatically in 1955. The year started out very dry, and by mid-August a severe drought appeared imminent. This changed quickly. On August 12, Hurricane Connie dumped up to 12.5 inches of rain in the Delaware watershed. On August 18 Hurricane Diane dumped an additional 11 inches of rain on the already saturated soils. The ensuing floods claimed one hundred lives along Delaware River tributaries and caused many millions of dollars in property damage. The

flooding did not cause planning for a Delaware River dam. That planning was already far along. It did cause a widespread call for flood control dams and, by placing the Delaware within the Corps of Engineers flood control mandate, it paved the way for massive Federal involvement.

Responding to the calls for flood control and a thorough re-evaluation of water management options, the Corps began a large and uniquely comprehensive survey of the Delaware Basin in 1956. A Tocks Island portion of the study was released in 1957 indicating that an earth fill dam was feasible. In comparison with the Wallpack Bend site, capacity would be doubled and costs would only be increased by 50 to 60 percent. From this point, the Wallpack Bend site was no longer seriously considered.

Even though the report addressed only the dam's practicality in comparison with the Wallpack Bend proposal, and did not evaluate its economic feasibility or relationship to other water management projects in the basin, there was widespread call for immediate construction. Additional evaluations were completed by January 1959, and a report was released recommending the construction of 5 dams (including Tocks Island) before 1980 and the construction of sixteen dams as needed afterward. Tocks Island was by far the largest of the dams, and was a multipurpose structure providing water supply, low-flow augmentation, flood control, hydroelectric power, and recreational benefits. By November 1961, the four Delaware River Basin Commission states (New Jersey, New York, Pennsylvania, and Delaware) and the federal government had agreed to the plan.

Intensive geologic investigation of the site began following Congressional authorization in 1962 and continued through several years. A few borings were available from the 1930s, 1942, and the 1950s. Much more work was needed prior to construction. Ultimately 20 or more miles of seismic line and a total of 7 miles of cores were collected. As summarized by Depman and Parrillo (1969) the axis of the dam was to cross the valley above a southwest plunging asymmetric syncline (figure 2). The New Jersey abutment of the dam was to be excavated into the Bloomsburg Red Beds (table 1, recognized as the High Falls Formation at the time of original publication). The Pennsylvania abutment was to overly Silurian and Devonian limestone, shale, and sandstone from the Bossardville Formation through the New Scotland Formation. Engineering significance of the bedrock formations is summarized in table 1. Most of the valley floor is underlain by roughly 200 feet of unconsolidated material. Within the unconsolidated materials, the usual sequence is late Wisconsinan till overlying bedrock, a complex assemblage of late Wisconsinan stratified sands and gravels together with fine-grained lake sediments, then post-glacial alluvial sands and gravels. Significant geologic obstacles to be overcome were:

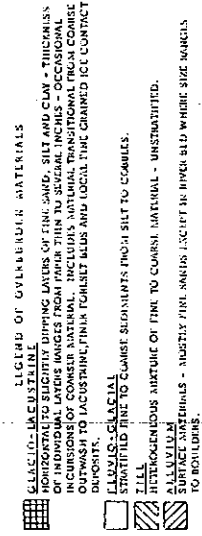
#### Instability of the Lacustrine Sediments

Instability of lake sediments underlying the valley affected both the location of the dam and its design. The originally proposed location crossed the valley at the northern tip of Tocks Island. In 1964, it was concluded based on geophysical evidence and a few borings that the dam could not be constructed at the proposed location or at most other locations in this part of the valley because of the predominance of lake sediment. The lake sediments had little strength and were prone to liquefaction. Some cores, in fact, liquefied before reaching the lab. An earthquake or rapid water-level fluctuations could lead to liquefaction and dam failure. The only area in which



Table 1. Stratigraphic column at Tocks Island Dam site and engineering significance of rock types (from Depman and Parrillo, 1969).

Age	Formation	Member	Thickness of Unit at Dam Site	Description	Engineering Significance & General Remarks
Devonian	Marcellus		<div style="text-align: center;"> ↑ Not Present at Site ↓ </div>	Black, fissile carbonaceous SHALE.	<p><i>Marcellus</i>—forms steep walls and extensive talus slopes along right rim of reservoir from Wallpack Bend to Matamoras. Intense wave action and fluctuating water levels may cause local slides &amp; slumping.</p> <p><i>Onondaga through Bossardville</i>—used mainly for stratigraphic &amp; structural correlation. These formations form the left rim of the reservoir from Wallpack Bend to Port Jervis, N. Y., and the right rim from Wallpack Bend to Tocks Island. All limestones are susceptible to solution activity &amp; potential reservoir leakage; however, no cavernous conditions or areas of large scale solution activity are known to exist. At the dam site these formations will not be involved in any major excavation.</p>
	Onondaga			Dark, thin-bedded SHALE and med.-bedded cherty LIMESTONE.	
	Oriskany			White, f. to c. conglomeratic SANDSTONE.	
	Port Ewen			Gray, calcareous & siliceous silty SHALE.	
	Minisink			Gray, argillaceous LIMESTONE & SHALE.	
Silurian	New Scotland	Flatbrookville	35'±	Med. dk. gy. calcareous fossiliferous SHALE & argillaceous LIMESTONE with nodules and layers of chert; cleavage.	
	Coeymans	Total	82'-89'	Med. gy. quartzose conglomeratic SANDSTONE w. calcareous cement. Local limestone beds & cherty zones.	
		Stormville Disconformity		Massive fossiliferous LIMESTONE with reef structure 25' thick overlain by sandy LIMESTONE & black SHALE; mud cracks.	
		Shawnee I.	42'		
		Peters Valley	5'-7'	Lt. gy. f.-c. calcareous SANDSTONE.	
		Depue I.	20'	Med.-thin bedded clayey LIMESTONE.	
	Rondout	Total	31'-34'	Thin bedded dk. gy. calc. SHALE & sandy LIMESTONE; bedding undulatory; mud cracks common. Buff, platy weathering	
		Mashipicong	11'-12'		
		Whiteport	5'-7'	Med. bedded to massive DOLOMITE.	
		Duttonville	15'	Interbedded calc. SHALE & LIMESTONE.	
	Decker Ferry	Wallpack Center	55'	Med.-thin bedded sandy LIMESTONE & DOLOMITE, calc. SILTSTONE, SANDSTONE & SHALE. Fossiliferous, reef structures.	<p><i>Poxono</i>—underlies valley fill in the reservoir area &amp; at the dam site. Several zones exhibit extensive solution activity &amp; much rehealing.</p> <p><i>High Falls</i>—forms left rim of reservoir from Wallpack Bend to the dam site. All structure in left abutment will be founded in this formation.</p> <p><i>Shawangunk</i>—will not be encountered in dam structures; possibly will be encountered if underground powerhouse is constructed in pumped storage scheme. Is not exposed in reservoir. Potential source of excellent quality concrete aggregate and dimension stone.</p>
	Bossardville		112'	Laminated to thin bedded clayey, v.f. crystalline LIMESTONE; calc. SHALE & SILTSTONE, some beds massive & dolomitic.	
	Poxono Island		675'	Green, red & mottled calc. SHALE, MUDSTONE, dolomitic SHALE, DOLOMITE & LIMESTONE.	
	High Falls (Bloomsburg)		1,500'	Red & green mottled SHALE, MUDSTONE, SILTSTONE, SANDSTONE & QUARTZITE; cross bedding common in coarser grained rock.	
	Shawangunk		1,500'	Cross-bedded QUARTZITE & CONGLOMERATE, with interbedded black ARGILLITE.	
Ordovician	Unconformity or fault				Not of significance.
	Martinsburg		Not present at site	SLATE & GRAYWACKE.	



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a dam might be feasible was a 3,000-foot stretch of the valley between the southern tip of Tocks Island and Labar Island.

Further work within this area identified a section of the valley centered about 100 feet south of Tocks Island in which sand and gravel were more abundant than elsewhere. Borings on a 200-foot grid within this area generally showed a predominance of till, sand, and gravel and a lesser volume of lake sediment. Till formed a hummocky surface above bedrock and fluvioglacial sediments rose, in some places, completely through the lake sediment. Depman and Parrillo attributed the hummocky till and the abundant gravel to deposition along a stagnant ice margin and identified this same margin to the east and west of the valley fill based on moraines extending diagonally up the valley walls. Between the stagnant margins, lake sediment was predominant over till and gravel and rendered the valley unsuitable for dam construction. Witte (2001) confirmed an ice margin, the Zion Church margin, at this location, but interpreted it as left by an active glacier rather than remaining from widespread stagnation.

The initial design called for a steep-sloped structure, with run-to-rise of 2.5 to 1 and 3 to 1. This would have required removal of the bulk of the lake deposits. This was considered feasible, but expensive. Also, it could have led to unforeseen problems. Instead, the dam was re-designed as a flat-topped structure with sides at 10 to 1. Instead of being 400 to 900 feet wide, the re-designed dam was to be over 3,000 feet wide. The potential instability of lenses of lake sediment was considered less of a problem under a dam of this width. While a considerable volume of lake sediment would have to be excavated, much could remain in place.

#### Permeability of Coarse-grained Materials

Significant problems were foreseen from seepage through sand and gravel and, to a lesser extent, solution cavities and bedrock fractures. If not controlled, seepage could have affected stability of the dam, and a costly seepage control program was anticipated (Albert, 1987).

Removal of an extensive blanket of permeable glacial deposits on the Pennsylvania bluff was not considered necessary (Depman and Parrillo, 1969). Weathering to a depth of 10 feet had created a naturally impervious blanket of decomposed shale. The costly aspects of seepage control were to include emplacement of an impervious sediment blanket where necessary upstream from the dam, drainage beneath the dam and downstream through strategically placed beds of coarse materials, installation of pressure relief wells, grouting of upslope permeable deposits where they constituted recharge areas, and grouting of bedrock fractures and solution cavities (Corps of Engineers, 1965-1972).

#### Suitability of Bedrock for Foundations

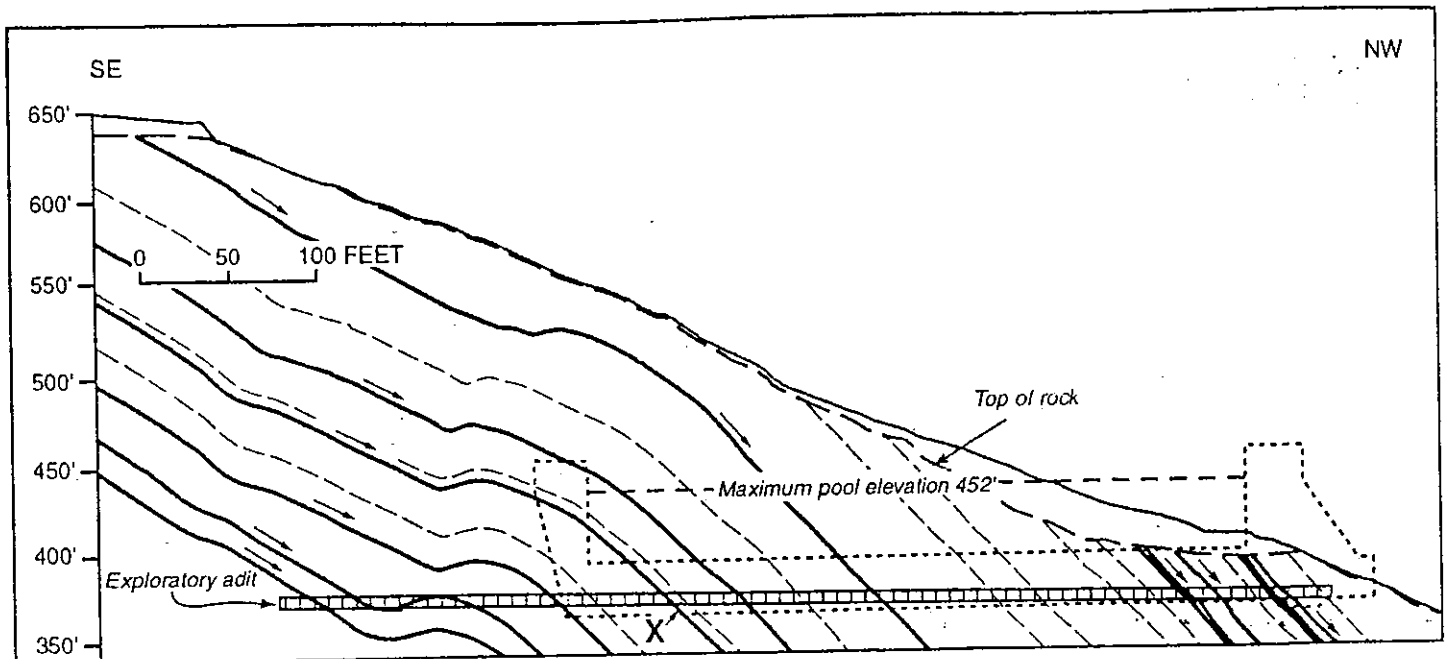
According to Depman and Parrillo (1969), the spillway location was governed by rock type. Originally, the spillway and generators were to be on limestone adjacent to the Pennsylvania bluff. While the sources reviewed for this presentation do not specifically identify dissolution as the reason for not building there, they do mention solution channeling visible in cores and downhole cameras in the foundation area. Permeable sediments upslope would be a possible

source of recharge (Corps of Engineers, 1965-1972). In the final design, the spillway was moved to an excavation in sandstone, siltstone, and shale on the New Jersey side.

### Slope Instability

The primary slope failure possibilities recognized during planning for the Tocks Island Dam were: 1) Local sliding and slumping due to wave action or water level fluctuations along steep valley walls and extensive talus slopes where the Marcellus formation borders the Pennsylvania side of reservoir. 2) Similar sliding or slumping along bluffs consisting of varved lake sediments, also on the Pennsylvania side. And, more significant, 3) Failure along bedding-plane faults in the Bloomsburg Red Beds in excavation walls over 300 feet high at the spillway and intake structures (Corps of Engineers, 1965-1972, Depman and Parrillo, 1969). Epstein (2001) describes, in addition, failures in the valley from soil slips on glacially polished bedrock surfaces, rockfalls along fractures that parallel roads, and debris flows in glacial till. While the failures described by Epstein have led to an estimated \$150,000 in remedial costs, these were either not recognized or not considered major problems during the Tocks Island planning process.

Rock conditions at the 300-foot high cuts above the intakes and spillway were investigated by driving a 5 by 7 foot adit 600 feet into the Bloomsburg at the location and elevation of the spillway base (figure 3). Numerous bedding plane slips were identified dipping towards the



**Figure 3.** Cross section at site of spillway showing location of spillway (dotted line) and exploratory adit (from Epstein, 2001 as modified from Depman and Parrillo, 1969). Solid heavy lines are bedding-plane faults. Arrows show direction of movement. Dashed lines are normal bedding surfaces. X is lower of the two the weathered bedding-plane faults discussed in the text.

excavation at angles between 17° and 35° (Depman and Parrillo, 1969). Many of these are zones of abundant ground water flow (Epstein, 2001). Similar faults were identified in the Bloomsburg throughout eastern Pennsylvania by Epstein and Epstein (1967, 1969). Regardless of position on a fold, the overriding beds consistently moved from east to west. Two of the faults identified in Depman and Parrillo (1969) were at or near the base of laminated shales and sandstones with deep desiccation cracks. Both showed weathering and decomposition (Depman and Parrillo, 1969). In a detailed investigation of these two zones, 1) cross cuts were extended 100 feet from the adit along the deeper of the two decomposed zones and at the end of the adit, 2) three 36-inch diameter core holes were drilled from the land surface to the faults to allow in situ observation and strength evaluation, and 3) 4-inch cores were drilled behind the proposed excavation to investigate fault geometry and to install piezometers. The faults were found to be continuous through the area. Stress measurements above and below the deeper of the faults found there to be little strength across the fault, and it was predicted that the entire mass would move downhill if the toe of the fault were daylighted (Dan Parrillo, U.S. Army Corps of Engineers, personal communication to Epstein, 1970, reported in Epstein 2001).

Further investigation was planned in a specially designed quarry to be dug in the early stages of reservoir construction. The slopes above the intakes and spillway were to be designed in a safe manner based on the results of findings at the quarry.

Other major changes to the dam not directly related to geologic conditions were as follows:

#### Increase in Dam Height.

As a result of a severe drought, which lasted for several years through the mid-1960s, safe yield estimates for the basin were revised downward. To compensate for the decreased safe yield, the height of the Tocks Island pool level was increased to the maximum practical height of levees at Port Jervis. This was to store water for low-flow maintenance and to repel salt water intrusion in the Delaware estuary. The proposed dikes caused considerable anger in the Port Jervis area.

#### Pumped Storage

A pumped storage facility built in the early 1960s at Yards Creek, close by the Tocks Island reservoir, uses two reservoirs, upper and lower, connected by pipelines and turbines. Water is pumped from the lower reservoir on Yards Creek, east of Kittatinny Mountain to an upper reservoir atop the mountain during off-peak hours (nights and weekends, for example). The water is then dropped to the lower reservoir for power generation during peak need periods. About 70 percent of the energy used in pumping is recovered, but the difference in value between peak power and off-peak power more than makes up for this loss (Smith, 1969).

Kittatinny Mountain was first considered for pumped storage in 1947, but the idea was not feasible until large, reversing turbines were developed in the 1950s. Interest in pumped storage atop Kittatinny Mountain revived in 1956. Not by coincidence, this was the year in

which the Corps of Engineers released their report favoring a dam at Tocks Island. With the Tocks Island reservoir to the west of Kittatinny Ridge and Yards Creek to the east, pumped storage appeared to be an ideal way to transport water across Kittatinny Ridge at a profit to supply northern New Jersey. In an initial design, Delaware River water was to be pumped in off-peak hours to a series of three reservoirs atop the mountain and, for peak need generation, dropped to the Yards Creek reservoir in the Paulins Kill watershed. The water was then to be transferred as needed to the Round Valley Reservoir.

The existing portion of the system did not depend on the Tocks Island Dam and was completed in 1965. Numerous issues, particularly involving funding, ownership, and revenue distribution were unresolved at the time of the 1962 Tocks Island authorization, and pumped storage was not included the Congressionally authorized project. Over the next several years, these and other issues (particularly preservation issues at Sunfish Pond) were addressed, and, in a 1970 re-authorization, pumped storage was included as a purpose of the dam. Generators were eliminated from the dam plans, and conventional power generation was de-authorized.

### Failure of the Tocks Island Project

From the time of its authorization in 1962, the Tocks Island project experienced financial difficulties. Many claimed that the original cost estimates had been understated to assure approval. From a 1962 estimate of \$90 million, costs rose to \$400 million by 1975, and were still climbing. While soaring costs and budget shortfalls were clearly important in the demise of the project, their main effect may have been to cause delays which allowed time for other questionable aspects to come forward. Aspects which presented the greatest concern as the project moved forward were the cost benefit ratio, eutrophication, questionable recreation benefits, infrastructure needs which had not been addresses in the original proposal, and a near absence of evaluation of alternatives in the original proposal. Perhaps equally important in leading to strong grass roots opposition to the project were: 1) seemingly unending mismanagement and public relations disasters in land acquisition and the management of acquired land and 2) changing public attitudes towards large dams in general and Corps of Engineers in particular through this stage in the development of the environmental movement.

Although no specific issue stands out as the one that killed the Tocks Island Dam, and although the failure of the project was seen by many water resource managers as a prelude to continuing public supply shortages and low-flow related water quality issues in streams, the project had become politically untenable before the groundbreaking. The governors of New Jersey, New York, and Delaware rejected its continuation in 1975. Only the governor of Pennsylvania, citing water supply needs, continued to support the project. The project was formally deauthorized in 1992.

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## Road Log and Stop Descriptions

All of the stops on this trip are in federal or state parkland. All collecting and use of hammers is by permit only. We do not have a permit and are not allowed to use hammers or collect any materials. We will be visiting historic sites and unique geologic occurrences. Please help us preserve these sites by not collecting or using hammers.

Some of the descriptions in this road log are modified with permission from Inners, J. D., and Fleege, G. M., 2001, eds., 2001- a Delaware River odyssey, Guidebook, 66<sup>th</sup> Annual Field Conference of Pennsylvania Geologists, Shawnee-on-Delaware, PA, 314 p.

Miles		
Interval	Cumulative	
0.0	0.0	Leave from circle in front of Shawnee Inn and Golf Resort. The inn and golf course are on postglacial stream terraces that reach a maximum elevation of about 330 feet, about 35 feet above the mean annual elevation of the Delaware River. An Early Archaic occupation site excavated on Shawnee Island (Stewart, 1991) was dated at $9330 \pm 545$ yr. B.P. (Uga-5488).
0.3	0.3	Turn left onto River Road. The road passes over a sequence of Silurian shale and dolomite that is covered in many places by thin, late Wisconsinan till.
0.1	0.4	Limestone of the Shawnee Island Member of the Coeymans Formation on the right. The Stormville Member, capping the Coeymans Formation, is seen in the private driveway to the right.
0.4	0.8	Top of hill, continue straight ahead. Buttermilk Falls Road on right. New Scotland Formation on left.
0.3	1.1	New Scotland Formation on right.
0.4	1.5	Minimart on left and Smithfield School on right sit on a late Wisconsinan outwash terrace. The terrace lies at an elevation of 400 feet, about 100 feet above the Delaware. Based on its location at the mouth of Marshalls Creek, it was probably laid down by a meltwater stream flowing down the Marshalls Creek valley.
0.3	1.8	Gap View Road on right.

0.1	1.9	Village of Minisink Hills. Good 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 Ridgely Sandstone (the "Indian Chair") from which Amerinds extracted a good quality flint (P. Laporte, personal communication to J. Epstein, reported in Inners and Fleege, 2001, p. 158). Bear left at intersection. Postglacial terraces of Brodhead Creek on right. Late Wisconsinan outwash terraces form the higher ground on the left.
0.3	2.2	Cross Brodhead Creek. About 1,500 feet eastward is the Shawnee-Minisink Paleoindian site Island. (McNett et al, 1977) It is located on a post-glacial stream terrace about 20 feet 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 nine feet deep yielded a date of $10,590 \pm$ B.P. (W-2994). The hearth is located in a cultural zone containing Paleoindian components (Clovis point, scrapers, hammerstones).
0.1	2.3	Cross railroad (Norfolk Southern, originally Delaware, Lackawanna, and Western)
0.1	2.4	I-80 overpass.
0.2	2.6	Turn left onto US 611 toward village of Delaware Water Gap. We are at the lower end of Cherry Creek valley near its confluence with the Delaware River. During late Wisconsinan glaciation, proglacial lakes formed in the ice-dammed (northeast-draining) valley. Several ice-contact deltas mark ice retreat (Epstein, 1969).
0.3	2.9	Traffic light. Turn left onto US 611 South.
0.4	3.3	Northwest dipping rocks of the Shawangunk Formation on right.
0.1	3.4	Crest of Cherry Valley anticline in the Shawangunk Formation at top of road. The contact between the Shawangunk Formation and the Bloomsburg Red Beds is conventionally placed at the base of the lowest red bed. However, at this locality this color change migrates up and down section by as much as 700 feet, making for a peculiar map pattern (Epstein, 1973). Enter upstream side of Delaware Water Gap.
0.1	3.5	Southeast dipping rocks in the Bloomsburg Red Beds. US 611 traverses the Bloomsburg for the next 0.8 miles in a series of small, undulating, low-amplitude folds. Note the southeast-dipping cleavage.
0.8	4.3	Contact between the Shawangunk and Bloomsburg dipping $35^\circ$ NW.
0.7	5.0	Turn right into parking lot at Point-of-Gap. Disembark.

## References

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## STOP 1. DELAWARE WATER GAP: GEOLOGIC OVERVIEW—STRATIGRAPHY, STRUCTURE, FORMATION OF THE GAP, AND GLACIAL GEOLOGY. Leader: Jack B. Epstein.

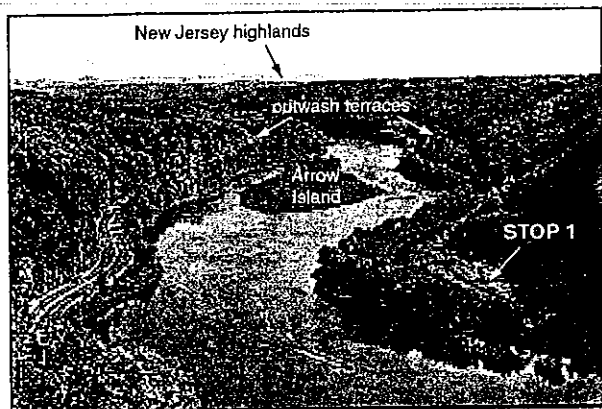


Figure 113. Entrance to Delaware Water Gap National Recreation Area as viewed from atop Kittatinny Mountain, Pennsylvania on the right, New Jersey on the left. The Delaware River flows through the constricted gap behind the view, and as it widens into the valley beyond and its velocity lessens, it deposits 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 Recreation Area, in proximity to the New York-Philadelphia metropolitan complex, is the most heavily visited National Park facility in the northeastern United States, attracting more than four million visitors a year.

### INTRODUCTION

Many of the parks within National Park System (NPS) owe their uniqueness to their geologic framework. Their scenery is the result of natural processes acting upon the variety of rocks that were deposited in diverse environments in the geologic past. Knowledge of these attributes, training of NPS personnel in their proper interpretation, development of a resource database, and communication of this information to the public are important priorities of the National Park Service. Bedrock and surficial geologic mapping by the federal and two state geologic surveys in the Delaware Water Gap National Recreation Area (DEWA) has been used to prepare a variety of products useful for the unit's mission of park management and service to the public. DEWA draws 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-mile stretch of the Delaware River between Port Jervis, New York, and the world-famous Delaware Water Gap in New Jersey and Pennsylvania (Figure 113). It straddles the Pocono

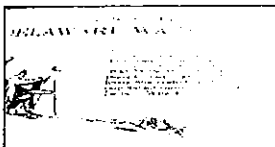
Stop 1 description reprinted with insubstantial modifications from Inners, J. D., and Fleegeer, G. M., 2001, eds., 2001- a Delaware River odyssey, Guidebook, 66<sup>th</sup> Annual Field Conference of Pennsylvania Geologists, Shawnee-on-Delaware, PA, 314 p.

Plateau on the northwest, underlain by gently inclined Devonian sandstones and shales, and complexly folded Ordovician to Devonian rocks of the Valley and Ridge to the southeast. The stratigraphic sequence spans about 65 million years. Wisconsin 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.

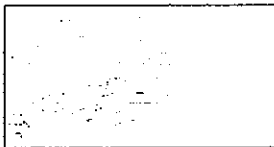
The application of our geologic efforts emphasizes scientific interpretation, land-use planning and management, points of scientific interest to be enhanced or protected (paleontologic, structural, geomorphic, stratigraphic, glacial, economic resources), landslide susceptibility, facility location and 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. Hopefully, much of the information in this guidebook will serve this useful purpose.

## STRATIGRAPHY

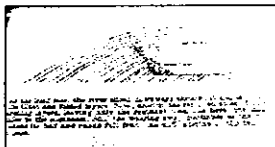
Delaware Water Gap owes its notoriety to the depth to which the river has cut through Kittatinny Mountain. Exposures of 3,000 feet of Silurian clastic rocks are nearly continuous; the entire Shawangunk Formation, with its three members, and most of the Bloomsburg Red Beds are visible (see Figure 11). To the west, in central Pennsylvania, the Shawangunk merges into the Tuscarora Sandstone below and the Clinton Formation above. To the east, in New York State, as seen from the heights of



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 vacationers, 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 114. 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 115.

This structural interpretation alludes to the fact that the Green Pond Conglomerate, the correlative of the Shawangunk, is exposed about 25 miles 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

High Point, 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. For details, see Epstein, this guidebook, p. 1.

## STRUCTURE

Shortly after the Delaware Water Gap National Recreation Area was established in 1965, an exhibit in the kiosk at the south end of the parking lot presented an interpretation of the structure in the gap. The plaques have since disappeared from the site as well as from most memories. Figure 114 brings back those memories.

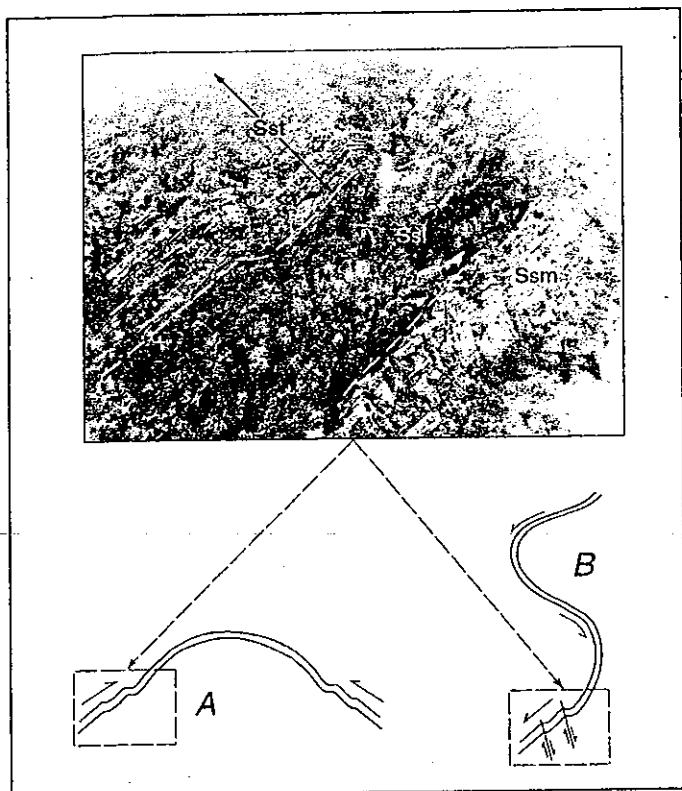


Figure 115. Satellitic folds in the Shawangunk Formation in Delaware Water Gap, New Jersey (Ssm, Minsi Member; Ssl, Lizard Creek Member; Sst, Tammany Member).

A, interpretation of an anticlinal crest to the southeast as shown in Figure 114 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.

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. Numerous lines of evidence point to the conclusion that cleavage developed after the rock was indurated. Plasticity increased during increased tectonism and the mobility (intrusion of pelitic and sandy material along cleavage planes) may have been aided by silica derived from pressure solution and derived either from connate water squeezed out of the rocks during tectonic compaction or by the release of water from hydrous minerals during continued deformation. New growth of quartz, chlorite, muscovite, calcite, and probably albite in most rocks suggests formation of cleavage at and just below the limits of low-grade metamorphism (quartz-muscovite-albite-chlorite subfacies of the greenschist facies). Slip cleavage crenulates earlier foliations. Transposition of minerals into the new cleavage plane is common, and in this respect it is similar to slaty cleavage. It is also similar to slaty cleavage in that new minerals may grow parallel to the cleavage direction. To the southwest in Pennsylvania the 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.

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 115A). On the contrary, mapping along strike and down the plunge of the folds to the southwest on Kittatinny Mountain (Epstein, 1973), shows that an overturned syncline extends upwards from the rocks at Delaware Water Gap (Figure 115B). 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 Arch of Cleavage

Most pelitic rocks in the Delaware Water Gap area, regardless of age, have a secondary foliation, or slaty cleavage, which becomes more prominent northwestward and into higher stratigraphic units. A second slip cleavage, which crenulates the earlier-formed slaty cleavage, is locally developed in all units. 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



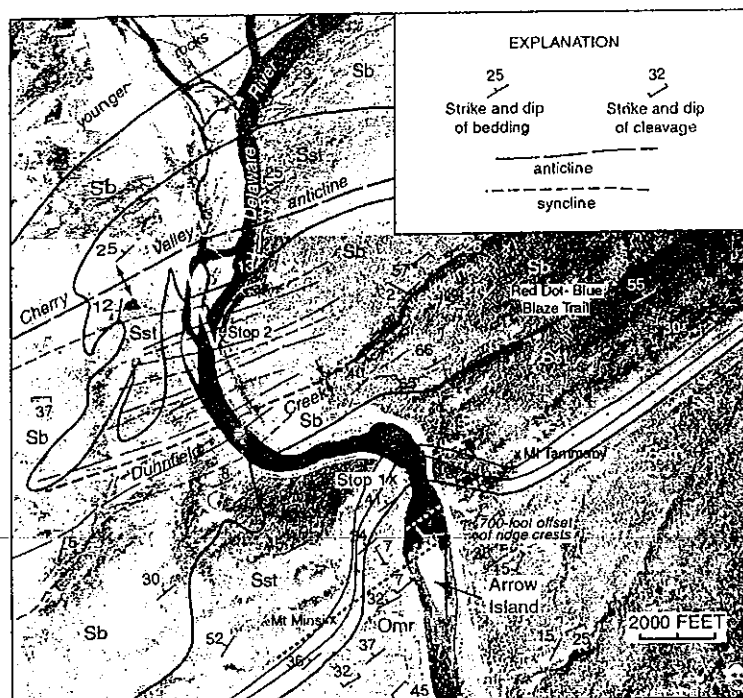


Figure 116. Aerial photograph and geologic map of Delaware Water Gap showing 700-foot offset of the ridge crests (dotted line) on either side of Kittatinny Mountain. Omr, Ramseyburg Member of the Martinsburg Formation; Shawangunk Formation: Ssm, Minsi Member; Ssl, Lizard Creek Member; Sst, Tammany Member; 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). The Red Dot-Blue Dot trail is a popular hiking trail which has abundant sites of geologic interest.

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, Pennsylvania, a distance of more than 100 miles. 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 117 and initially described by Epstein and Epstein (1967, 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 around synclinal troughs and is either poorly developed or absent in the pressure-shadow area next to the trough (Figure 117B). This relationship is the same on a larger scale (Figure 117A), explaining the arching of cleavage at Delaware Water Gap and Yards Creek. It also explains the dying out of cleavage near the Martinsburg-Shawangunk contact elsewhere, such as at Lehigh Gap (Epstein et al., 1969). 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

Intensity of slaty cleavage development increases to the southwest in Pennsylvania, and commercial slates appear higher in the section where, near Lehigh Gap, slate has been extracted from the Mahantango Formation, although now those operations have ceased. 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. In many places, particularly in the Martinsburg, but not exclusively, the slaty cleavage is cut by a second generation slip cleavage and the earlier slaty cleavage is rotated into arches by the folding process. At Delaware Water Gap, and at other localities near the contact with the competent rocks of the Shawangunk Formation, the slaty cleavage is also arched, but by a different process than by external rotation. Figure 116 is a generalized geologic map of the Delaware Water Gap area. Note that about 2,000 feet south of the Martinsburg-Shawangunk contact the cleavage dips to the southeast, but turns to the northwest as the contact is approached (Figure 116). This is similar to the structural situation seen at Yards Creek.

Drake et al. (1960) and Maxwell (1962) attributed this arching of the slaty cleavage to refolding during the

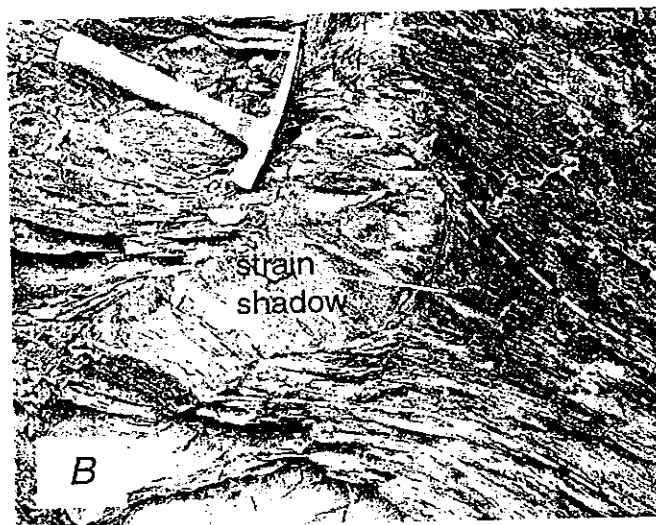
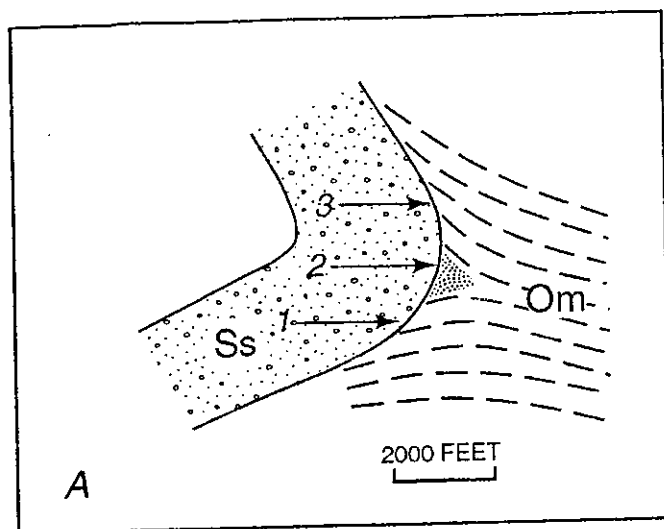


Figure 117. Strain shadows and arching of slaty cleavage in interbedded rocks at different scales and of different competencies.

A, cross section at Delaware Water Gap 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 (1) can be seen at Delaware Water Gap and at Yards Creek. The dying out of cleavage (2, fine stippled area) can be seen at Yards Creek and at Lehigh Gap 35 miles southwest of Delaware Water Gap (Epstein and Epstein, 1969). Steeply dipping cleavage in the Martinsburg next to the overturned synclinal limb (3) can be seen at the south portal of the Pennsylvania Turnpike tunnel 16.1 miles southwest of Delaware Water Gap (Epstein and Buis, 1991). B, flattened folds near the base of Martinsburg Formation (Bushkill Member) along US Route 46, 1.8 miles northeast of Belvidere, NJ. 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.

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."

A few additional comments about the relationships at the Taconic unconformity at Delaware Water Gap and the surrounding area are worth noting. Quartz, chert, and quartzite pebbles in the basal beds of the Shawangunk, in places more than 5 inches 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, such as at Yards Creek and High Point. 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 above), again showing that the cleavage is post-Taconic in age.

## A STORY OF THE GAP

Anyone who maps in the Delaware Water Gap area is compelled to contemplate the history of formation of the gap and why it is where it is. The following thoughts are summarized from Epstein (1966, 1997).

Many different sediments were deposited in eastern Pennsylvania and northern New Jersey during the Paleozoic. Later, during consolidation, some of these became sandstones and conglomerates, resistant to subsequent erosion and formed mountains; others became shales, limestones and dolomite, less resistant to erosion and formed valleys. Following orogenic uplift of these diverse sediments during the late Paleozoic, the original divide of the Appalachian Mountains that formed 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 towards its present position in the Appalachian Plateau because the steeper stream gradients towards the Atlantic Ocean created 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. In the area of this Field Conference, there are many wind and water gaps in Blue and Kittatinny Mountains. That ridge is held up by resistant quartzites and conglomerates of the Shawangunk Formation of Silurian age in Pennsylvania and New Jersey, extending into Shawangunk Mountain in New York (see Figure 9). The Shawangunk thins to the northeast and disappears above Ellenville, NY (Epstein, 1993). 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). 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*, 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.

Sixteen gaps and cols in Blue, Kittatinny, and Shawangunk Mountains between Lehigh Gap in eastern Pennsylvania and Ellenville, 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.

### Delaware Water Gap

Delaware Water gap is often cited as the classic water gap in the Appalachian Mountains. Figure 116 portrays its geology. The Delaware River flows through the gap at an altitude of 300 feet. Kittatinny Mountain rises about 1,240 feet above the Delaware River on the New Jersey side, and it is nearly 100 feet lower on the Pennsylvania side. Also, the trend of the ridge crest lies about 700 feet

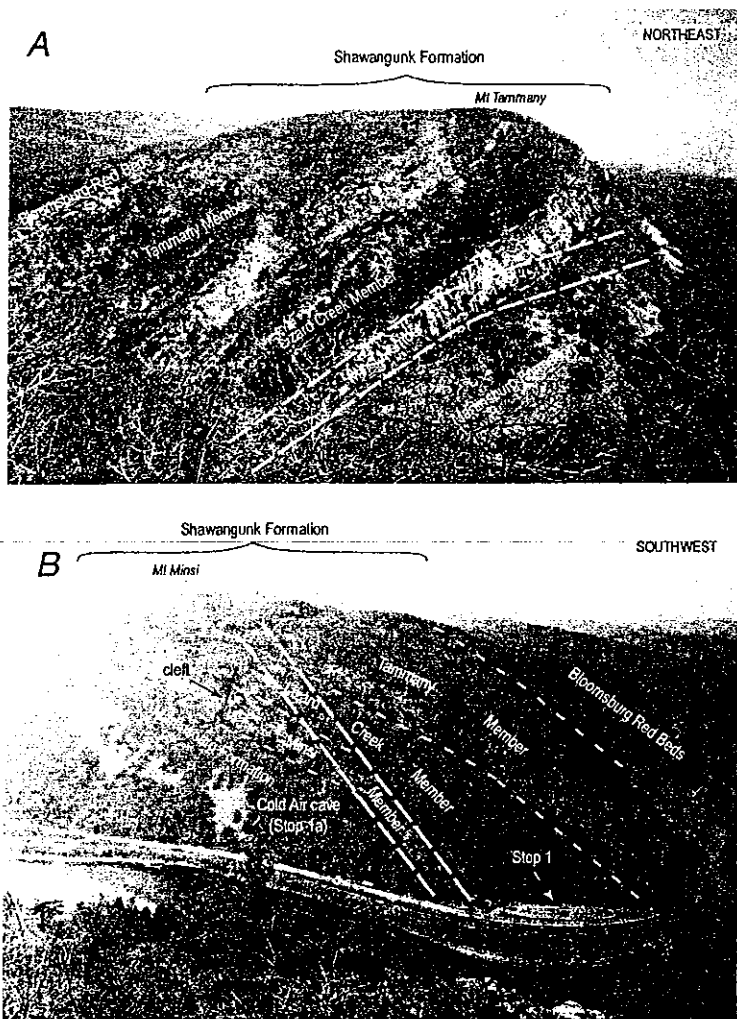


Figure 118. Middle Silurian rocks in Kittatinny Mountain in New Jersey (A) and Pennsylvania (B) at Delaware Water Gap. Long-dashed yellow lines are the projected structural configuration of the Minsi Member of the Shawangunk Formation projected across the Delaware River from the opposite side of the gap. Figure 119 demonstrates the interpreted flexure at the gap site. Note the deep cleft in Pennsylvania in the Shawangunk cliff. It supplied much of the talus blocks above the Cold Air cave.

straight line towards the southern part of the gap. At that time, the river was cutting down through the Bloomsburg Red Beds, and when it intersected the more resistant Shawangunk quartzites and conglomerates, it migrated down the plunge of the anticline. Subsequently, the "meander" migrated downstream until it impacted the northwest-dipping rocks of the Shawangunk coming down off the main ridge. The projection of this proposed course of the river to the present top of the Shawangunk places the river at about 900 feet altitude, or about 600 feet above the present level, when it first encountered the Shawangunk.

farther southeast on the Pennsylvania side than in New Jersey. 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  $45^{\circ}$  (Figure 118A), but in Pennsylvania the dip decreases about halfway up the mountain to about  $25^{\circ}$  (Figure 118B). Therefore, there must have been a kink in the rocks that formerly occupied the gap site (Figure 119) 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 (Figure 116). 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.

The Delaware River curves in a loop mimicking the curve of bedding in the southwest-plunging Cherry Valley anticline (Figure 116). This probably resulted when the river flowed at a higher altitude in a

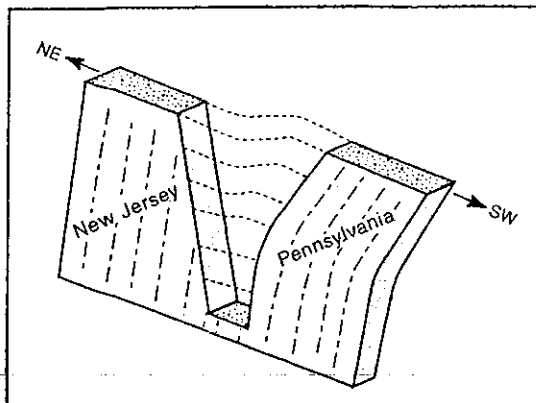


Figure 119. Reconstructed flexure at Delaware Water Gap. Dotted line shows strike of beds before the gap was cut. The flexure accounts for the offset of the ridge between the two sides and presumably resulted in considerable fracturing of the Shawangunk at the gap site. View looking eastward.

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

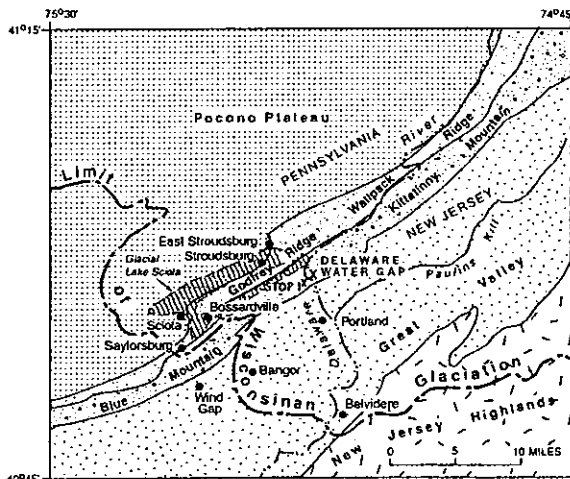


Figure 120. Physiographic map of part of easternmost Pennsylvania and northwestern New Jersey showing the position of the maximum advance of the Wisconsin glacial advance. Modified from Epstein (1969).

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.

All of the major gaps within the Delaware Water Gap area and beyond are located at sites of geologic structures that appear to have weakened the rocks at those sites. These features are plunging folds, sharp flexures, cross fault, kinks along strike, and narrow widths of outcrop of the resistant Shawangunk rocks. There also is evidence that structural control influenced the development of smaller gaps in ridges to the north (Epstein, 1966, p. B83-B85). 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 erosion was most effective during the course of stream competition along the ancestral drainage divide. 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

The latest (Wisconsin) glacial advance into eastern Pennsylvania and northern New Jersey resulted in the deposition of a conspicuous terminal moraine which crosses the Delaware River about 11 miles south of the gap near Belvidere, NJ (Figure 120). The moraine then trends northwestward to cross Blue Mountain about five miles west of Delaware Gap, locally reaching heights of more than 100 feet in places. As the glacier retreated from its terminal position north of Blue Mountain, the meltwater was dammed between the terminal moraine, the surrounding hills, and the retreating ice front. A series of stratified sand and gravel deposits were laid down in the lake that formed, recording the sequential retreat of the glacier. The lake has been named Lake Sciota, after the classic delta and varved lake-bottom sediments that are found there. The lake reached a depth of about 200 feet in places. Initially, the outlet for the lake was over the terminal moraine at Saylorburg and the water flowed

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-bottom, kame, kame-terrace, and outwash deposits). Below the gap is an outwash terrace, more than 150 feet high on both sides of the river, comprising very coarse gravel with boulders exceeding eight feet long.

Numerous striae, grooves, and *roches moutonnee* formed by Wisconsin 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, including White (1882), Lewis (1884), Salisbury (1902), Leverett (1934), Ward (1934, 1938), Happ (1938), Miller et al. (1939), Mackin (1941), Epstein (1969), Bucek (1971), Crawl (1971), Ridge (1983), Cotter et al. (1986), and Witte (2000).



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Miles		
Interval	Cumulative	
2.5	7.5	Exit parking lot to left. Retrace route to I-80.
1.6	9.1	Cross Delaware River into New Jersey. Take first New Jersey exit (Information – Delaware Water Gap National Recreation Area).
1.8	9.3	Turn right into visitor parking. Proceed straight ahead to the end of the parking lot to begin u-turn.
0.2	9.4	Left turn at exit of parking lot to complete u-turn. Proceed upriver and beneath I-80 overpass.
0.4	9.8	Southern end of Old Mine Road. 3-minute light for single lane section. Be patient. It will change.
0.4	10.2	One-lane road. The roadway has been rebuilt several times over the last century. The principal geologic hazards to Old Mine Road are slumping (due to undercutting of the slope below the road by the Delaware River) and rockfall from undercutting of the steep outcrops above the road. Many of the Bloomsburg Red Bed outcrops along the route show glacial striations showing valley-parallel ice flow. Striae along the mountain's crest show that the ice generally moved southward across the mountain's northeast-southwest topographic grain.
0.8	11.0	Outcrop of Bloomsburg Red Beds, dipping northwestward, on right side of road. The rock contains numerous dorsal and ventral plates of the ostracoderms <i>Veronaspis</i> and <i>Americaspis</i> . The outcrop is within the National Park, and collecting is strictly forbidden.
0.6	11.6	Pass Shawnee Inn and Golf Course across river to your left.
1.0	12.1	Enter Worthington State Forest.
1.0	13.1	Douglas parking lot on left, just past campgrounds. The campgrounds are on a postglacial stream terrace. The long hillslope to the right is held up by the Bloomsburg Red Beds, and is overlain by thin till.
0.8	13.9	Tocks Island on left (downstream end). Site of proposed Tocks Island Dam. Outcrops of Bloomsburg Red Beds with prominent steep sheeting dipping towards the road ahead on right. (We will visit this area at stop 4, after lunch)
0.6	14.5	Tocks Island (northern end)
0.2	14.7	Exit Worthington State Forest.
0.6	15.3	Pass over high-standing remnant of the Zion Church valley train (about 100 feet above Delaware). Most of the glacial outwash in this part of the valley was eroded by meltwater and the Delaware River.
0.8	16.1	Dimmicks Ferry (to left across post-glacial stream terrace). Initial ferry service probably begun in the 1820s. Service continued until the death of Michael Dimmick in 1937. This was one of sixteen ferries to have operated between the Water Gap and Milford
0.3	16.4	Trailhead to Pahaquarry copper mine. Disembark.

## STOP 2 Pahaquarry Mine

We will be stopping at the old parade ground for Camp Pahaquarra where Mine Brook drains into the Delaware River. There are out-house facilities available. This site is in the National Recreation Area, so in the words of the park ranger "if we are going to 'manipulate the resource', we will need a permit". In terms you all should understand: **NO HAMMER STRIKES AND NO COLLECTING.** Guest Don Pace will give us a historical orientation and provide some photographs for viewing. We will then proceed across the road to the south to first visit the portal of Tunnel No. 1. Along the way we will traverse a concrete slab that remains from the Boy Scout Mess Hall and past stone foundation walls from the 1903-1913 mill complex.

Further along the trail the sunken expression of the collapsed 1901 adit is to the west of the trail. The portal of Tunnel No. 1 is in a rather tight area, it may get crowded, so watch your step. The dip of the sandstone can be seen in the outcrop, but little else. Look carefully in the trail in this area for tiny euhedral faces of quartz crystals from the vuggy quartz in the mine. Cornwall (1945) shows that both Tunnel No. 1 and No. 2 were following along (drifting) bedding parallel fractures that contain quartz with chalcocite stringers and knots. Tunnel No. 1 was started in the 1750's, and was cleaned out and enlarged during both the 1840s and 1900s. Cornwall (1945) provided as Figure 4 of the guidebook shows there is a cross-cut at the back-end of the adit with another short drift off-set to the south. A gate has been installed across the portal by the Park Service. The Boy Scouts used to refer to the tunnels as the "Hairy Hand Cave", and tell scary stories to deter adventurous souls. Please do not enter the mine.

We will turn around and travel north, back to the mill foundations, make a left, then follow the old Boy Scout trail uphill to the top levels of the former mill. At this point we will see foundations for the tramway and the trail to Tunnel No. 2. We will not travel to Tunnel No. 2, because it looks much the same as Tunnel No. 1, except earth at the portal has collapsed. Tunnel No. 2 is also a 1750s opening.

We will then walk southwest up a long inclined trail/forest road to the "Main Quarry" or open-cut mine site from the 1903-1913 mining attempt. This exposure contains finely disseminated chalcocite in sandstone, locally malachite and chrysocolla can be found, but it is not the ore mineral. Cornwall (1945) found the grade of this material is 0.38% Cu, while Keith, the metallurgist claimed that the average grade was approximately 3%, and Woodward suggests that 100 samples provided an average of 3.25%. The open cut provides excellent exposures of dip slopes of the quartzite. Both gray and red coloration of the sandstones are visible. At the southwest end of the pit, mud-cracks can be seen in the oxidized red variant.

A series of closely-spaced, parallel, scrape marks on the dip-slope rock surface result from the mining technique. From these marks, it appears that the miners were using slushers to pull the ore toward the northeast end of the quarry to load small ore cars that would then take the ore to the tipple, or loading bin area. A slusher consists of a light metal scaper pulled by cables anchored to a dead-man pulley and controlled by a tugger-winch at the control station. This device can be run back and forth quickly and in time the material is pulled to the control-station end. By moving the dead-men, a broad area can be worked. Slushers are cheap, portable and the technology can be used underground or on surface. Shallow anchor-bolt holes are visible on the rock face.

A walk to the east end of the quarry will allow a view of the Delaware River, the remains of the tipple, a waste dump at the tramway head and the alignment of the funicular tramway. Test pits, inclined shafts and exploration trenches are all visible to the south and east of the main quarry. Please be careful, you are in "real woods" at this location.

## Pahaquarry Copper Mine History Relating to Existing Surface Features

by Mark Zdepski, with assistance from Don Pace<sup>1</sup>

The Pahaquarry Copper Mine is located near the Delaware River and reportedly has a long history (Figure 1). The length of this history is controversial to some and the real answer on the actual age of mining at this site is not yet known, but may some day be discovered.<sup>2</sup> We will not become mired in this obscure controversy. Kraft (1996) has gone to great length researching and reporting this issue. Depending upon who performs the research, they may say that the Dutch started the mines and they used a road alignment that originated at Kingston, NY, traveled to Port Jervis, then was extended south to service this endeavor.<sup>3</sup> The truth of this legend is unknown. It is also said that the Native American Indians first showed the Dutch the copper occurrence.

Native Americans in New Jersey certainly knew about native copper and they fashioned both decorative and utilitarian objects from it.<sup>4</sup> There is no evidence that copper artifacts were the result of mining and smelting, they most likely result from trade.<sup>5</sup> Native copper nuggets were found in the Bound Brook and New Brunswick area by European settlers<sup>6</sup>, it is not known if the local Indians also found native copper. Stone is always an important raw material to aboriginal people and the original natives most-likely looked closely at both float and outcrop. The bright green and blue of copper carbonates make for a showy mineral occurrence, so it seems reasonable that they were well aware of the Pahaquarry Mine site and they may have even shown it to the first explorers. No undisputed evidence of the early mining or prospecting has been found. The earliest known mining attempts date to

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<sup>1</sup> Don Pace is a local expert on the Pahaquarry site. Part of his childhood was spent with his family in the caretaker's residence of the former Boy Scout Camp. He is a persistent researcher who has collected numerous original and primary references on the site. He is interested in any historical material that may be available for this site. Don may be reached by writing to: 1343 Indian Trail, Easton, PA, 18040.

<sup>2</sup> Kraft, Herbert C., 1996, *The Dutch, the Indians and the Quest for Copper, Pahaquarry and the Old Mine Road*, Seton Hall Univ. Museum, 183 p.

<sup>3</sup> Weiss, H. B. and G.W. Weiss, 1963, *The Old Copper Mines of New Jersey*, Past Times Press, Trenton, 94 p. See also Woodward, Herbert P., 1944, *Copper Mines and Mining in New Jersey*, Bull. 57, NJ Dept. Conserv. and Devel., pgs 124-129.

<sup>4</sup> Collection of N.J. State Museum, see also Kraft (1996).

<sup>5</sup> Kraft, *ibid*.

<sup>6</sup> Weiss and Weiss, *ibid*.

the 1750's.<sup>7</sup> These early attempts are known only from deeds and wills, not from maps or business records. The remnants of this mining are Tunnels 1 and 2, in addition to surface trails.

The visible features of the Pahaquarry Mine result from three periods of mining, the 1750s, 1840-1862 and 1901-1913. Business and published records are available for the later two periods of mining. These started during 1848, by making new openings as well as cleaning out and enlarging earlier openings. The most recent mining venture began during 1901. The 20<sup>th</sup> century mining attempt left the largest visible remains. This modern mine and mill may have obliterated some of the earlier evidence of mining and settlement. Evidence of all attempts are superimposed upon each other (Figure 2). Neither of the most recent two ventures increased the national stockpile of copper by any appreciable degree.

### Alleghany Mining Company<sup>8</sup>

On March 9, 1848 the Pahaquarry Mining Company was incorporated by a group of men from Flemington.<sup>9</sup> This group included Charles Bartles a prominent Flemington attorney. These men also had a copper "mine" in Flemington which was incorporated just one year earlier. Charles Bartles and his business partners engaged in shameless stock promotions beginning in 1847<sup>10</sup>, apparently in an attempt to cash-in on contemporary investor optimism that was fueled by extraordinary copper strikes on the Keweenaw Peninsula of Michigan. At both sites Charles Bartles actually employed experienced miners, importing some of them from Cornwall, England. It appears that Mr. Bartles initially thought that mining could be accomplished, because he built surface facilities, supervised underground development, tried to smelt ore and even shipped concentrates to Swansea, Wales. His serious attempts at mining seemed to end by 1855. He then turned his attention to mining the pockets of investors.

Fanciful and optimistic "geologic" reports were prepared for both properties by one Prof. Montroville Wilson Dickeson, M.D. during 1859 and 1862. This was the tail-end of Charles Bartles involvement, it may have been his effort to produce favorable reports to promote the sale of the properties. By 1861, the Pahaquarry Mining Company had reorganized and was known as the Alleghany Copper Company.

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<sup>7</sup> Burns-Chavez, Steve R. and A. Berle Clemensen, 1995, Final Cultural Landscape Report Vol. 1, Pahaquarry Copper Mine, Delaware Water Gap, 373 p. This is the definitive history on the Pahaquarry Mine site. Nearly every useful reference, map and photograph is reproduced in this excellent report.

<sup>8</sup> This section prepared from original research conducted by Mark Zdep̓ski 1988-1998.

<sup>9</sup> Weiss and Weiss, *ibid.*

<sup>10</sup> Charles Bartles Papers, Hunt. Co. Hist. Soc.



Professor Dickeson signed the Alleghany (Pahaquarry) Mine report with the title "economic geologist".<sup>11</sup> On the title page of the Flemington report Prof. Dickeson lists his professional memberships: Member of the American Association for the promotion of Science; the Historical Society of Pennsylvania; the Academy of Natural Sciences of Philadelphia; the Ethnological Society of New York; Fellow of the Royal Society of Antiquarians of Copenhagen, etc. etc. For the Pahaquarry Mine Report he drops the last two "qualifications" and adds: the Society for Developing The Mineral Resources of the United States and changes the last bit to &c, &c., suggesting that his involvement in pertinent professional pursuits just keeps going on and on.

The December 20, 1861 signed-report of Prof. Dickeson provides a useful description of the locations for the actual mine openings and a longitudinal cross-section showing the fourteen existing-openings in relation to topography. All of these openings can still be identified, they appear on Figure 2. From his descriptions, it can be inferred that a number of the ground openings pre-dated the operations that were active during his visits. Prof. Dickeson made several trips to the mine during 1862 when he examined the newest workings to update the report. The map, letter updates and published report are all dated 1862.

Although Dickeson speaks in glowing, promotional terms, he actually did try to understand the geology and it is obvious that he walked the site. He carefully examined the outcrops and mine headings, providing information on the dip and bearing of the mineralized zone. Dickeson incorrectly refers to the mineralization as a "vein" and notes that it "breaks with clean walls" (a reference to a favorable mining condition). Stratabound ore deposits were not widely known at the time, and in an attempt to convey the promise of the ore deposits, he refers to both the Pahaquarry and Flemington Mines as "true-veins". Dickeson does know something about good mining practice. He criticizes the placement of some shafts at the Pahaquarry mine, suggesting that other locations or heading directions were superior. He correctly suggests that undercut drifting with overhead stoping would be better than sinking an inclined shaft along the trend of the ore. He also suggests that earlier operators had miscalculated and failed to intersect a shaft, wasting effort that "has been of but little service in developing [the property]".

Prof. Dickeson was a true promoter, hired to be optimistic, and concludes his observations on the Pahaquarry Mine with, "My surprise was excited that so much wealth, rearing its index so plainly and boldly to view, should have remained latent or neglected for so long a time; though the attempt heretofore made for its development, were not characterized with the comprehension and *persistence*, which are so essential for redeeming much of the mineral wealth of our country,

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<sup>11</sup> Dickeson, Montroville W., 1862, Report of the Geological Survey and Condition of the Alleghany Mining Company's Property, Warren County, New Jersey, with map and drawing, Phila., 30 p.

from the stigma of sterility, so unjustly applied to it."<sup>12</sup> The Alleghany Mine ceased operations during 1862 and the land was sold during 1867.<sup>13</sup>

### The Montgomery Gold Leaf Mining Company<sup>14</sup>

In 1901, two brothers Henry and Oliver Deshler of Belvidere, NJ, began mining at the site by driving a new adit, using expertise gained at a failed gold mining venture at Tott's Gap, PA. In 1902, they purchased the land formerly controlled by the Alleghany Mining Company and began plans for developing a relatively large-scale mine and mill. They drove the new adit to 300 feet in length and extended older adits, remaining from the 1750s and 1840s attempts. The 1901 adit appears to be a cross-cut through the hanging wall to access the ore-zone, it would be almost entirely in waste-rock.<sup>15</sup> Burns-Chavez and Clemensen (1995) state that the ore from this first adit was found to be low-grade but the Deshlers continued with the construction of the mill and support complex. In 1904, Deshlers reorganized as the Pahaquarry Mining Company and installed an unproven concentrating technique the "Keith Process"<sup>16</sup>, invented by Dr. Nathaniel S. Keith, a metallurgist, Columbia University Professor and an advisor to Thomas Edison.

The mill construction took two years. The Keith process consisted of crushing ore, mixing with coal, then passing it through a down-draft shaft furnace fired by producer gas. The sulfur was supposed to burn off and the copper was supposed to be reduced. The powder was supposed to be treated with dilute sulphuric acid to dissolve the copper, which then when electrolyzed would precipitate in the pure form.<sup>17</sup> Weed (1911) provides a slightly different description saying that after the roasting the copper would form globules in the rock, that when cooled could be crushed and concentrated by gravity methods.

In 1906, the mine plan was changed from underground to surface methods. An open cut was started on the outcrop expression of the ore bed. The area selected was later identified by Cornwall (1945) as containing the highest grade copper.

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<sup>12</sup> Ibid, pgs 17 & 18.

<sup>13</sup> Burns-Chavez and Clemensen, *ibid*.

<sup>14</sup> This section condensed from Burns-Chavez and Clemensen, 1995

<sup>15</sup> M. Zdepski, personal observation by examination of maps and sections.

<sup>16</sup> Kieth also unsuccessfully applied this technique to the Schuyler Mine during 1901, see Woodward, 1944, pg. 56.

<sup>17</sup> Description from Woodward, 1944, pg. 56. Woodward notes that the Kieth Process was described under U.S. Patent 700941, Dec. 7, 1901. He also notes that Kieth published the process in *Eng. Mining World*, v. 75, p. 755, May 16, 1903; and the *Jour. Franklin Inst.* Aug. 1905, pp. 148-155. He also notes that Kieth formed Metals Recovery Company of Camden, NJ with H.D. Deshler as a director.

In addition, a hill-top tippie with a 2,500 foot gravity, funicular tramway<sup>18</sup> was built connecting the mine with the mill. The mill was enlarged by building a new upper level, with a 1,000 ton ore bin. The interior of the mill was changed significantly to accommodate the new mine plan, delaying the complete installation of the Keith Process equipment. Dr. N.S. Keith evidently published an account of the Pahaquarry Mine attempt in 1906, stating that he'd conducted systematic sampling.<sup>19</sup> His results were an order of magnitude greater than representative sampling conducted during 1943.

Between late 1908 and September 1909 it became evident that the Keith Process did not work properly. The Deshler brothers were not deterred. In 1909, they remodeled the mill to use another untested process, froth flotation. The re-fitting required a new 320 h.p. producer-gas-powered 722 K.V.A. generator, new water pump, new dam, and new water tower. Unfortunately, froth floatation for chalcocite-bearing ores was not perfected until 1915, several years after the Pahaquarry Mine failed. Perfection of the process was no-doubt made possible by testing and failure. The Pahaquarry Mine was one of the failures.

The surface mine was operated for three months during 1911. The mining produced ore that was lower grade than expected. The milling showed that the chalcocite was too fine to handle and some of the values were washed away with the tailings. Despite the financial losses and setbacks, the Deshlers tried once again. In late 1911, Oliver's son George O. Deshler began re-tooling the mill to use yet another concentrating technique. He chose an older, proven technology. The crushing circuit remained the same, but a six-hearth McDougall Roasting Furnace followed with an acid leach was selected for the copper concentrating. The acid leach failed to produce a copper precipitate. This system produced no refined copper. The Pahaquarry Mine was once again bankrupt in 1913.

The experimentation with mining and milling was finally finished. The entire effort reportedly produced only three ingots, but independent research suggest it could have been more. Don Pace notes that his research shows the Deshlers produced souvenir ingots and that copper foil was made to accompany letters to stockholders. Don has also tracked down heirs of the Deshlers and been able to examine and photograph a previously unknown ingot. One large ingot with plaque was donated and a souvenir ingot are in the collection of the New Jersey State Museum. The location of the large ingot is not certain, but the small ingot was on display during 1996. The large ingot is known from old photographs, but it cannot be located in the collection.

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<sup>18</sup> Vivian, C. H., 1951, The Mystery of Pahaquarry Copper, Compressed Air Magazine, March 1951, Ingersoll-Rand Co., Phillipsburg, NJ.

<sup>19</sup> Mining Magazine, 1906, v. 13, p. 473, not viewed, as reported by Cornwall, 1945.

Using modern hindsight, examination of the Deshler attempts shows that they spent most of their time constructing infrastructure. They were willing to commit monetary resources for both construction and innovative milling technology, but they failed to properly evaluate the mining ore-reserve. The business relationship between Dr. Keith and H.D. Deshler in the Metals Recovery Company may have clouded the decision-making process. The two men were clearly mill-oriented, and they never conducted a proper geologic or engineering evaluation of the ore-grade. The Deshlers sold stock, spent the investors money, and apparently stayed employed in the mining "business" over an extended period of time. In the end, they returned to the bankrupt mine-property during 1920 and attempted another extractive industry, logging and saw-milling, but were unsuccessful.

### Historical Geologic Evaluations of the Mine

Virtually every geologist, except Montroville Dickeson M.D. (geologic qualifications uncertain), reached a similar conclusion - The copper mineralization is too low-grade for economic extraction. Prof. Dickeson reported assays up to 30% Cu, but these were certainly the result of high-grade mineralization that could only occur over a narrow interval or hand-cobbed concentrates. The Deshlers seemed to be knowledgeable in both mining and milling, but their sampling results were anomalous<sup>20</sup>, and were not borne-out by mining. The earliest mining attempts were focused on finding rare high-grade pockets, most-likely resulting from late-stage, supergene remobilization. Late-stage vugs are certainly present, because small euhedral quartz crystals can be found in the spoil piles of "Tunnel No. 1". The finely-disseminated nature of the copper mineralization was repeatedly noted by trained observers:

1830s, H. Rogers, NJ State Geol.	Specimens of ore indicated nothing to warrant mining attempts.
1840, J. Jordan, Mining Eng.	Veins thin, three to four inches thick. [Probable clots in fracture zones.]
August 1942, US. Bur. Mines	Little opportunity for development, no further work recommended.
June 1943, US Geol. Survey	Too low grade to develop.
1944, NJ Dept. Conserv. & Devlp.	Ore too lean, transport too expensive.

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<sup>20</sup> Cornwall, 1945, notes that Dr. N.S. Keith claimed to have collected 100 samples that "averaged about three percent copper". In contrast, Cornwall found only 0.11 to 0.38% in his systematic samples.

The 1943 map produced by H. R. Cornwall (Open-file Report, 1945) provides the most accurate plan-view representation of the mine workings, complete with bedding attitudes and notes on the mineralization (Figure 3). He mapped both the accessible underground headings and the surface cuts (Figures 4 and 5). The evaluation conducted by USGS Strategic Mineral Branch was thorough and it included four diamond drill holes. The sampling was representative, with true channel sampling across the width of the mineralization. No map exists for the 1901 adit, reported to penetrate 300 feet into the hill.

Cornwall described the occurrence of the copper quite nicely:

Exploration and development have been largely confined to a 40-foot horizon in the moderately dipping gray quartzite (see pls. 1 and 2 and fig. 1). [Not provided in this guidebook.] The richest occurrence of copper is at the main quarry. A composite sample from this area ran 0.38% Cu. The assays in table 1, p. 3, indicate that, although the copper mineralization may be uniform throughout the 40-foot horizon, the rock is low grade, averaging from 0.1 to 0.2 percent copper. Locally there are rich seams up to 2 inches across, knots up to 3 inches in diameter, of chalcocite. Surrounding these the quartzite contains disseminated chalcocite grains. The rich chalcocite seams usually occupy fractures which are parallel to the bedding. These fractures also often contain vuggy quartz.

Cornwall, (1945) concludes that there may be as many as 2 million tons of ore present, but that the grade is very low. For reference, western porphyry copper deposits contain grades of 0.3 to 0.5% Cu and 50 to 200 million metric tons.

The evaluation by Dr. N. S. Keith between 1903 and 1906 reportedly made use of 100 systematic samples. By Dr. Keith's account these samples "averaged nearly three percent".<sup>21</sup> Woodward (1944, pg. 135) says "It has been reported that 100 samples of the ordinary gray sandstone averaged 3.25 percent copper in the form of chalcocite." Woodward provides no reference for the data. It appears that this statement is derived from Dr. Keith's work and it is most likely in error, because H.D. Cornwall found the grade to be 0.38 percent copper in 1943.

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<sup>21</sup>Mining Magazine, 1906, v. 13, p. 473, not viewed, as reported by Cornwall, 1945.

# GEOLOGY OF THE PAHAQUARRY COPPER MINE

by

Donald H. Monteverde<sup>22</sup>

The Bloomsburg Red Beds are the Pahaquarry mine's host rock. These Upper Silurian clastic units overlie the Shawangunk Formation, which holds up the main ridge of Kittatinny Mountain. The Bloomsburg covers the western subsidiary ridges and the rock's northwest dip produces the western slope of the ridge. Copper in the Bloomsburg is an uncommon occurrence. When hiking across the Bloomsburg and into the mine workings malachite and chrysocolla supply the first evidence of the copper mineralization. This is probably the indicator that first led to developing the Pahaquarry mine (Weed, 1911). The ore occurrence, genesis and regional geology that led to the Pahaquarry mine will be described. The description of the ore mineralization and genesis will be based entirely on Woodward (1944).

## GEOLOGY

### Regional

Kittatinny Mountain geology is dominated by the Silurian-age Shawangunk Formation and Bloomsburg Red Beds. The Middle Silurian Shawangunk consists of light-gray, quartz-pebble conglomerate, quartz sandstone and minor shale. Cuts on both sides of the Delaware Water Gap beautifully expose the Shawangunk's three members. These consist of an upper and lower conglomerate, sandstone and quartzite facies (Tammany and Minsi Members, respectively) separated by an intervening gray shale dominated member (Lizard Creek Member) (Epstein and Epstein, 1972).

Bedding generally dips northwest, though there are many folds and faults cutting the Shawangunk. Regionally the Shawangunk averages 1,400 feet thick. These coarse clastic sediments are resistant to weathering and support the ridgeline of the Blue-Kittatinny-Shawangunk Mountains. Even though the Shawangunk holds up the highest regions of New Jersey it was not deposited in such lofty regions. Supplied by clastic debris from a weathering eastern mountain source, Shawangunk deposition occurred under braided stream and marginal marine paleoenvironmental conditions along a northwest-facing coastline (Epstein and Epstein, 1972).

The Middle to Late Silurian-age Bloomsburg conformably overlies the Shawangunk throughout the length of the Blue-Kittatinny-Shawangunk mountain chain. Red and

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<sup>22</sup> From Monteverde, D. H., 2001, Pahaquarry copper mine, in, Inners, J. D. and Fleeger, G. M., eds., 2001—a Delaware River Odyssey, Guidebook, 66<sup>th</sup> Annual Field Conference of Pennsylvania Geologists, Shawnee-on-Delaware, PA, p. 150 - 155.

less common gray and green, sandstone, siltstone, shale, and minor conglomeratic sandstone, arranged in repetitive fining-upwards cycles, characterize the Bloomsburg. Sandstones commonly have an erosive base and upward exhibit crossbedding and laminations. Siltstones overlie the sands and gradually grade upward into shale that may be mudcracked. Bloomsburg deposition occurred in a shallow to marginal marine paleoenvironment. The fining-upwards cycles represent the effects of rising and lowering relative sea level during deposition. The sediments can be burrowed, mottled, and locally fish scales occur. A fish scale locality exists at mile 15.4 on the alternate road log, south of the Pahaquarry trail parking lot. Dorsal and ventral plates of the ostracoderms *Vernonaspis* and *Americaspis* have reportedly been found there. Bloomsburg thickness is approximately 1,500 feet thick. Bloomsburg sandstones may be clean, quartz-rich sands equally resistant to weathering as the Shawangunk or clayey sandstones that erode and underlie the lower topographic locales on Kittatinny Mountain.

The Bloomsburg and Shawangunk Formations have similar deformational histories. Due to their relatively uniform rock strengths and combined thickness they reacted to the northwest-directed progressive strain of the Alleghanian orogeny in a uniform way. The weaker siltstone and shales below (Late Ordovician in age) and limestone units above (Late Silurian to Devonian in age) more readily folded and faulted than the stronger, more resistant Shawangunk-Bloomsburg rock package. This allowed Epstein et al. (1967) to divide these rocks into different lithotectonic units according to their combined rock strength and subsequent reaction to the Alleghanian applied stresses. Lithotectonic unit 2 containing the Shawangunk and Bloomsburg displays broad, open to locally overturned folds that commonly exhibits flexural slip. Wedge and thrust faulting are common as seen on both sides of the northern section of Delaware Water Gap. Cleavage is better developed in the Bloomsburg due to its higher clay content than the Shawangunk. Regional cleavage is steep to moderately southeast dipping.

### Ore geology

The host Bloomsburg beds dip northwest, forming a dip slope (average bedding orientation is N53° E/42° NW) that has been bisected by the Mine Brook drainage. A cross sectional view of the layers was exposed when this brook downcut to its present level. Interbedded layers of gray clean sandstone, red and gray clayey sandstone and reddish siltstone and shale are well exposed in the cuts. Sandstone beds dominate the area. Excellent glacially polished ledges of sandstone can be seen in the quarry on the upper ridge southwest of Mine Brook. There, the sandstone is gray, medium to thick bedded, crossbedded to massive. Joints cut the sandstone and parallel the well-developed cleavage in the finer grained siltstones and shales. Fining-upwards sedimentary cycles repeat throughout the mine region. Sandstones dominate the overall cycles, as shale layers tend to be thin.



Early workers identified chalcocite ( $\text{Cu}_2\text{S}$ , copper sulfide) as the main copper-bearing mineral in the mine. Secondary copper minerals, malachite ( $\text{Cu}_2(\text{CO}_3)(\text{OH})_2$ , copper carbonate hydroxide) and chrysocolla ( $\text{CuSiO}_3 \cdot n\text{H}_2\text{O}$ , hydrated copper silicate), probably first caught the eye of early prospectors. Examples can still be found in the rock exposures and along old dump piles of these secondary minerals. They coated the bedrock along bedding planes and certain joint surfaces and were restricted to exposed rock surfaces, penetrating only slightly into the rock. The chalcocite is disseminated in select gray sandstone beds and very difficult to discern without magnification. Chalcocite may also form either as thin seams paralleling bedding or joints, or as irregular shaped patches and/or nodules several inches or up to a foot long that have partially replaced the host Bloomsburg bed.

Thickness of the copper bearing Bloomsburg may be as much as 200 feet. The highest reported natural samples contained 3.25% copper, but the entire copper-bearing horizon has a much lower percentage. Pahaquarry is thought to be an epigenetic deposit. The copper is believed to have been disseminated throughout the original beds as primary detrital grains. Waters high in salt (sodium chloride) and gypsum (calcium sulfate) remobilized the copper into solution. The copper was reprecipitated in nearby sandy horizons supporting a suspected more highly acidic condition. Temperature levels are thought not to have exceeded  $91^\circ\text{C}$ . Later, meteoric-water interaction aided the growth of the secondary minerals, malachite and chrysocolla.

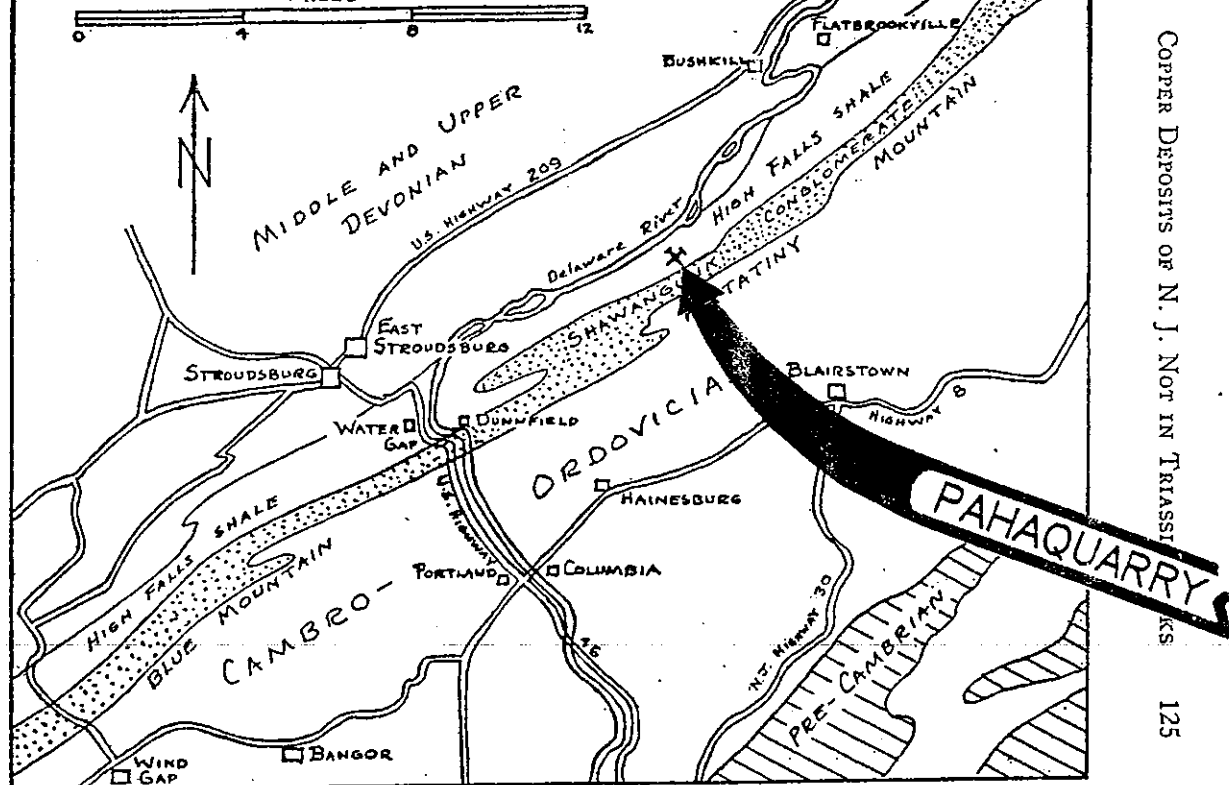


FIG. 10. Generalized sketch map of the Pahaquarry area, showing location of the old mine workings, the surface outcrop of the Shawangunk conglomerate and High Falls shale. The old Mine Road followed the Delaware River down to Water Gap.

Figure 1, from Woodward (1944)

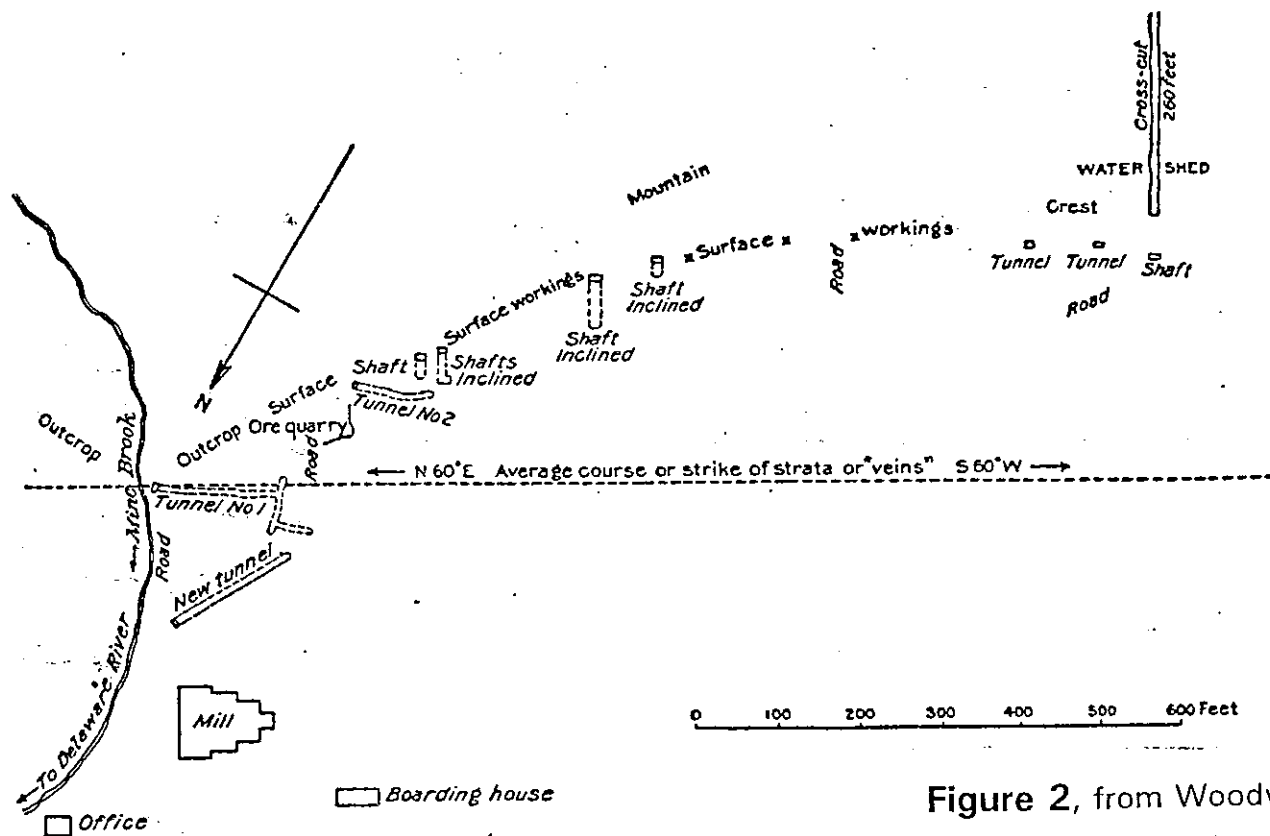


Figure 2, from Woodward (1944)

FIG. 11. Sketch map of the Pahaquarry area made during period of last mining activity. (Source: Wm. Lee Phyfe's unpublished M.S.)

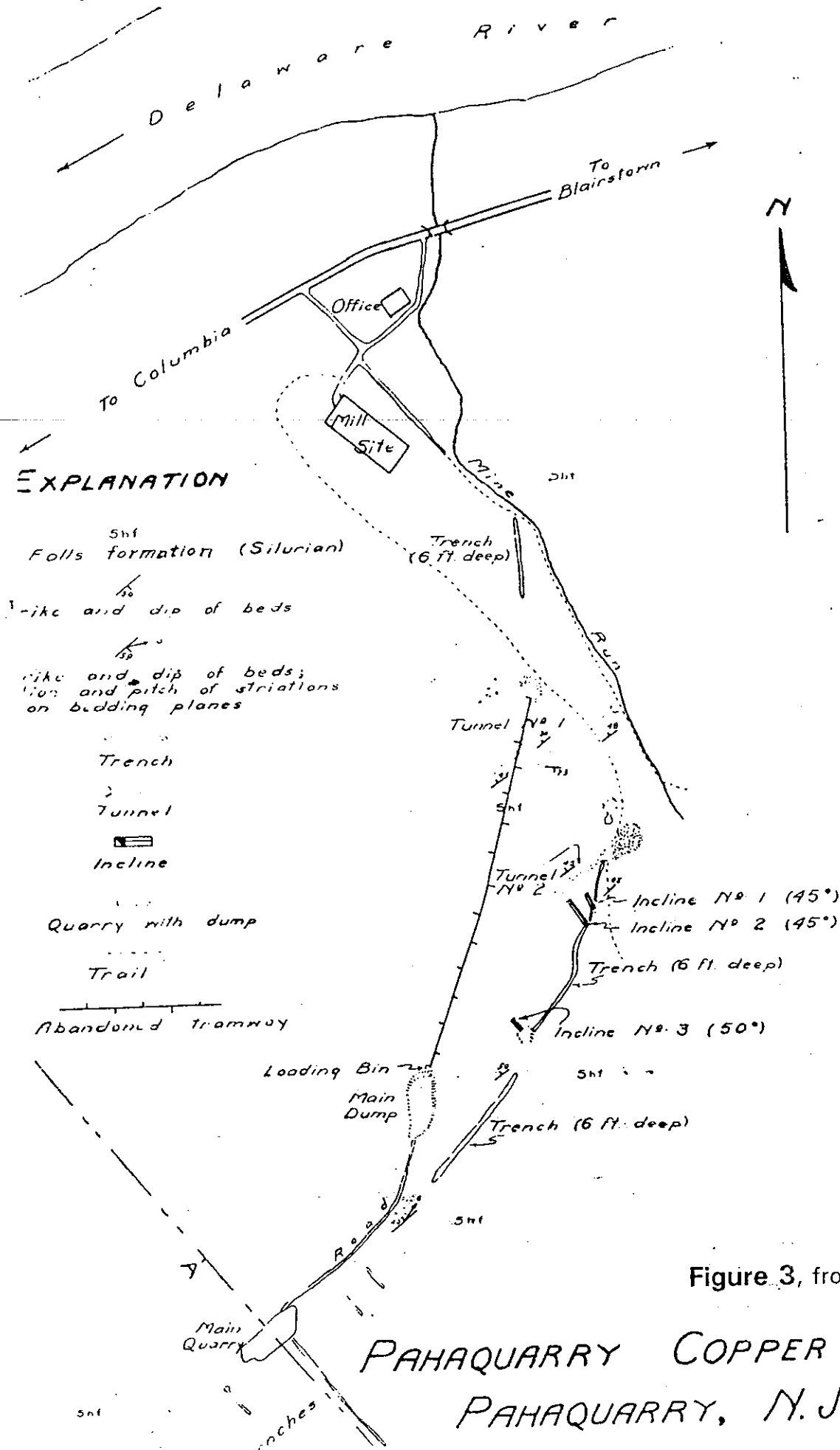


Figure 3, from Cornwall (1945)

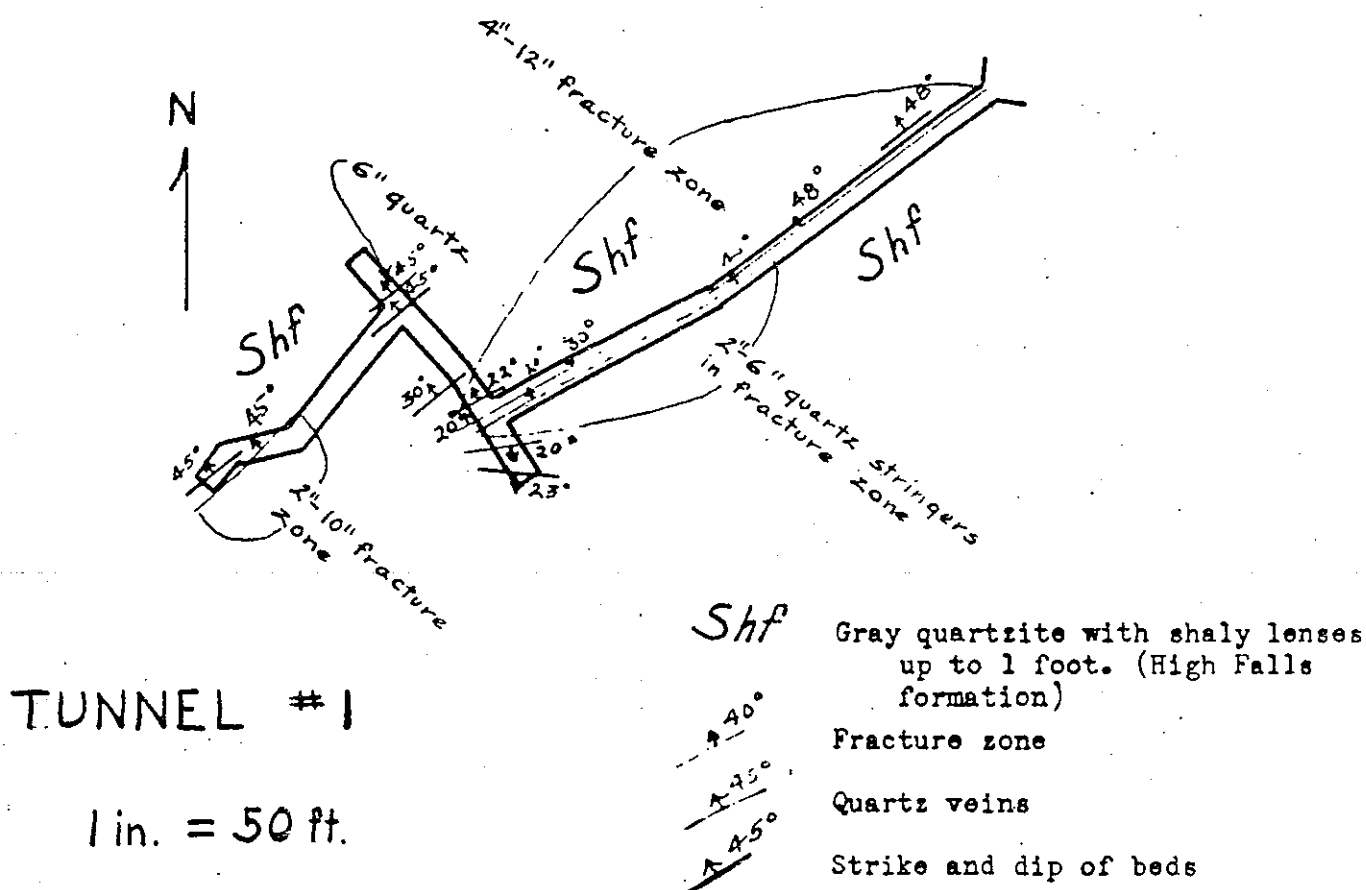


Fig. 2 Plan of Tunnel 1.

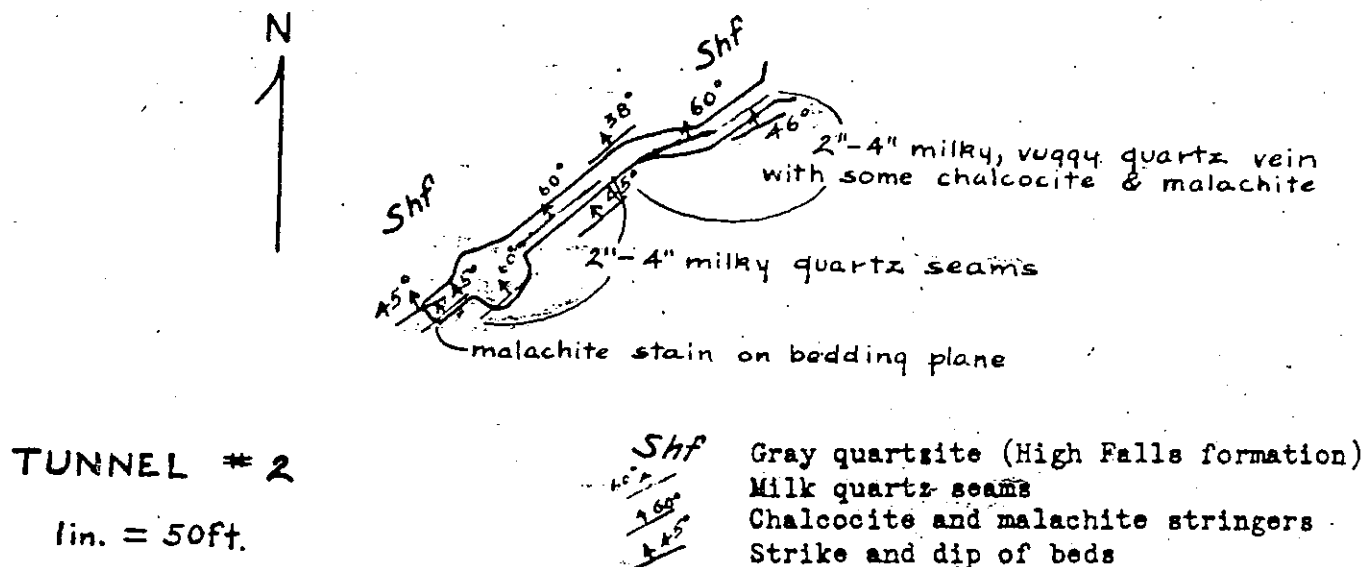
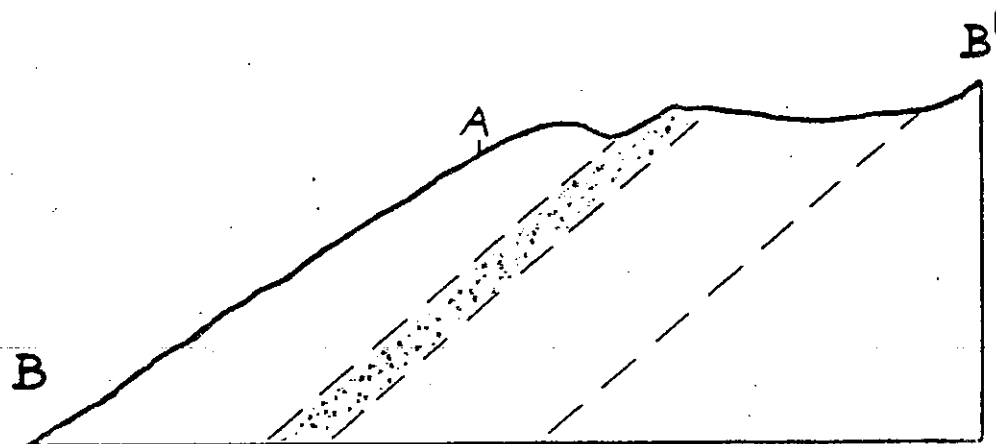


Fig. 3 Plan of Tunnel 2.

Figure 4, from Cornwall (1945)



Section B-B' 1 in. = 200 ft.



-  Uniform copper mineralization as indicated by 7 trenches, 3 inclines & 2 tunnels
-  Uniform copper mineralization as indicated by 1 trench at main quarry

Fig. 1 Cross section B-B' of the whole area developed.  
Pahaquarry Copper Mine

H. R. Cornwall, June 1943

# THE PAHAQUARRY COPPER MINES

## PAHAQUARRY COPPER CO.

Incorporated under the laws of New Jersey

CAPITAL STOCK, \$500,000

500,000 Shares at \$1.00 per value. Fully paid  
and non-assessable

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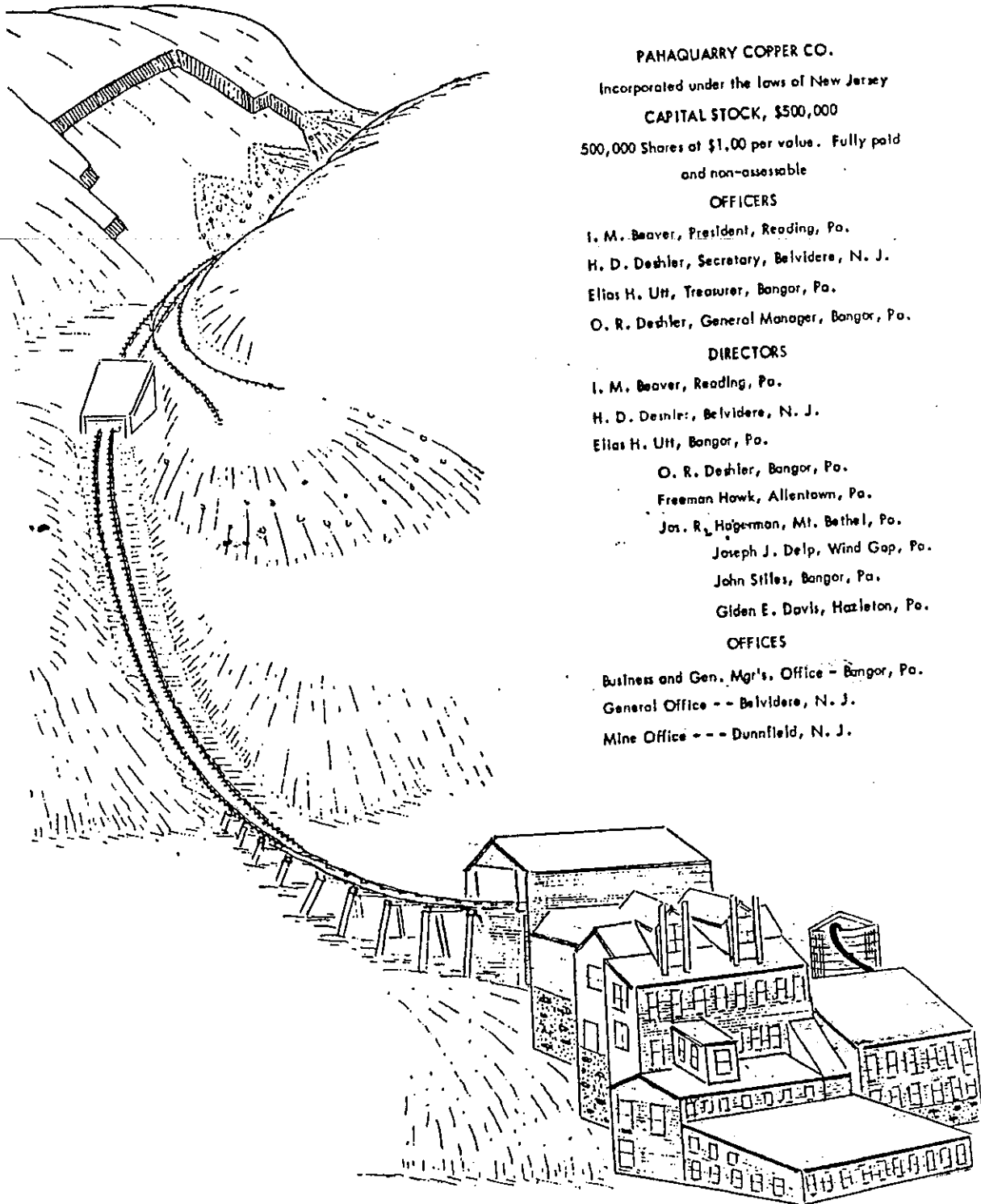
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Miles		
Interval	Cumulative	
0.3	16.7	Continue upriver (northeastward). Pass Poxono Island access site on left. One of several boat launches operated by the National Park Service.
1.1	17.8	Pass Calno School on left. Built in the 1850s. The low terraces in this area are postglacial. Several Amerind occupation sites are located on the broad terraces west of the school. One is located just behind the school.
0.3	18.1	Climb onto outwash-fan terraces where Van Campens Brook enters the Delaware Valley. These terraces are as much as 60 feet higher than the post-glacial terraces near Calno School.
0.6	19.7	Outcrop of Bloomsburg Red Beds on left.
0.5	20.2	Striated Bloomsburg Red Bed pavement behind farmhouse on left. Striae point S56°W and S78°W.
1.1	21.3	Entrance to Water Gate Recreation Area on right.
0.3	21.6	Cross over Franklin Grove recessional moraine. At this location, the moraine is barely a bump on the road.
0.1	21.7	Turn right onto Millbrook-Flatbrookville Road.
0.1	21.8	Enter Millbrook Village.
1.6	23.4	Turn right onto Blue Mountain Lake Road.
1.3	24.7	Blue Mountain Lake parking area. A broad dip-slope exposure of the Bloomsburg Red Beds is visible to the left. Glacial striae trending in at least two directions are visible.
1.5	26.2	Enter parking area on right, opposite entrance to sign for Ken-Etiwa-Pec. The crest of Kittatinny Ridge is visible just ahead. Disembark. Proceed past weather station southward along the Appalachian Trail about 1,500 feet to the third overlook cutoff to the left (gravel-surfaced).



### STOP 3 - FAIRVIEW LAKE OVERLOOK

This stop is located on Kittatinny Mountain along the eastern edge of the Delaware Water Gap National Recreation Area (DEWA) in New Jersey. Parts of this description were liberally lifted from my discussion in the 2001 Field Conference of Pennsylvanian Geologist. The hike up to this point along the Appalachian Trail followed an old road constructed during the initial stages of a Kittatinny Mountain housing development. The two subordinate trails passed before the one taken to this lookout were all driveways entrances to proposed homes or those already built. The proposed Tocks Island dam stopped all development on this ridge crest. Though the landowners of that time were very dissatisfied with the governmental intervention, the years have advanced and hundreds of thousands have enjoyed the relative pristine landscape that we stand in today.

This lookout affords its visitors exceptional vistas.... To the southwest one can see the cooling towers of Martins Creek Steam Generation Electrical Plant, located just south of the late Wisconsinian glacial terminal moraine (figure 1). As your eyes scan from this point towards the east northeast trending ridges underlain by Proterozoic-aged metamorphic rocks form the topographic high elevations. On of more southern ridges is Jenny Jump Mountain which has been thrust up over lower Paleozoic carbonate rocks during the Alleghanian Orogeny. Jenny Jump State Park lies at the top of this ridge. Route 80 cuts across the northeastern terminus of Jenny Jump Mountain. To the northeast, in the far distance (if the weather is agreeable) one can see the end of the New Jersey Highlands, just over into New York State (figure 2).



Figure 1 – Overlook view towards the southwest across the strike of Kittatinny Mountain. The Martins Creek cooling towers can just be seen in the distance. These towers lie along the Delaware River in Pennsylvania, just south of the Wisconsinan terminal moraine. Jenny Jump Mountain is a muted feature in the center of the photograph just to the right of the prominent tree covered knoll.

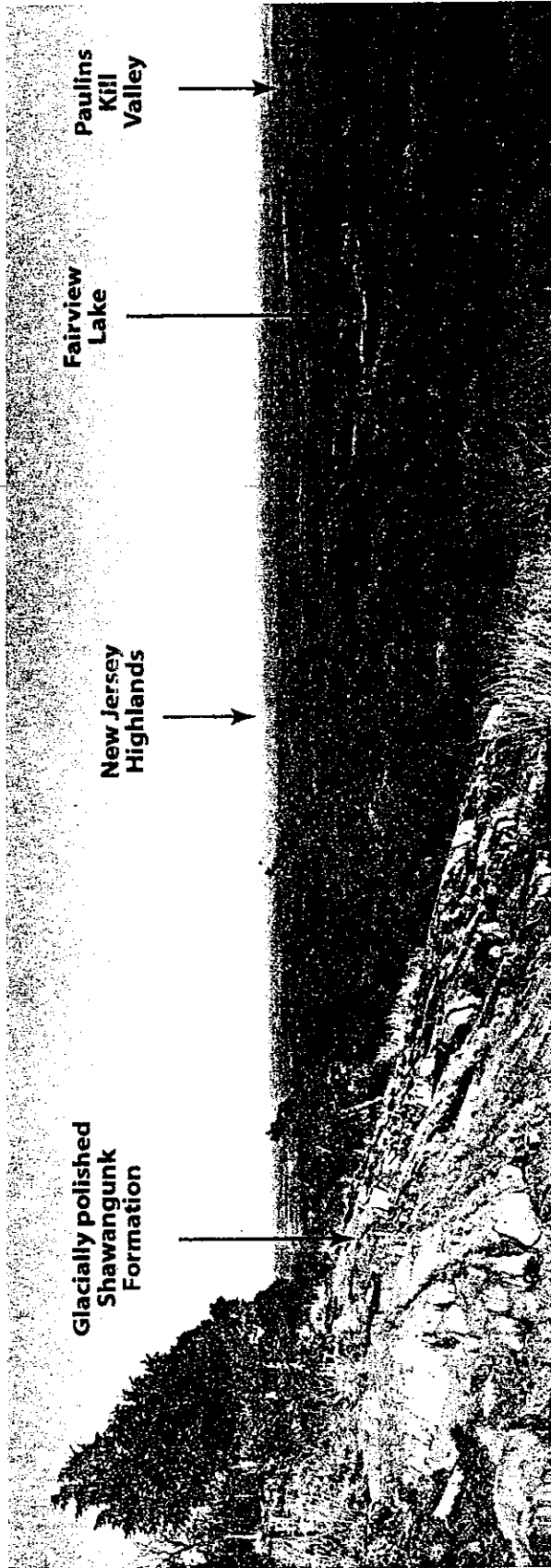


Figure 2 – Panoramic view from the Fairview Lake overlook. View is looking northeast on the left to east of the right. The distant ridges are composed of Proterozoic-aged metamorphic rocks. The next slightly elevated ridge marks Martinsburg Formation on the east side of Paulins Kill Valley. The Martinsburg hides a belt of carbonate rocks between it and the Proterozoic. Martinsburg covers the rest of the topography from the Paulins Kill to the base of Kittatinny Mountain. Some of the topography in this Martinsburg belt was constructed by glacial deposits.

If one now looks across towards the far eastern horizon older and older rocks will be traversed (figure 3). The Shawangunk Formation upholds the Kittatinny Mountain ridgeline. Extensive erosion of these rocks over millions of years has created a rugged landscape that remains largely uncultivated. The slopes to the south and east of this lookout, in the western Kittatinny Valley, house graywacke and slates of the Ordovician-aged Martinsburg Formation. Sequestered within the Martinsburg is Paulins Kill Valley, underlain by Cambro-Ordovician carbonate rocks. Paulins Kill is an exposed carbonate fold and thrust belt that records phases of both Taconic and Alleghanian orogenic events. Continuing eastward the Martinsburg again creates moderate topography. A second carbonate belt forms just slightly lower elevation before reaching the ridges on the eastern horizon. These well-defined ridges are in the Proterozoic-aged metamorphic rocks of the New Jersey Highlands.

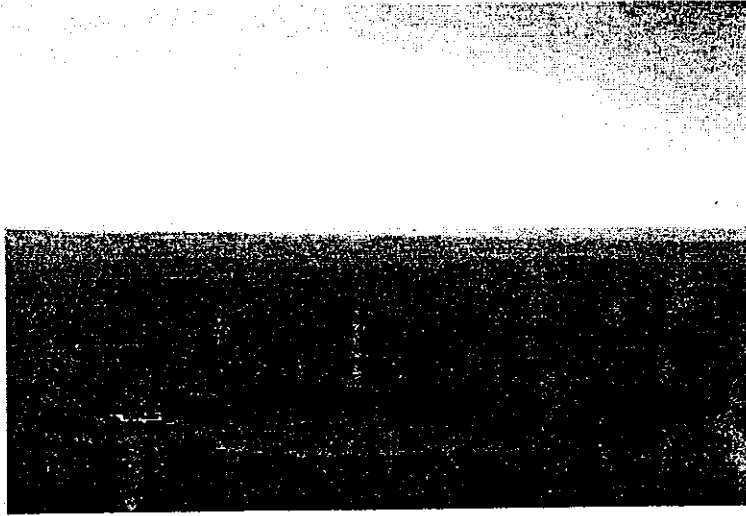


Figure 3- View looking directly across Kittatinny Valley over Fairview Lake. From the base of Kittatinny Mountain to the first ridge is all underlain by Martinsburg Formation. Martinsburg also underlies the ridge across the small valley just west of the first ridge. The small valley, Paulins Kill is a carbonate valley.

Perhaps, after our long day in the field, it is a time for quiet contemplation, rather than a lengthy and loud discussion about the past. So if you look behind you I will try to sneak off and have lunch.

### **That Lake Below**

Fairview Lake is the body of water just below the overlook (figure 3). On its northeastern banks lies the Fairview Lake Camps and Conference Center run by the Metro YMCA's of the Oranges. This camp has been continuously open since its founding in 1915. Neither the 1930's depression nor two World Wars have forced it to close. The camp serves as a summer camp for kids between 6 to 16 years old as well as a retreat for diverse conferences. Another important aspect of Fairview Lake is the

Environmental Education Center which serves New York and New Jersey school district children as well as Teacher Workshops and Elderhostel participants.

## **BEDROCK GEOLOGY**

### **Regional**

At this overlook, we are standing on the Shawangunk Formation of probable Middle Silurian age. The Taconic unconformity between the Shawangunk atop and Martinsburg below is an important surface in this region. The trip has already traversed this unconformity twice, but unfortunately the contact was not exposed. I-84 construction just north of the New Jersey border uncovered the contact (Figure 4), approximately 20 miles north and displayed a thin clayey fault gouge separating the Martinsburg from the overlying Shawangunk. Epstein recorded a slight angular divergence between the two units. Another exposed contact originally described in New Jersey Geological Survey historical notes depicts a classic erosional unconformity where Shawangunk coarse clastics bevel the Martinsburg without apparent structural deformation (Figure 5). Again only a slight angular discordance separates the Shawangunk and Martinsburg Formations. Colluvium covers the Martinsburg beneath the contact. Colluvium also covers the contact here. The approximate unconformity location can be seen by approaching the Shawangunk cliff and looking directly down. Please be careful in attempting this observation.

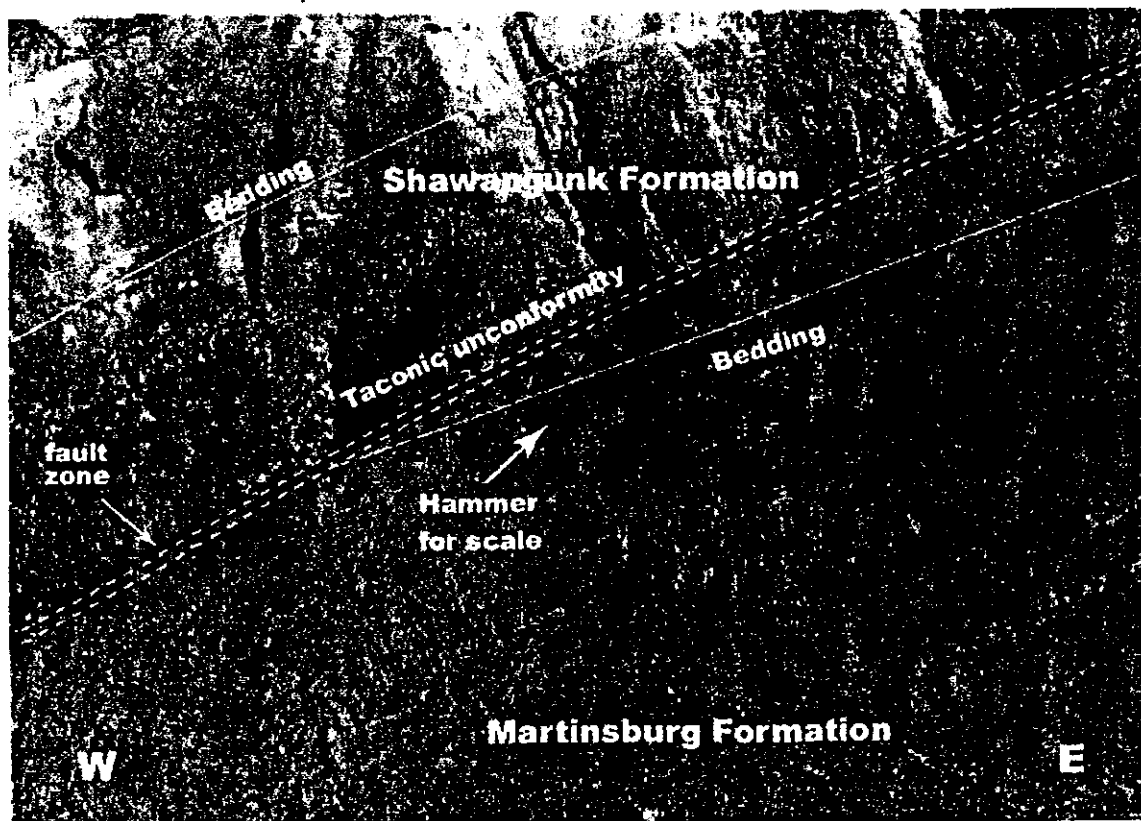


Figure 4 -- Taconic unconformity exposed in the Interstate Route 84 construction cut. A thin fault zone exists along the contact. There is a slight angular divergence between the Shawangunk Formation bedding above and the Martinsburg Formation below.

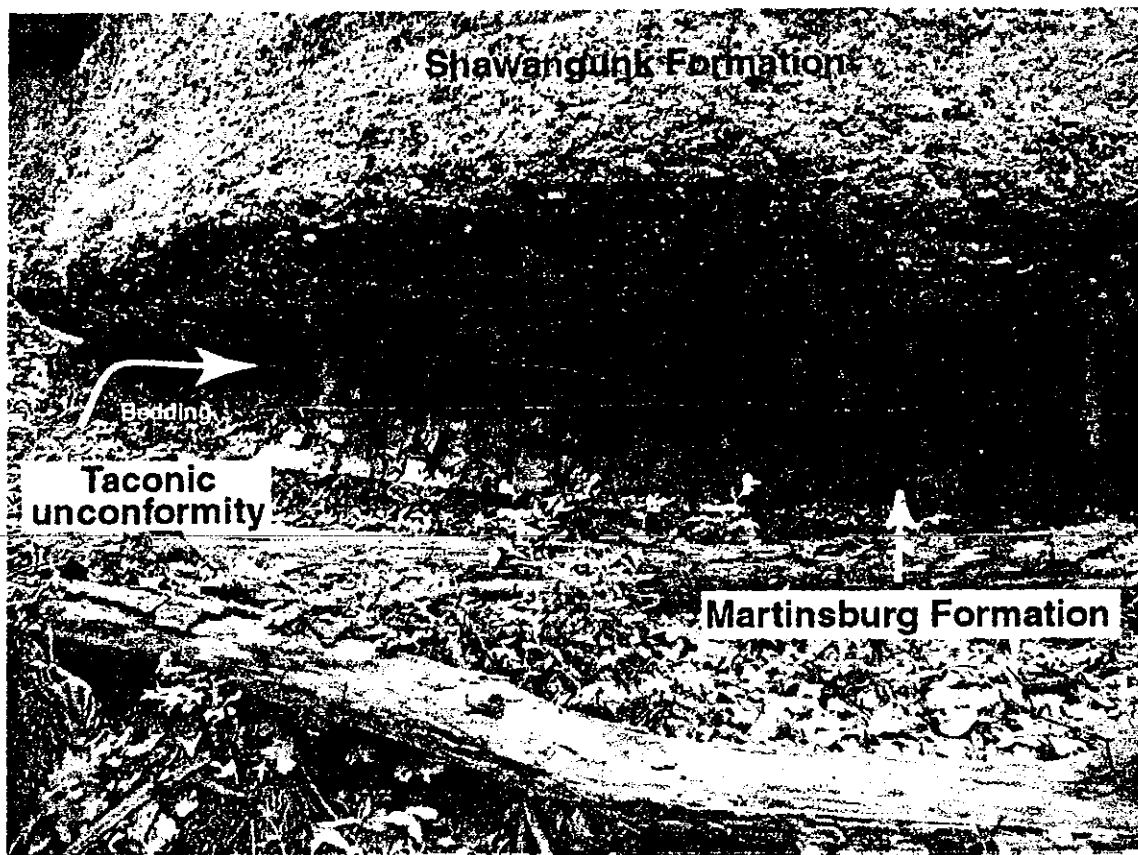


Figure 5 – Taconic unconformity exposed in Stokes State Forest, several miles north of this location in the Branchville quadrangle. The contact shows an angular unconformity that down cuts to the north. Dotted line marks the unconformity and solid line the Martinsburg bedding. No deformation was evident along this contact. The basal Shawangunk is a thick bedded, quartz pebble conglomerate. This basal unit portrays this characteristic rough weathering profile all along the Kittatinny Mountain front. Only the upper two feet of Martinsburg is exposed.

The Taconic unconformity represents a major break in the rock record. It separates two diverse units representing distinctly different paleoenvironments. Beneath the unconformity the Martinsburg sediments mark deposition in a deep foreland basin. Turbidite deposition occurred both under northwestward-directed downslope conditions as well as parallel to the southwest-northeast trending basin axis (McBride, 1962). The Martinsburg foreland basin displays a pronounced along-strike morphology with deeper environments represented by the commercial slate of the Penn Argyl Member in eastern Pennsylvania and the thick sandstone beds of the locally occurring High Point Member signifying more proximal position (Drake and Epstein, 1967; Drake, 1991). McBride (1962) showed that paleoflow in New Jersey parallels the bathymetric basin axis towards the southwest whereas Martinsburg sediments, located farther westward, were carried northeast. This indicates a deep basin depocenter in eastern Pennsylvania, around the

Penn Argyll outcrop belt. The youngest Martinsburg is late Middle Ordovician in age (Parris and Cruikshank, 1992) with deposition synorogenic in the Taconic orogeny.

The Shawangunk resides on the other side of the unconformity. This clastic wedge developed after filling and uplift of the Martinsburg foreland basin. A mountain range to the east built by the progressive Taconic northwest verging fold and thrusting supplied clastic detritus transported westward in fluvial systems until final deposition under braided stream conditions (Epstein and Epstein 1972, Epstein, 1993). A sedimentological problem, common throughout the Appalachians, is why there is a dearth of pebbles derived from rocks overlying the Precambrian. Sediment provenance shows the source as an uplifted and unroofed Grenville terrain (Gray and Zeitler, 1997).

## Local

Epstein and Epstein (1972), Epstein and Lyttle (1987) and Epstein (1993) characterize the Shawangunk as a basal conglomerate overlain by shale, sandstone and conglomerate formed as a braided fluvial deposit. Regionally towards the southeast the Shawangunk is characterized by three members, the lower Minsi, grading upwards through the Lizard Creek and into the Tammany Member. The Minsi is light- to medium-gray to light-olive-gray, thin- to thick-bedded quartz and feldspathic sandstone, quartzite, and quartz-pebble conglomerate. It is a matrix-supported conglomerate that is poorly- to well-sorted. Cross- to planar-bedding occurs throughout. Clasts are primarily quartz and some dark-gray argillite and black chert. Sandstone is feldspathic and locally approaches an arkose in composition. This is overlain by the Lizard Creek. This middle member is locally occurring, and where found is light- to medium-dark-gray, greenish-gray. It consists of interbedded thin- to medium-bedded shale and sandstone that is planar tabular to trough cross-bedded. Grains are well rounded and moderately to well sorted. Contains sparse graphite flakes. The upper Tammany Member is medium- to medium-dark-gray, or dark-greenish-gray in color. Lithology ranges from medium- to thick-bedded sandstone to pebble conglomerate having well rounded grains; some limonite staining is evident. The conglomerate consists of matrix-supported quartz and subordinate shale pebbles as long as 5 cm (2 in) in poorly- to well-sorted, planar tabular to trough cross-bedded sandstone. Local black to dark-greenish-gray, thin-bedded shale occurs near upper contact with the Bloomsburg Red Beds. Bloomsburg outcrops were passed on the bus ride to this stop.

The Shawangunk is highly polished by late Wisconsinian glaciers. These glaciers left a streamlined rock surface as well as various striations, concentric gouges and chatter marks, all glacial markings indicating the direction of glacial flow (figures 6, 7). The highly polished Shawangunk exposes the nature of this unit. This location correlates to the Tammany Member. Geologically field mapping noted few thin shale beds at the apparent stratigraphic position of the Lizard Creek Member. Therefore the Shawangunk was mapped as a single unit. This unit along with the overlying Bloomsburg represents a continental-to-marine transitional deposits of the Taconian clastic wedge. Epstein and Epstein (1969, 1972) note that these rocks were deposited by northwest-draining streams in fluvial, estuarine, lagoonal, tidal flat and offshore bar and beach environments.

Excellent examples of fluvial sedimentary structures can be seen in these glacially polished outcrops. These structures include channel lag deposits, trough cross bedding, cut and fill structures (figure 8) and stacked cross beds.

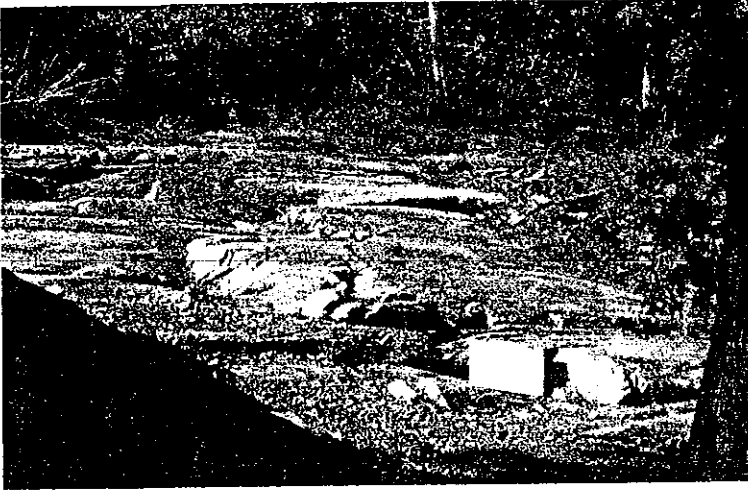


Figure 6 – Exposure showing glacial streamlining of upstream bedrock surfaces (to right) and plucking of downstream surfaces (to left).

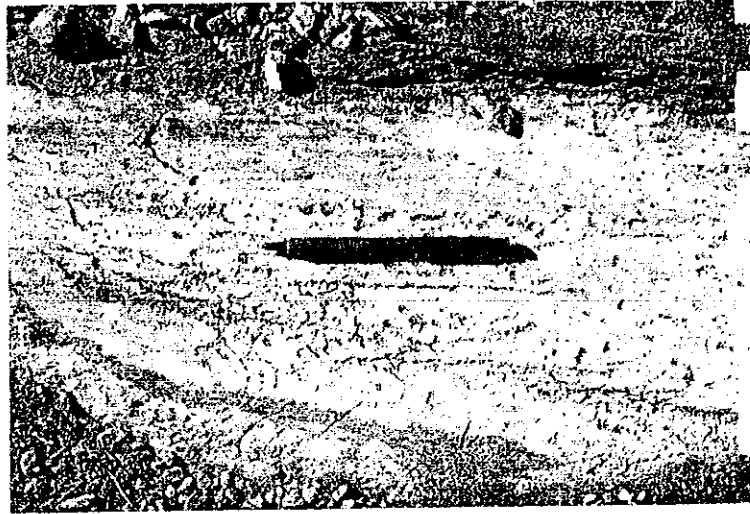


Figure 7 – Exposure showing chattermarks (below pen, concave downstream) and crescentic fracture (above pen, concave upstream). Ice moved from right to left.



Figure 8 – Oblique view looking southwest across outcrop face. Head of hammer rests on channel that down cuts into a finer grained sandstone bed. Channel is coarser grained quartz arenite.

Miles		
Interval	Cumulative	
12.3	38.5	Retrace route to head of Rock Cores Trail, near the southern end of Tocks Island. (Left out of parking lot and downhill to end of Blue Mountain Lake Road. Turn left at the intersection and follow the road to Millbrook Village, then an additional 7.9 miles along Old Mine Road to the head of the Rock Cores Trail. Disembark.

## **STOP 4. New Jersey Abutment of Tocks Island Dam**

Leaders: David Harper; Environmental Evaluation Group; Robert Metz, Kean University

This stop is within Worthington State Forest. Colonial settlement of the area began in the 1720s, and the area was contested between the Lenape Indians and the settlers until the revolutionary war. During the revolution, to forestall the possibility of an alliance between the Lenape and the British, George Washington sent troops to clear the area of Indians. The only pitched battle within this area of the Delaware Basin appears to have been to the north, near Lackawaxen, where a force under Joseph Brant, a Mohawk, soundly defeated the colonial militia.

Settlement continued after the war, and the area prospered until into the mid-1800s. Local commerce centered in the village of Brotzmanville, which stood in what is now a campground on a terrace between the field stop and the Water Gap. The village had a post office, several houses, a sawmill, a gristmill, a school, and a limestone quarry and limekiln. As in many rural areas of the northeast, the local economy went into decline after the 1850s. Somewhat later, the Water Gap became a popular summer resort area. Beginning in the 1890's, the New Jersey industrialist Charles Worthington (manufacturer of Worthington pumps among other equipment) began buying tracts of land, including the village of Brotzmanville, for Buckwood, his personal estate. Beginning in 1954, the State of New Jersey began purchases of this estate for Worthington State Forest.

The field stop is located at the crest line of the proposed Tocks Island Dam. Tocks Island was chosen for the dam site to maximize reservoir storage, not because conditions for dam construction were optimal. Construction conditions are more favorable at Wallpack Bend, about 10 miles upstream, where a dam could be anchored in rock rather than unconsolidated deposits. Locating the dam further downstream increased storage between the dam and the practical northern limit of the reservoir at Port Jervis. More importantly, it captured tributary storage in the Flatbrook valley.

Exploratory borings for a dam at Tocks Island were done to 140 feet in 1942. The borings did not encounter bedrock, and a dam was judged to be either impractical or excessively expensive. Severe flooding and the loss of 100 lives in 1955 placed the upper Delaware within the Corps of Engineers flood control mandate and paved the way for massive federal involvement. It did not, as commonly presented, create the impetus for a dam on the Delaware. Planning for a dam to be constructed jointly by Pennsylvania and New Jersey at Wallpack Bend was well along at this time. A 1957 Corps of Engineers study, however, found that a reservoir at Tocks Island was feasible and would



have double the storage capacity of a Wallpack Bend reservoir while adding only 50 to 60 percent to the cost. From that time, Tocks Island became the preferred site.

Seven miles of cores and 20 or more miles of seismic line were run to choose the location and complete the design. Seismic work and preliminary borings identified only one reach of the valley within the Tocks Island area that might be suitable for construction of a dam. In all other sections of the valley, excessive thicknesses of unstable glaciolacustrine sediment made the construction of a dam impossible. After the selection, foundation borings were done in the unconsolidated deposits and in rock, and a 100-foot adit was driven at the western abutment. Shortcomings of the site were found to be substantial, but amenable to engineering solutions (see Harper, this volume).

Features of interest at this stop are:

1) Outcrops showing steeply dipping jointing.

Prominent, west-dipping joints are characteristic of outcrops along this section of the valley. Epstein (2001) attributes the joints to sheeting or exfoliation caused by rapid erosion. Failure along such joints has destroyed sections of roads and hiking trails cut into the hillsides, and repairs have cost an estimated \$150,000 (Epstein, 2001). Epstein interprets the failures to be the combined result of the sheeting, prominent fractures perpendicular to the sheeting which break the sheets into blocks up to several feet on a side, and road cuts into the hillsides which left the blocks without downslope support on fracture surfaces dipping 50° to 70° towards the roadway. The failures occurred by sliding or toppling.

Bedding is less steep and not prominent. It is most easily visible as bleached bands. The bedding did not contribute to the failures at surface exposures, but failure along bedding-plane faults was a significant consideration in planning for the Tocks Island Dam (below).

2) The remains of an adit.

Stability of rock cuts more than 300 feet high above the spillway and intake structures was a major concern. As further described in Harper (this volume), a 5 x 7 foot adit was driven into the hillside to investigate rock conditions (Depman and Parrillo, 1969). The findings were not encouraging. Numerous bedding-plane faults dipped towards the excavation, and many of them were zones of abundant ground water flow. Two of the faults showed weathering and decomposition. These two zones were further investigated by cross cuts from the adit, 36-inch core holes drilled from the surface, and 4-inch core holes to investigate geometry of the fault surface and hydrostatic conditions in the bedrock. The faults were found to be continuous through the area. Stress measurements above and below the deeper fault found there to be little strength across the feature, and it was predicted that the entire overlying mass would move downhill if the toe of the fault were daylighted in the spillway excavation (Dan Parrillo, U.S. Army Corps of Engineers, personal communication to Epstein, 1970, reported in Epstein 2001). Further investigation was planned in a specially designed quarry to be dug in the early stages of reservoir construction. The slopes above the intakes and

spillway were to be designed in a safe manner based on the findings at the quarry. The adit has been blocked except to preserve it as a habitat for bats.

3) 36-inch diameter rock cores

Some of the cores from drilling to the bedding plane faults remain on the hillside a few hundred feet up the Rock Core Trail from the road.

4) Trace fossil

An excellent example of *Rusophycus*, a trace fossil, is visible where one of the cores has broken along a bedding plane.



Cores from 36-inch diameter holes drilled to investigate foundation conditions at Tocks Island site.

Depman, A.J., and Parrillo, D.G., 1969, Geology of Tocks Island area and its engineering significance: *in* Subitsky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania, Rutgers University Press, New Brunswick, NJ, p. 354-362.

Epstein, J.B., 2001, Geologic controls of landslides in the Delaware Water Gap National Recreation Area, New Jersey-Pennsylvania, and Lehigh Gap, Pennsylvania: *in* Inners, J.D., and Fleeger, G.M., eds., 2001 – a Delaware River odyssey, Guidebook, 66<sup>th</sup> Annual Field Conference of Pennsylvania Geologists, Shawnee-on-Delaware, PA, p. 119 – 135.

U.S. Army Corps of Engineers, 1965-1972, Tocks Island Lake, Pennsylvania, New Jersey, New York: Design Memorandums 1 – 10, variously paginated.

### Miles

#### Interval Cumulative

7.0	45.5	Retrace route to Point-of-Gap Parking Area. (Continue south on Old Mine Road to Delaware Water Gap Information Center. Follow signs to I-80 West (Pennsylvania). Take the first Pennsylvania exit (US 611, Delaware Water Gap. At bottom of ramp, follow signs to US 611 South. Proceed an additional 2.6 miles to Point-of-Gap parking area.).
0.7	46.2	Arrow Island Parking Area. Disembark.

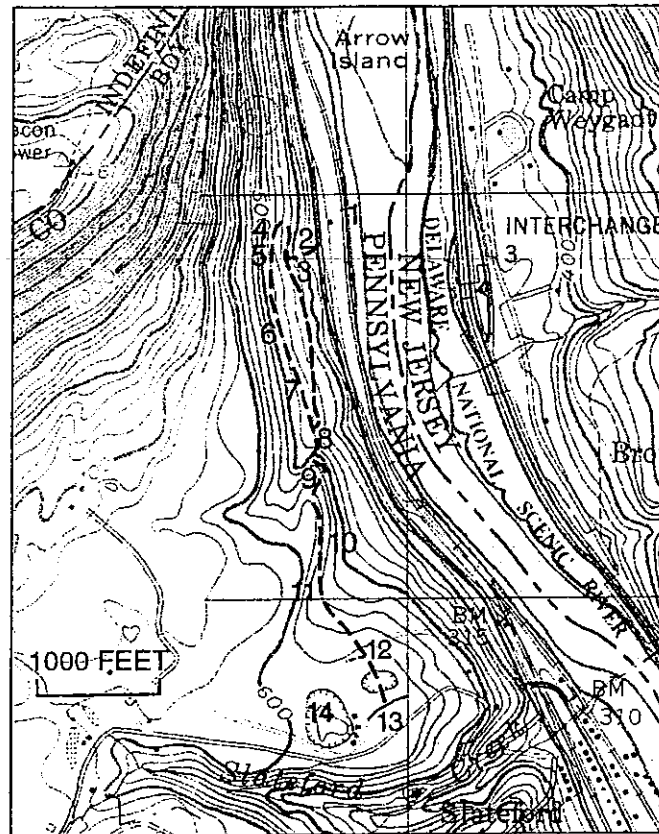


# DELAWARE WATER GAP

National Recreation Area  
Pennsylvania/New Jersey  
National Park Service  
U.S. Geological Survey



## GEOLOGIC FEATURES ALONG THE ARROW ISLAND TRAIL



*Trail map showing stops of geologic interest*

- Stop 1: Parking lot. Delaware Water Gap; northwest-dipping beds; joints; talus; Arrow Island sand bar.
- Stop 2: Round glacial erratics (red rocks; cherty siltstone) at start of trail; angular talus blocks to right.
- Stop 3: Slate dump.
- Stop 4: 20-foot talus boulder of the Shawangunk quartzite and conglomerate; sedimentary structures including cross bedding and channeling.
- Stop 5: Slate quarry; Washington Brown quarry?
- Stop 6: Waste pile of slate and small slate prospect.
- Stop 7: Twenty-foot high slate pit in a ravine about 50 feet above the trail.
- Stop 8: Creek near the junction of the yellow and white dot trails. Many large erratic boulders including red sandstone and an 8-foot long boulder of calcareous siltstone with some dark-gray chert. Downstream the creek has cut down through 30 feet+ of this glacial deposit.
- Stop 9: Exposure of graywacke sandstone making up this topographic rib.
- Stop 10: Another slate pit.
- Stop 11: The bouldery nature of the glacial deposit does not make for good agricultural soil, but does supply boulders for this fence row.
- Stop 12: Intersection with a cross country ski trail.
- Stop 13: Parking lot and end of Arrow Island Trail.
- Stop 14: Duck pond, a kettle hole.



Welcome to the Arrow Island Trail.



Stop 2. Angular boulders (talus) that came off the cliff above. Compare to rounded glacial boulders nearby.



Stop 3. Slate dump of waste slate at top of trail.



Stop 3. Foundation remnants below slate quarry.



Stop 5. Slate quarry. Bedding and cleavage can be seen at arrow.



Stop 5. Original horizontal sediment layer (bedding; solid line) is now tilted. The rock break along cleavage (dashed line).



Stop 8. Large erratic (glacial) boulder of siltstone beneath leaves.



Stop 8. Rounded and polished glacial boulder north of creek.

