The Geological Society of America
Field Guide 16
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Teachers guide to geologic trails in Delaware Water Gap National Recreation Area, Pennsylvania–New Jersey

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INTRODUCTION

The Delaware Water Gap National Recreation Area (DEWA) contains a rich geologic and cultural history within its 68,714 acre boundary. Following the border between New Jersey and Pennsylvania, the Delaware River has cut a magnificent gorge through Kittatinny Mountain, the Delaware Water Gap, to which all other gaps in the Appalachian Mountains have been compared. Proximity to many institutions of learning in this densely populated area of the northeastern United States (Fig. 1) makes DEWA an ideal locality to study the geology of this part of the Appalachian Mountains. This one-day field trip comprises an overview discussion of structure, stratigraphy, geomorphology, and glacial geology within the gap. It will be highlighted by hiking a choice of several trails with geologic guides, ranging from gentle to difficult. It is hoped that the "professional" discussions at the stops, loaded with typical geologic jargon, can be translated into simple language that can be understood and assimilated by earth science students along the trails. This trip is mainly targeted for earth science educators and for Pennsylvania geologists needing to meet state-mandated education requirements for licensing professional geologists. The National Park Service, the U.S. Geological Survey, the New Jersey Geological Survey, and local schoolteachers had prepared "The Many Faces of Delaware Water Gap: A Curriculum Guide for Grades 3–6" (Ferrence et al., 2003). Copies of this guide will be given to trip participants and can be downloaded from the GSA Data Repository[1]. The trip will also be useful for instruction at the graduate level. Much of the information presented in this guidebook is modified from Epstein (2006).

Please note: It is illegal to collect rocks, plants, or parts of animal life in National Park lands.

[1]GSA Data Repository item 2006191, "The Many faces of Delaware Water Gap," and a color version of Figure 14, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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PREFACE (from "The Many Faces of Delaware Water Gap")

Geology is a topic that many students, both children and adults, find confusing. And because they do not see how geology relates to their own personal situation, they also find it dull. Yet beneath their feet are stories hidden in the rocks. If these rocks could speak, they would tell of dramas that have unfolded. Of colliding continents, of oceans come and gone, of inhabitants that are no more, of mountains of ice that scraped away the evidence of time gone by. These rocks have seen much. They have controlled the fate of the Delaware Valley and have passively influenced everything from the local environment to human history and economics.

To engage students in the study of geology, we must teach them the basics, but we must also help them to understand how the rocks that they see relate to more intangible ideas. We must help them to discover clues to the ancient past. We must encourage them to explore how local geology controls the distribution of plants and animals, through its influence on soil types, precipitation, and temperature. We must engage them in inquiry about how the landscape has controlled human settlement, keeping folks out of hard to reach places or luring them in for valuable natural resources. We must facilitate an understanding of how geology is tied to our freedom, having changed the pathways and outcomes of wars.

Delaware Water Gap National Recreation Area is an outdoor classroom waiting to be discovered. Hidden in the ridges and valleys of the park, the patient explorer can find a seemingly endless array of animals and plants, each living in a microhabitat controlled by the rocks. The plant and animal communities range from aquatic river communities to cactus barrens, providing myriad opportunities for students to study biological and geological concepts and the inter-relationships between the two.

Today, the Poconos is a major destination (as it has been since the early 1800s), attracting visitors with hundreds of waterfalls, heart-shaped lakes, and the famous Delaware Water Gap. Though transportation has changed from carriage, to train, to automobile, the scenic river valley continues to inspire its guests. It is a landscape shaped by glaciers, a mountain shaped by time, an economy shaped by geology.

Teachers, geologists, and National Park Service staff worked in partnership to develop these materials. It is our hope that this curriculum will make it easier for students to understand geology and recognize the significance of the geologic story preserved in our National Parks. It is our belief that a visit to the park, for a personal encounter with the local geology, will help students to internalize the materials studied in class and will inspire curiosity about the role of geology in their lives and those of their ancestors. We hope these materials make it easier for you to use park resources to teach geology.

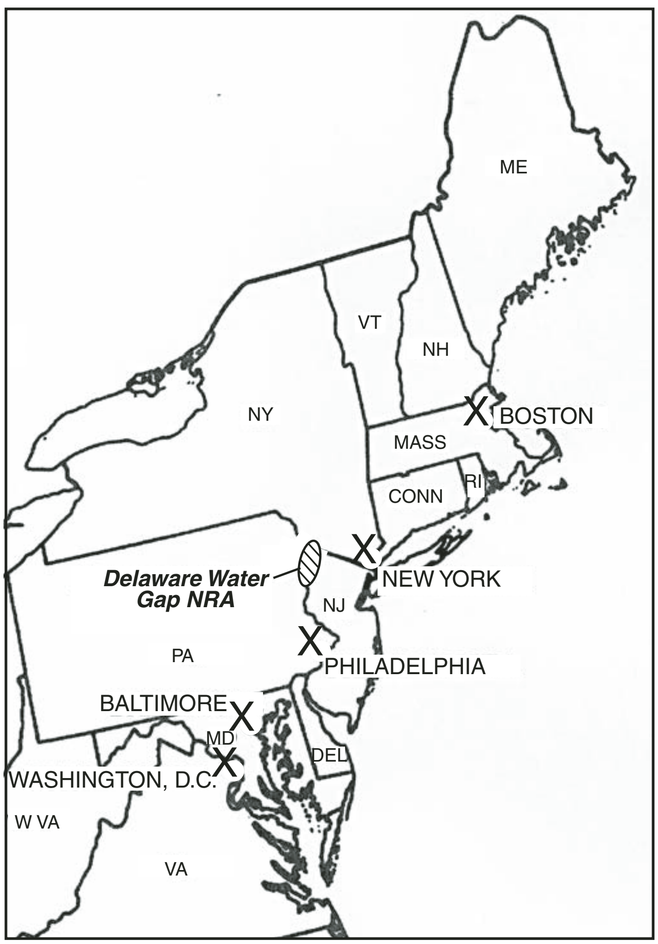

Figure 1. The Delaware Water Gap National Recreation Area lies within the center of the northeast megalopolis and within a few hours' drive of one-third of the nation's urban population.

DELAWARE WATER GAP NATIONAL RECREATION AREA

Following a disastrous flood on the Delaware River in 1955, the U.S. Army Corps of Engineers had proposed building a dam across the river at Tocks Island, about eight miles upstream from the Gap, and forming a reservoir nearly 40 miles long ending near Port Jervis, New York. The dam was authorized by Congress in 1962, but following much controversy, the dam was considered environmentally and structurally unsound, and it was officially de-authorized in 1992. The land in the Delaware Valley that was acquired by Congress for the proposed dam was officially designated a Recreation Area in 1965 and in 1992 the river became part of the National Wild and Scenic Rivers System.

The DEWA is the most heavily visited National Park Service (NPS) facility in the northeastern United States, attracting more than five million visitors yearly. It offers an oasis of solitude in the midst of this urbanized megalopolis. Recreational opportunities include fishing, hunting, boating, swimming, and hiking. The area also offers insight into the biologic diversity, cultural history, and geologic evolution of this part of the Appalachian Mountains.

DEWA straddles two physiographic provinces—the Pocono Plateau on the northwest and the Valley and Ridge to the southeast. Three Paleozoic orogenies affected patterns of sedimentation, resulting in a wide range of depositional environments, ranging from deep-sea, shallow marine, to terrestrial. Additionally, the area also experienced a varied and complex history of deformation. The Pocono Plateau is underlain by flat-lying to gently inclined sandstone and shale of Middle and Late Devonian age. More complexly folded rocks form the Valley and Ridge Province. The rocks include a variety of shale, sandstone, limestone, and dolomite of Ordovician, Silurian, and Devonian age, aggregating ~9000 feet in thickness within the park boundaries (Table 1). The entire stratigraphic sequence exposed in the Recreation Area spans ~65 million years. The Delaware Valley is carved into the softer shale and limestone, whereas the surrounding mountains are held up by the more resistant sandstone. The northeast-trend of the folds in the area controls the orientation of these features.

During the past 2 million years, the area experienced several periods of glaciation. Retreat of the latest (Wisconsinan) glacier, which began ~20,000 years ago (Witte, 2001), left behind varied scenery. The glacier carved and sculpted the landscape, deposited a variety of glacial drift, carved out lakes, and rearranged some of the stream drainage. The present Delaware River has cut through a silt and sand terrace that was occupied by Native Americans ~11,000 years ago. The area offers a wide variety of geologic subjects for future study and re-evaluation, including the regional framework and plate tectonic history of the Appalachian Mountains. Many controversial concepts in geomorphology are emphasized in this classic area, including accordant summits and peneplains, the formation of wind and water gaps, and the origin of waterfalls as they relate to the complex glacial history of the area.

STRATIGRAPHY

Delaware Water Gap owes its notoriety to the depth to which the river has cut through Kittatinny Mountain. Exposures of 3000 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 (Fig. 2). The underlying Martinsburg crops out in widely scattered exposures and small abandoned quarries just south of the gap.

The Martinsburg is more than 15,000 feet thick in eastern Pennsylvania, consisting of three members: a lower Bushkill Member of thin-bedded slates, middle Ramseyburg Member with abundant greywacke packets, and an upper Pen Argyl Member with medium- to thick-bedded slate and some greywacke (Drake and Epstein, 1967). These sediments were deposited in a rapidly subsiding flysch-turbidite basin (Van Houten, 1954) formed during Middle Ordovician continental plate collision. The highland source for the Martinsburg was “Appalachia” to the southeast, and the sediments covered a foundered Cambrian and Ordovician east-facing carbonate bank. The greywackes were probably deposited in submarine channels and were triggered by earthquakes during the Ordovician. The contact between the Pen Argyl and Ramseyburg Members disappears under the Shawangunk just within the confines of Delaware Water Gap National Recreation Area one mile west of Delaware Water Gap (Epstein, 1973). The Pen Argyl does not reappear in New Jersey to the northwest. Several small slate quarries and prospects in

TABLE 1. GENERALIZED DESCRIPTION OF ROCK UNITS
IN THE DELAWARE WATER GAP NATIONAL RECREATION AREA, NEW JERSEY AND PENNSYLVANIA

Age	Formation	Approximate thickness (ft)	Description
Devonian	Catskill Formation	500+	Sandstone and lesser shale; forms uplands in Pocono Plateau
	Mahantango Formation	2000	Siltstone and silty shale; forms steep slopes northwest of the Delaware River
	Marcellus Shale	800	Shale; underlies the Delaware River northeast of Flatbrook Bend
	Buttermilk Falls Limestone	275	Limestone, calcareous shale, and chert
	Schoharie Formation	100	Calcareous, argillaceous siltstone
	Esopus Formation	180	Shaley siltstone and shale
	Oriskany Group	100	Sandstone, calcareous shale and siltstone, chert
	Helderberg Group	300	Limestone, calcareous shale, calcareous sandstone
Devonian / Silurian	Rondout Formation	30	Dolomite, calcareous shale, limestone
Silurian	Decker Formation	80	Arenaceous limestone, calcareous sandstone, dolomite
	Bossardville Limestone	100	Limestone
	Poxono Island Formation	500	Dolomite, shale, limestone; underlies Delaware River southwest of Flatbrook Bend
	Bloomsburg Red Beds	1500	Red sandstone, siltstone, shale; forms northwest slope of Kittatinny Mountain
	Shawangunk Formation	1400	Sandstone and conglomerate; holds up Kittatinny Mountain
Ordovician	Martinsburg Formation	1000+	Slate and greywacke; forms southeast slope of Kittatinny Mountain

Note: The Martinsburg, Shawangunk, and Bloomsburg are the only formations that will be visited on this field trip.

the Ramseyburg Member, all long since abandoned, are found within the DEWA boundaries (Epstein, 1974a). The deepening of the Ordovician basin in which the Martinsburg detritus was deposited was followed by tectonic uplift reflecting intense Taconic mountain building, which peaked with emergence of the area during the Late Ordovician. This period of orogenic activity and regional uplift was followed by deposition of a thick clastic wedge, the lowest unit of which consists of coarse terrestrial deposits of the Shawangunk Formation. The contact between the Shawangunk and Martinsburg is a regional angular unconformity. The discordance in dip is not more than 15 degrees in northeastern Pennsylvania, New Jersey, and southeastern New York (Epstein and Lyttle, 2001).

The Shawangunk was divided into three members at the gap (Epstein and Epstein, 1972). The upper and lower conglomeratic-sandstone members, the Minsi and Tammany are believed to be fluvial in origin and are interposed by a transitional marine-continental facies (the Lizard Creek Member). The fluvial sediments are characterized by alternations of polymictic conglomerate with quartz pebbles more than 2 inches long, conglomeratic sandstone, and sandstone (cemented with silica to form quartzite), and subordinate siltstone and shale. The bedforms (planar beds and cross-bedding) indicate rapid flow conditions. Cross-bed trends are generally unidirectional to the northwest. The minor shale and siltstone beds are thin, and at least one is mudcracked, indicating subaerial exposure. These mudcracks may be seen at mileage 10.5 at the south entrance to Delaware Water Gap on the New Jersey side by looking up ~50 feet at an overhanging ledge (see Fig. 12). These features indicate that deposition was by steep braided streams flowing toward the northwest with high competency and erratic fluctuations in current flow and channel depth. Rapid runoff was undoubtedly aided

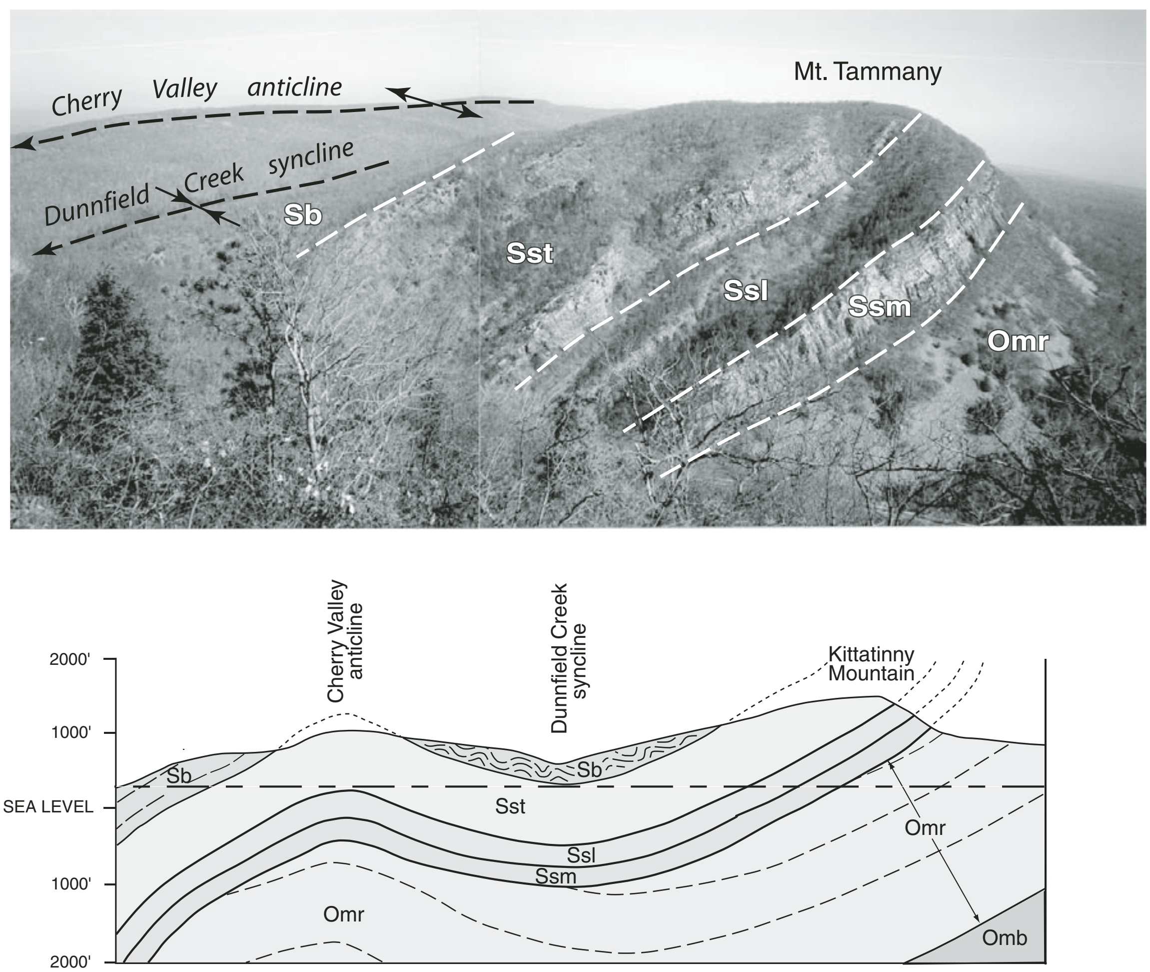

Figure 2. Delaware Water Gap in New Jersey as viewed from atop Kittatinny Mountain (Mount Minsi) on the Pennsylvania side. Omb—Bushkill Member of the Martinsburg Formation; Omr—Ramseyburg Member of the Martinsburg Formation; Ssm—Minsi Member of the Shawangunk Formation; Ssl—Lizard Creek Member of the 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 <5° (Beerbower, 1956). Horizontal dashed line shows rocks possibly visible along I-80 in New Jersey.

by lack of vegetation cover during the Silurian. The finer sediments present are believed to be relicts of overbank and backwater deposits. Most of these were flushed away downstream to be deposited in the marine and transitional environment represented by the Lizard Creek Member of the Shawangunk Formation.

The Lizard Creek Member contains a variety of rock types, and a quantity of sedimentary structures that suggest that the streams represented by the other members of the Shawangunk flowed into a complex transitional (continental-marine) environment, including tidal flats, tidal channels, barrier bars and beaches, estuarine, and shallow neritic. These are generally energetic environments, and many structures, including flaser bedding (ripple lensing), uneven bedding, rapid alternations of grain size, and deformed and reworked rock fragments and fossils support this interpretation (Epstein et al., 1974). The occurrence of collophane, siderite, and chlorite nodules and *Lingula* (phosphatic brachiopod) fragments at Lehigh Gap, 25 miles to the southwest, indicate near-shore 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 source to the southeast and a marine basin to the northwest. Erosion of the source area was intense and the climate, based on study of the mineralogy of the rocks, was warm and at least semi-arid. The source was composed predominantly of sedimentary and low-grade metamorphic rocks with exceptionally abundant quartz veins and small local areas of gneiss and granite. As the source highlands were eroded, the steep braided streams of the Shawangunk gave way to more gentle-gradient streams of the Bloomsburg Red Beds.

The rocks in the Bloomsburg are in well-defined to poorly defined upward fining cycles that are characteristic of meandering streams. The cycles are as much as 13 feet thick and ideally consist of a basal cross-bedded to planar-bedded sandstone that truncates finer rocks below. These sandstones were deposited in stream channels and point bars through lateral accretion as the stream meandered. Red shale clasts as long as three inches 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 (seen near the tollbooth along I-80 in Pennsylvania) suggest marine transgressions onto the low-lying fluvial plains, perhaps in a tidal-flat environment.

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

Upper Silurian and Lower Devonian rocks younger than the Bloomsburg Red Beds hold up Godfrey Ridge just north of the town of Delaware Water Gap. These rocks span the complete range of sedimentary types and reflect an equally complex series of depositional environments, including shallow marine shelf, supratidal and intertidal flats, barrier bars, and many neritic zones. Fossils are plentiful in many of the units.

STRUCTURAL GEOLOGY

Four rock sequences of differing tectonic style have been recognized in northeastern Pennsylvania. These *lithotectonic units* are presumed to be bound by décollements (detachments along a basal shearing plane or zone). Type and amplitude of folds are controlled by lithic variations within each lithotectonic unit.

Lithotectonic unit 1 comprises the Martinsburg Formation. Slaty cleavage is generally well developed in its pelitic rocks, and may be seen in several exposures along U.S. 611 south of the Gap. The slight angular discordance with the overlying Shawangunk is buried beneath talus at the Gap. At Stop 1 we will discuss this angular unconformity.

Lithotectonic unit 2 is made up of resistant, competent quartzite and conglomerate of the Shawangunk Formation and the overlying finer clastic rocks of the Bloomsburg Red Beds. Concentric folding by slippage along bedding planes is common. Cleavage is found within the shale 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 shale of the Martinsburg Formation were more uniform and of finer grain than those in the Silurian clastic rocks. Folds are generally open and upright (Fig. 2), but some limbs are overturned (discussed at Stop 1). In the Water Gap, the Bloomsburg is disharmonicaly folded, appearing as many small folds in the core of the Dunnfield Creek syncline. These can be seen south of the town of Delaware Water Gap in Pennsylvania. Cleavage in the Bloomsburg Formation dips southeast and appears to have been rotated during later folding. Numerous bedding-plane faults, 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 (see Figure 17). Dragging of cleavage along some of these faults indicate that faulting postdated cleavage development, which in turn, predated folding (see Fig. 15 at Stop 5, mile 11.7).

The home for rocks of lithotectonic unit 3 is in a narrow ridge (Godfrey and Wallpack ridges) northwest of Kittatinny and Blue Mountains. Folds in this sequence in the southwestern part of the area are of smaller scale than surrounding units. Axes of these folds are doubly plunging and die out within short distances, making for complex outcrop patterns (Epstein, 1973, 1989). Folding becomes less intense in the northeast part of the Recreation Area 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 but 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 shale and siltstones is so well developed that these rocks were quarried for slate in the past near Lehigh Gap.

Three décollements, or zones of décollement 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. Thin fault gouge and breccia, ~2 inches thick, is present at the contact, such as at Yards Creek, ~5 miles northeast of Delaware Water Gap (Inners and Fleeger, 2001, p. 171). Elsewhere, such as at Lehigh Gap (Epstein and Epstein, 1969), and at exposures in southeastern New York (Epstein and Lyttle, 1987), thicker fault gouge, bedding-plane slickensides containing microscarps or steps, and drag folds indicate northwest movement of the overlying Shawangunk Formation.

I have concluded that the dominant northwest-verging folds and related regional slaty cleavage in all rocks were produced during the Alleghenian orogeny and are superimposed upon Taconic structures in pre-Silurian rocks (Epstein and Epstein, 1967; Epstein, 1974b). 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. An Alleghanian age for the cleavage in the Martinsburg at Lehigh Gap, 25 miles to the southwest, was established by Wintsch et al. (1996) with whole rock $^{40}Ar/^{39}Ar$ dating of the micas in the slate.

GEOMORPHOLOGY OF DELAWARE WATER GAP

Following uplift during the late Paleozoic orogeny, the original divide of the Appalachian Mountains probably lay somewhere to the east within the area of the present Piedmont or Valley and Ridge physiographic province. During rifting and opening of the Atlantic Ocean, that divide shifted westward toward its present position in the Appalachian Plateau. The divide migration was due to the erosional advantage of the steeper streams that flowed eastward toward the Atlantic Ocean as compared to the gentler gradient of streams that flowed westward toward 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 and have been a source of considerable controversy for more than a century.

Several wind and water gaps are present in Kittatinny and Blue Mountains, the southernmost ridge of the Ridge and Valley Province. 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 the discussions about 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 favoring the present drainage divide having been 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.

Geologic mapping during the past few decades indicates that the gaps in northeastern Pennsylvania and nearby New Jersey 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 appear to be related to most 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; (6) cross faulting; and (7) progressive erosion exposing narrower widths of resistant rocks compared to areas nearby (Epstein, 1966). Details at Delaware Water Gap will be discussed at Stop 1.

GLACIAL GEOLOGY

The latest (Wisconsinan) glacial advance into eastern Pennsylvania and northern New Jersey resulted in the deposition of a conspicuous terminal moraine which crosses the Delaware River ~11 miles south of the gap near Belvidere, New Jersey (Fig. 3). The moraine reached 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 sequentially were laid down in the lake that formed and as the glacier retreated. The lake has been named Lake Sciota, after the classic delta and varved lake-bottom sediments that are found there (Epstein and Epstein, 1967). The lake reached a depth of ~200 feet in places. Initially, the outlet for the lake was over the terminal moraine at Saylorsburg and the water flowed west toward the Lehigh River. As the glacier retreated northeastward past the Delaware River, the waters drained through the gap and the lake ceased to exist.

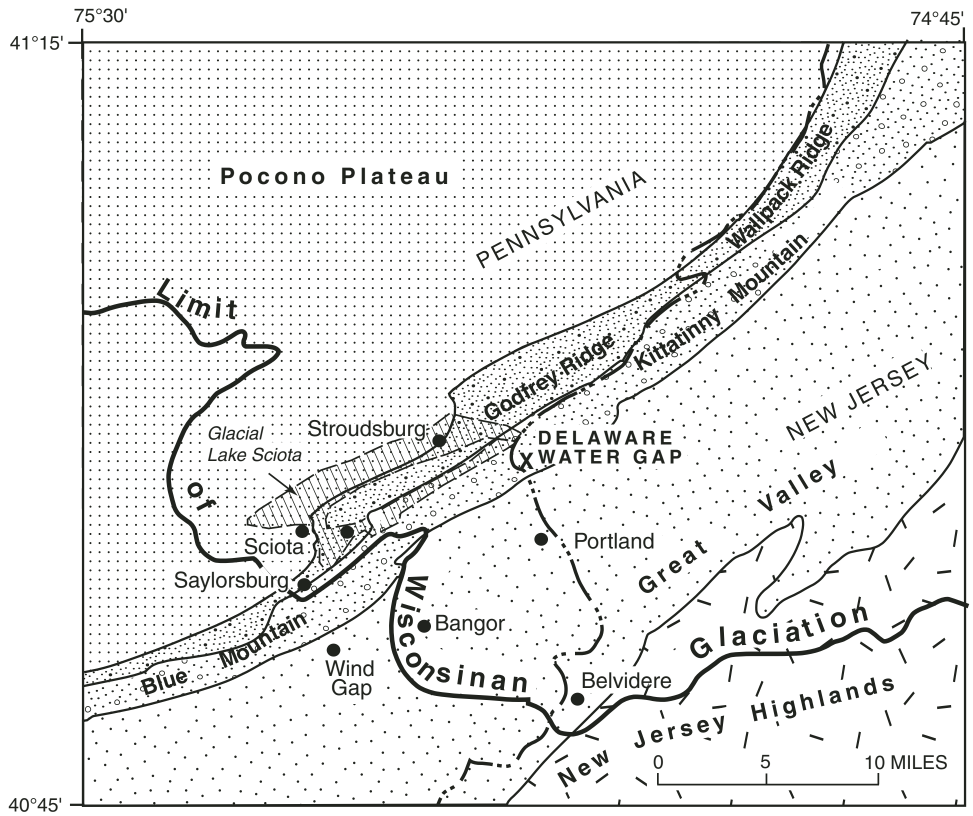

Figure 3. Physiographic map of part of easternmost Pennsylvania and northwestern New Jersey showing the position of the maximum advance of the Wisconsinan glacier. Modified from Epstein (1969).

A variety of glacial deposits formed in the Delaware Water Gap area, comprising 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 in length. This deposit may be seen at mile 3.5 and 9.0 of the road log.

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 around Delaware Water Gap was about S. 20°W., the base of the ice traveled more southwestward parallel to the valley bottoms and about due south over the ridge top. Several of these glacial features can be seen along the trail of Stop 5.

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.

ROAD LOG AND STOP DESCRIPTIONS (FIG. 4)

Miles (interval and cumulative)

Int.	*Cum.*	
0.0	0.0	Leave motel parking lot, turn left 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 deglaciation, proglacial lakes formed in the ice-dammed (northeast-draining) valley. Several ice-contact deltas mark ice retreat (Epstein, 1969). About 1000 feet straight ahead is a 60-foot-high terrace that may be one of the last deltas to form just before the lake drained as the ice plug in the water gap melted away.
0.1	0.1	Water Gap Diner on left. Favorite meeting place for trip leaders, cohorts, and other associates of dubious character.
0.2	0.3	Traffic light. Turn left on U.S. 611 South.
0.4	0.7	Northwest-dipping rocks of the Shawangunk Formation on right. We may decide to go to Stop 4 first. If so, turn right on Mountain Road and follow the directions for the Lake Lenape stop.

0.1	0.8	Crest of the Cherry Valley anticline in the Shawangunk Formation at top of road. The contact between the Shawangunk Formation and Bloomsburg Red Beds is conventionally placed at the base of the lowest red bed. At this locality, however, 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	0.9	Southeast-dipping rocks in the Bloomsburg Red Beds. U.S. 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	1.7	Contact between the Shawangunk and Bloomsburg dipping 35°NW.
0.7	2.4	Turn right into parking lot at Point of Gap.

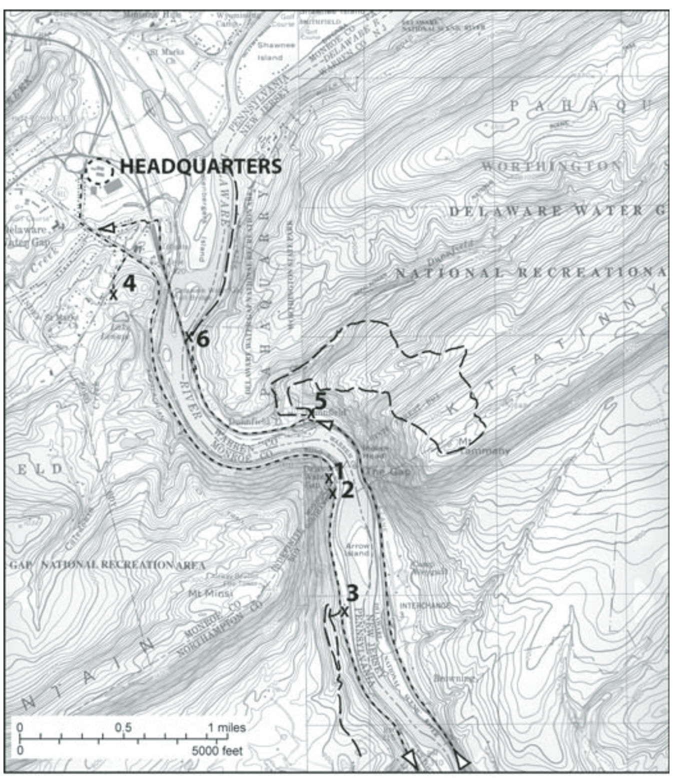

Figure 4. Topographic map of the Delaware Water Gap area showing route (short dashes), stop localities and trailheads, and trail routes (long dashes). 1—Point of Gap overlook; 2—Cold Air Cave; 3—Arrow Island trail; 4—Lake Lenape; 5—Red Dot–Blue Blaze–Dunnfield Creek Trail; 6—Karamac trail.

Stop 1. Point of Gap Overlook: Geologic Synopsis (Fig. 5)

Structure, Stratigraphy, Geomorphology, Glacial Geology

Note: The NPS has prepared a curriculum guide for school grades 3–6, "The Many Faces of Delaware Water Gap" (Ferrence et al., 2003). In that guide, the Point of Gap Overlook is discussed, and the guide includes exercises in how the rocks formed, how the mountains were built, and glaciation.

The following questions are typically asked—or at least thought about—by laymen visitors to Delaware Water Gap:

What is a water gap?
What is the layering in the rocks?
What are the rocks made of?
Why are they of different colors?
Why are they tilted and curve in different directions?
Why is the cliff irregular and not smooth?
Why does the mountain top look flat from a distance?
Why did the Delaware River cut through the mountain here?
Did it cut through anywhere else?

Possible answers to these questions will be discussed with trip participants.

A Story of the Gap

Delaware Water Gap is often cited as the classic water gap in the Appalachian Mountains. Figure 6 portrays its geology. Anyone who studies the area is compelled to contemplate the history

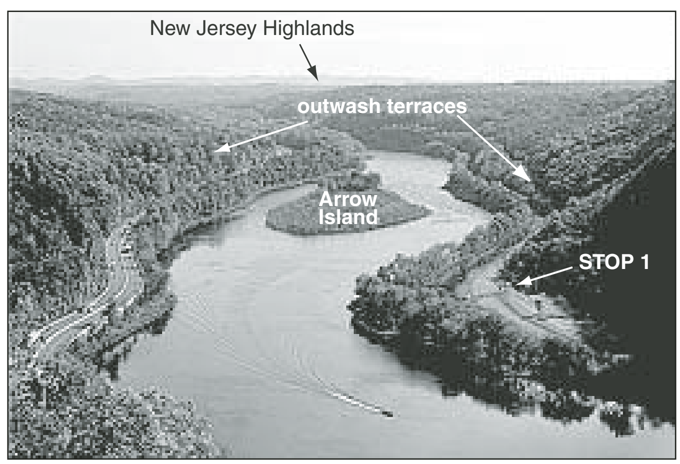

Figure 5. Entrance to Delaware Water Gap National Recreation Area as viewed from atop Kittatinny Mountain at locality 18 of the Red Dot–Blue Blaze–Dunnfield Creek trail. View looking southward; Pennsylvania is on the right, New Jersey on the left. The Delaware River flows through the constricted gap behind the view, and as it widens into the valley beyond and as its velocity decreased, it deposited a streamlined bar, Arrow Island. Between the mountain held up by quartzite 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.

of the gap and why it is where it is. Is the structure seen in the gap (Fig. 2) as simple as it looks? What story do the satellitic folds in the Shawangunk tell? Why does the cleavage dip to the northwest within several hundred feet of the contact with the Shawangunk? These issues were summarized in the last GSA trip to this area four years ago (Epstein, 2006) and will not be repeated here. A copy of that guide book will be given to trip participants.

Formation of Delaware Water Gap, a Popular Version

The spectacular Delaware Water Gap has inspired people for generations, and created wonder on how this magnificent chasm through Kittatinny Mountain could have been cut by the Delaware River. Its story goes back in geologic time many hundreds of millions of years, although the actual cutting took place within the last few million years.

Our planet has had a dynamic history for much of its existence. Mountains have risen and fallen as continents have shifted and collided with each other during the earth's more than 4.5 billion year history in a process called *plate tectonics*. Kittatinny Mountain is part of the Appalachian Mountain chain that extends for more than 2000 miles from Maine to Georgia. The birth of the Appalachians dates back several hundred million years. About 550 million years ago during the Cambrian period, a carbonate bank (*A* in Fig. 7) lying on the shelf of the old North American continental curst (*B*) faced eastward toward an ancient ocean, Iapetus (*C*). Africa lay across the Iapetus Ocean far to the east. A volcanic island (*D*) formed in the middle of the ocean as the African continent began to drift westward, beginning the closure of Iapetus. Thick sediments were deposited in the basin ahead of the volcanic island arc that were later consolidated into the Martinsburg Formation. As the ocean basin continued to close during continued plate convergence, sediments were deformed (*E*) and later, not shown in Figure 7, uplifted ~450 million years ago during the Ordovician period of geologic time, resulting in the buckling of the earth's crust and uplifting of the ancient Appalachian Mountains. This period of mountain building is called the *Taconic Orogeny*. Sands and pebbles from the rising mountains were shed to the northwest during Silurian time, deposited across the warps and folds in the underlying Martinsburg. These clastic rocks were to become the Shawangunk Formation that holds up the mountain at the gap. Other orogenies variously affected the rocks in the Delaware Water Gap area. During the Devonian period, the Acadian orogeny uplifted mountains to the southeast which resulted in deposition of thick sediments seen in the Pocono Mountains today, but it had little or no structural effects on the rocks here. The Alleghenian orogeny at the end of the

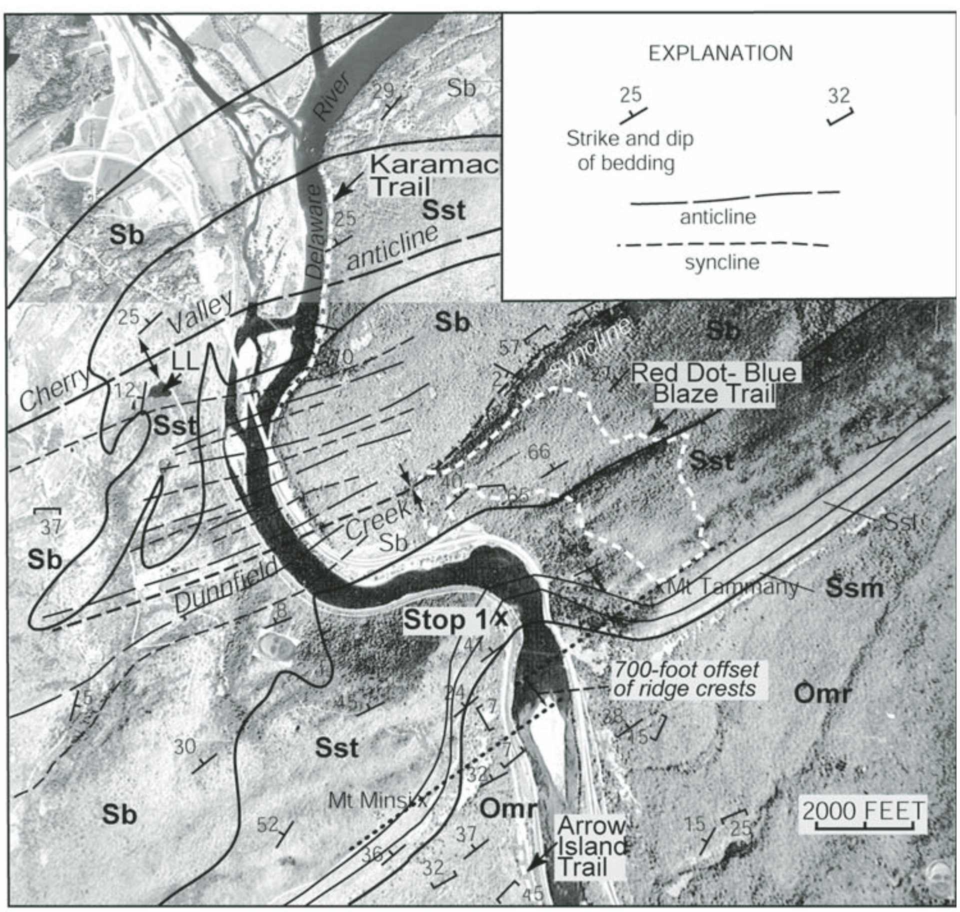

Figure 6. Aerial photograph and geologic map of Delaware Water Gap. Trails and stops are shown; LL—Lake Lenape. The 700 foot offset of the ridge crests (dotted line) on either side of Kittatinny Mountain is also shown and will be used in the discussion of the origin of the gap. Omr—Ramseyburg Member 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).

Paleozoic era, probably beginning in the Pennsylvanian period, folded and faulted all the rocks in eastern Pennsylvania, and was responsible for the folds seen in the Gap. It was at this time that Africa finally collided with North America.

For many millions of years erosion has worn down these rocks–the harder rocks stand as mountains while the softer rocks were eroded to form valleys. The sandstones and conglomerates of the Shawangunk Formation (shown by the stippled pattern in Figure 7) are among the hardest rocks in the entire Appalachian Mountains and form some of the highest ridges, extending all the way south to Alabama.

How the Gap was Formed

Some millions of years ago, the headwaters of a southeastward flowing river that was still south and east of here (perhaps near present-day Trenton, New Jersey) eroded backward toward the Kittatinny Ridge (*A* in Fig. 7). The hard rocks of Kittatinny Mountain presented an obstacle to erosion, and the Delaware found a place in the ridge where the rocks are more highly fractured and less resistant to the erosive power of the river. Thus, the river eventually worked its way *headward* through the mountain (*A*), "capturing" waters on the other side (*B*) and establishing the present course of the Delaware through Kittatinny Mountain (*C*). It carved it way through the rocks that make up the Pocono Mountains to the north. Carrying sand and pebbles, which eventually wind up in the Atlantic Ocean, the Delaware River continues to downcut and widen what was originally a small cleft in the rock. That cleft, over time, has been enlarged into today's mile-wide chasm: The Delaware Water Gap.

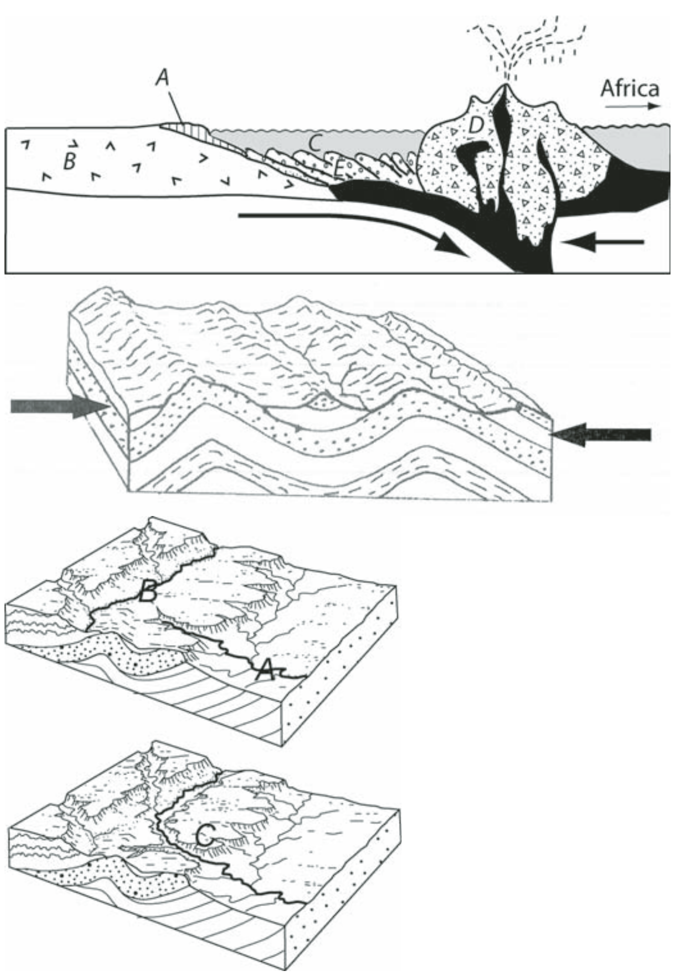

Figure 7. Formation of Delaware Gap.

Turn right out of parking area heading south on U.S. 611.

Miles *Int.*	*Cum.*	
0.3	2.7	Stop 2.

Stop 2. Cold Air Cave

This *talus* cave (Fig. 8A) was formed by juxtaposed alignment of large talus boulders derived from conglomerate and sandstone blocks of the Shawangunk Formation above. Some of these blocks are nearly 30 feet long. A large talus floe overlies the cave (Fig. 8B) and a large cleft in the cliff above (Fig. 8C) confirms the potential for generating these blocks during periods of freeze and thaw. The cave may be as long as 70 feet, although only ~30 feet of the cave is currently accessible to normal-sized individuals. According to Snyder (1989), the cave was discovered ca. 1870 when very cold temperatures, approaching 30 °F, were reported coming from the opening. The cave became an attraction sometime thereafter with a building erected at the entrance (Fig. 8D); tours given. Beginning in September 2000, a cooperative effort to understand the phenomenon of Cold Air Cave was undertaken by the U.S. Geological Survey and National Park Service. Readings for temperature, wind speed, wind direction, and weather conditions were recorded. The data indicates significant fluctuations in cave temperature; they are warmer in summer and cooler in winter. There are significant differences in temperature depending on whether the air is blowing into or out of the cave. Air blowing out is cooler than when it is blowing in the reverse direction, indicating that there is storage of cold air in the scree system and possibly the bedrock above. The average temperature in the parking lot is only slightly cooler than underground temperatures found at this latitude—normal is 54–56 °F. The average temperature in the cave is surprising, however, and was unexpected. In conclusion, Cold Air Cave continues to attract and mystify people with its local folklore, blowing cold air, and mysterious scientific explanation.

From here we may retrace route back to Stop 4 (Lake Lenape) or continue south to Stop 3, as indicated next.

If we go to Stop 4 (Lake Lenape): turn around heading north on U.S. 611 for 2.0 miles, turning left on Mountain Road just as you enter the town of Delaware Water Gap. After 0.1 mile turn left onto Lake Road to parking area.

Leave Cold Air Cave continuing south on U.S. 611.

Miles *Int.*	*Cum.*	
0.2	2.9	Small outcrop in the Martinsburg Formation on right. Note the gently northwest-dipping (7°) cleavage due to fanning in the A pressure shadow of the syncline defined by the Shawangunk Formation. Bedding here dips 32° NW.
0.2	3.1	Stop 3.

Stop 3. Arrow Island Overlook and Trail (Figs. 9 and 10)

Arrow Island, a streamlined bar, is presently being modified by the Delaware River. This occurs due to a decrease in the velocity of the river as it emerges from the narrow confines of the gap to the north. Such a feature has been termed an *expansion bar*.

From here we may retrace route back to Stop 4 (Lake Lenape) or continue south to Stop 5, as indicated next.

If we go to Stop 4 (Lake Lenape): turn around heading north on U.S. 611 for 2.0 miles, turning left on Mountain Road just as you enter the town of Delaware Water Gap. After 0.1 mile turn left onto Lake Road to parking area. Stop 4.

Stop 4. Lake Lenape

We will follow the Appalachian Trail along an abandoned blacktop road that once led to the top of Mount Minsi to a fire tower. At the north edge of the pond is a memorial to Sean Dolan, A Delaware Water Gap firefighter who died in a nearby car accident in 2004.

Lake Lenape is near the trough of one of many small folds in Delaware Water Gap (Fig. 11). It is in an area where the contact between the Shawangunk Formation and Bloomsburg Red Beds is based on change from gray in the Shawangunk to reddish in the Bloomsburg. In this immediate area, this color change variably cuts across ~700 feet of stratigraphic thickness, making for the complex boundary seen on the map.

Lake Lenape is a marvelous area to give students an opportunity to examine several rock types, including sandstones,

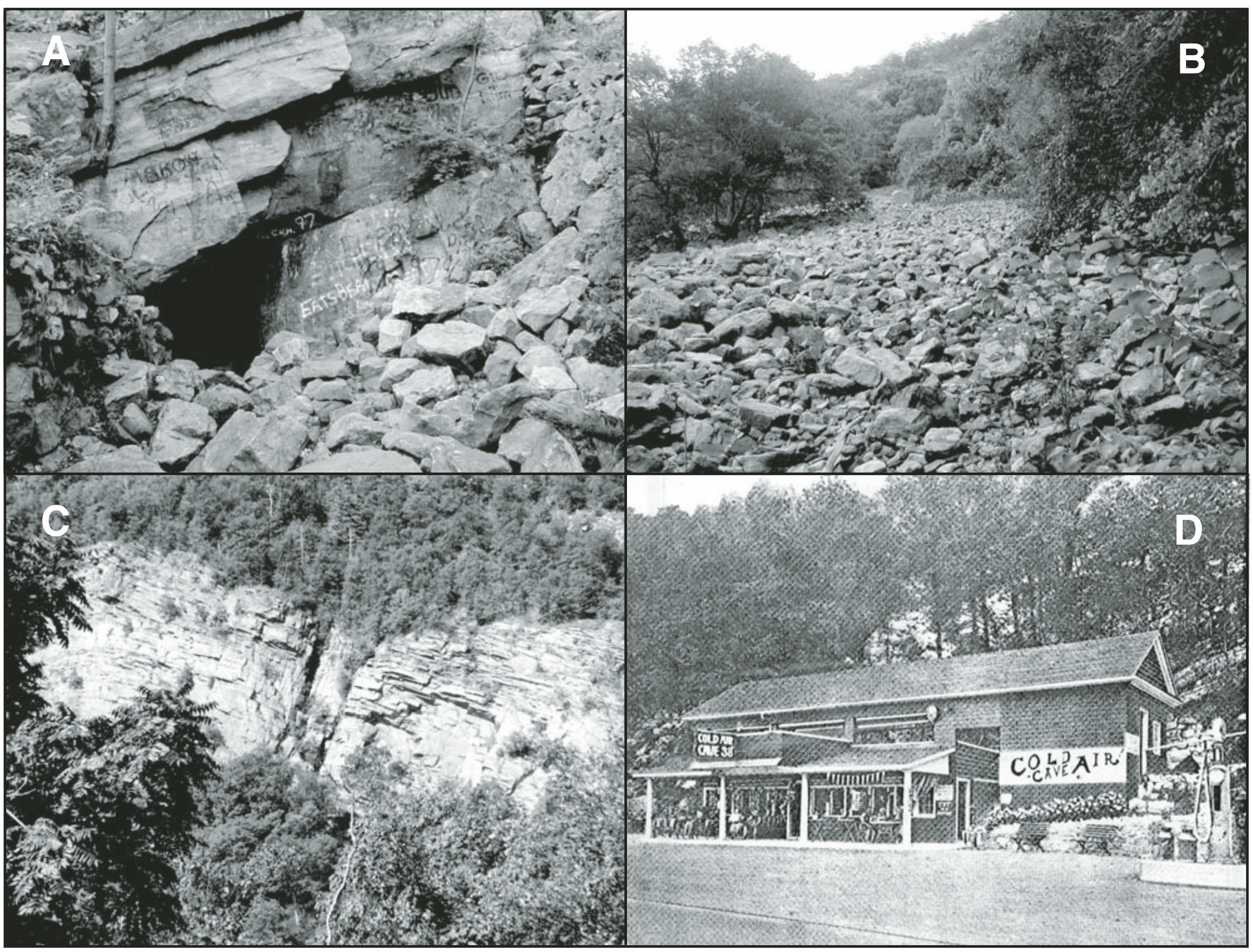

Figure 8. (A) "Cold Air Cave," a talus cave formed by conglomerate and sandstone blocks of the Shawangunk Formation along U.S. 611 south of Delaware Water Gap. (B) Talus above Cold Air Cave. (C) Cleft in cliff of the Shawangunk Formation above the Cold Air Cave, the possible source for the large blocks that supplied the talus. (D) Concession stand at Cold Air Cave, ca. 1940.

siltstones, and shales, to determine differences between bedding and rock cleavage, and to make a crude clinometer to prepare a map of the local gentle syncline. The curriculum guide handout (Ferrence et al., 2003) will provide instructions on how to use a compass, prepare grain size charts in order to determine sedimentary rock type, and encourage students to examine the local biota. Be wary of poison ivy, which covers the southernmost outcrop that will be measured. Have the students eyeball the dip with the clinometer rather than placing it on the rock. There is also an exercise that asks the geologic question, "How Do Lakes Form?"

"The Many Faces of Delaware Water Gap" is a 125-page geology curriculum (grades 3–6) available from the Delaware Water Gap National Recreation Area. It includes field trips for five locations in the park in Pennsylvania and New Jersey, as well as a 20-page introduction to general geologic topics for the park. Teachers are invited to contact the park for a copy (http://www.nps.gov/dewa/forteachers/curriculummaterials.htm).

An interesting exercise would be to have the students walk from the lowest point along the road for a little more than 100 feet up the trail to the south where the outlet is located, ~4 feet higher in altitude. Then ask them these questions: Why is the outlet not at the lowest point along the road? Did the lake formerly drain at the lowest point? (Have them look to the east of the road to determine where the most gully erosion occurred.)

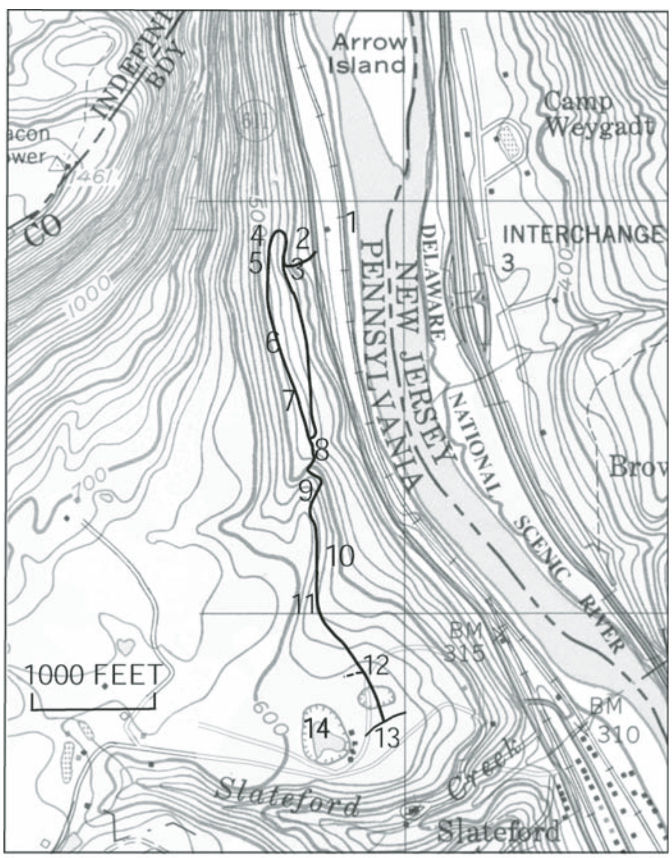

Figure 9. Map of Arrow Island.

Point out the location of rhododendrons–on the north slopes in the shade and on acid, organic-rich soil.

There is a splendid overlook and view of the Delaware Water Gap by following the Appalachian trail for a short distance where the trail leaves the road ~600 feet south of the pond (see Fig. 11).

If we did not visit Lake Lenape yet, continue south on U.S. 611 from Stop 3.

Miles *Int.*	*Cum.*	
0.4	3.5	Very coarse gravel in late Wisconsinan outwash terrace to right exceeds 80 feet in thickness. The gravel was either laid down between the valley's wall and stagnant ice forming a kame terrace, or it is the eroded remnant of a valley train that formerly filled the Delaware Valley.
0.2	3.7	Rock fence on right is composed of blocks of the Allentown Dolomite with abundant fine sedimentary structures.
0.3	4.0	Cross Slateford Creek. In 1805, the Pennsylvania Slate Company developed a slate quarry south of the water gap near Slateford Creek. It is abandoned.
0.1	4.1	National Park Drive on right leads to Slateford Farm, an example of a National Historic Site maintained by the National Park Service.
0.5	4.6	Faulted and overturned beds in the Bushkill Member of the Martinsburg Formation in ravine to right.
0.1	4.7	Flat-lying slate in the Bushkill Member in a 100-foot-long abandoned quarry overlain by 10 feet of glacial drift in ravine to right. A dolomite concretion, characteristic of basal beds of the Martinsburg elsewhere, lies in the bottom of the quarry.
0.4	5.1	Crossing the concealed Portland fault, which juxtaposes Martinsburg against the Jacksonburg Limestone and rocks of the Beekmantown Group where it is exposed.
0.3	5.4	Enter Portland, Pennsylvania.
0.6	6.0	Traffic light. Continue straight.
0.05	6.05	Cross Jacoby Creek. Deglaciation of the Jacoby Creek valley resulted in the formation of several proglacial lakes that became progressively lower as the ice retreated from the northeast-draining valley and lower lake outlets were uncovered (Ridge, 1983).
0.15	6.2	Road passes underneath U.S. 46.
0.1	6.3	Turn right following signs toward I-80 and Portland Toll Bridge.
0.2	6.5	Tollbooth (no toll leaving Pennsylvania).

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 breaks along cleavage (dashed line).

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

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

Figure 10. Arrow Island Trail.

0.2	6.7	Cross Delaware River into New Jersey. Good view of Delaware Water Gap to left.
0.2	6.9	Allentown Dolomite crops out on right. Continue straight.
0.1	7.0	Road signs for I-80 and NJ 94. Continue straight.
0.2	7.2	Cross the axis of the Ackerman anticline (Drake et al., 1969) in the Allentown Dolomite approximately at point where ramp bears off to I-80 West. Merge left onto I-80 West.
1.8	9.0	Note coarse kame-terrace deposits on right.
1.5	10.5	Unconformable contact (~5°) between the Martinsburg Formation (Ordovician) and Shawangunk Formation (Silurian) covered by talus on right. If you are quick, lucky, and can avoid a car crash, look up ~50 feet and see mudcracks in an overhang in a shale in the Shawangunk (Fig. 12).
0.4	10.9	Bear right onto service road. Park in parking area. Depending on facilities available here, we may turn left under I-80, then right to Jiffy John conveniences.

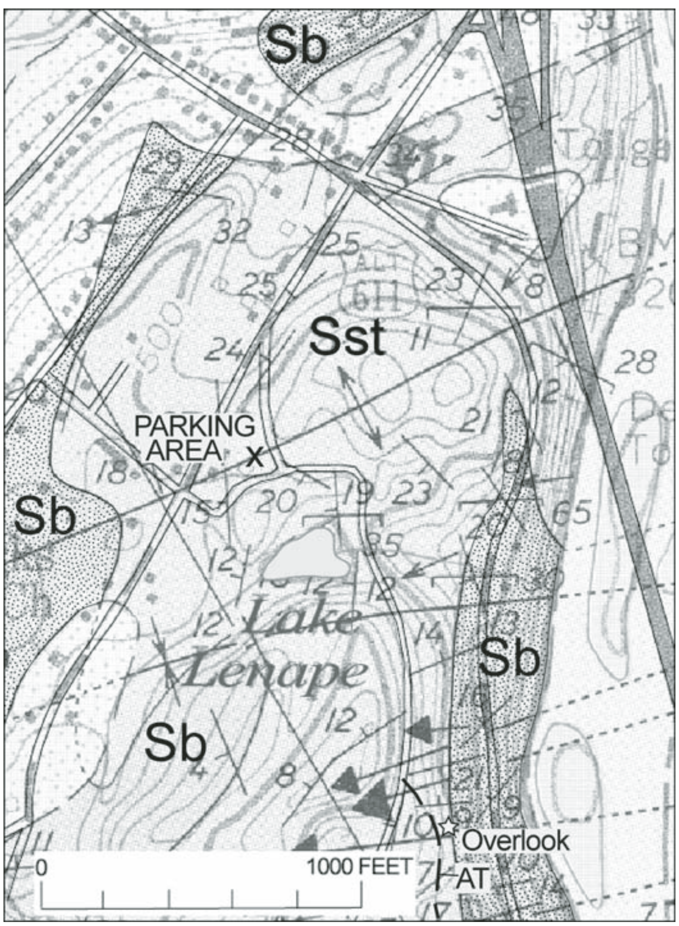

Figure 11. Geologic map of the Lake Lenape area (from Epstein, 1973). Sst—Tammany Member of the Shawangunk Formation; Sb—Bloomsburg Red Beds; AT—Appalachian Trail. Glacial deposits and alluvium in areas beyond bedrock exposures.

Stop 5. Geologic Features along the Red Dot–Blue Blaze–Dunnfield Creek Trails

The Red Dot–Blue Blaze–Dunnfield Creek Trail circuit takes the hiker to the top of Mount Tammany in Kittatinny Mountain, New Jersey (Figs. 13 and 14; Table 2), and in less than four miles, passes through many geologic phenomena, including a variety of rock types, landforms and glacial and structural features. The points of interest along the way provide insight into these natural elements that influenced the formation, history and composition of Delaware Water Gap. Note that the sedimentary layers that make up the cliffs in the main part of the gap dip to the left, but in Dunnfield Creek valley to the left the beds are horizontal. Trip time is ~4 hours.

GLOSSARY

Alluvial fan: Gently sloping mass of sediment fanning out from a river mouth.

Cleavage: Closely spaced fractures along which a rock may split.

Erratic: A rock that was carried some distance by a glacier from its place of origin.

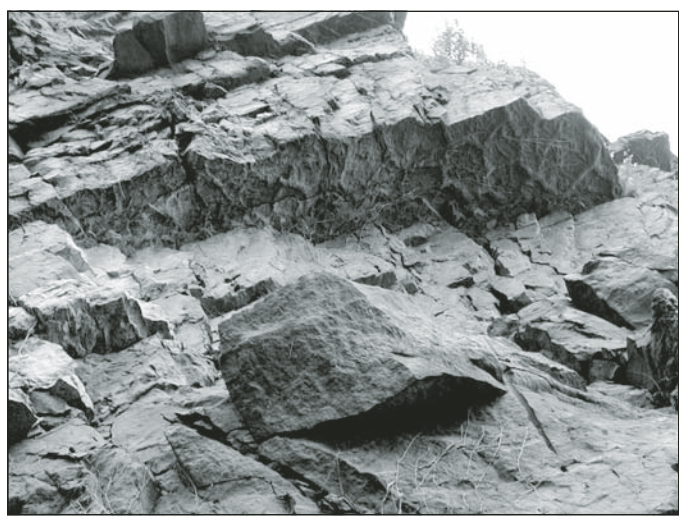

Figure 12. Mudcracks in shale interbedded with crossbedded sandstone of the Tammany Member of the Shawangunk Formation ~50 feet above I-80 at the entrance to Delaware Water Gap. The shales are interpreted to be overbank deposits that were dessicated in a fluvial environment.

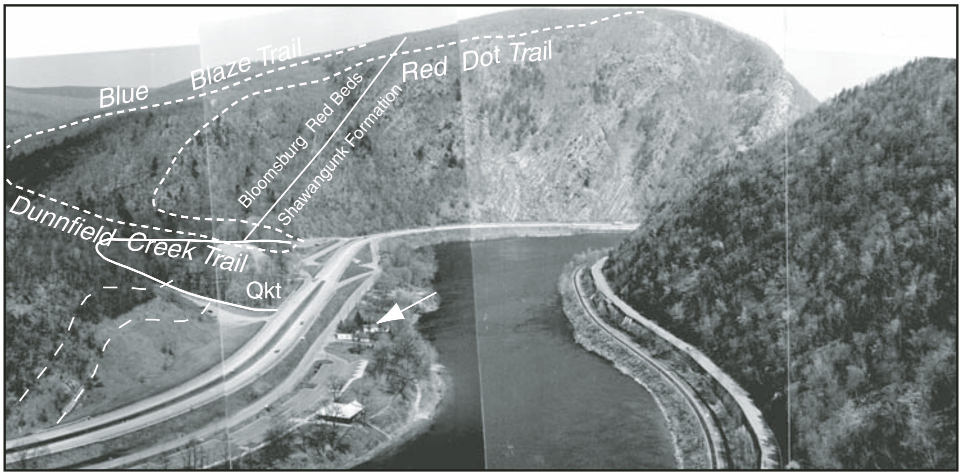

Figure 13. View of the trails at Stop 5. The Delaware River makes a sweeping bend as it heads through the world-famous Delaware Water Gap. The bend of the river mimics the underlying geology. The Shawangunk Formation of Silurian age, comprising very hard quartzite and conglomerate and holding up Kittatinny Mountain, dips moderately northward and is overlain by finer clastics of the Bloomsburg Red Beds, also Silurian in age. The dip flattens out under Dunnfield Creek beyond which the Bloomsburg is thrown into a series of small folds overlying a broader fold in the buried Shawangunk. The bend in the river mimics the form of that anticlinal fold. Approximately 20,000 years ago, Wisconsinan glacial ice occupied this valley and a kame terrace (Qkt) of sand and gravel was deposited along Dunnfield Creek. The National Park Service visitor's center is located at the arrow.

Kame terrace: Flat-topped hill formed from sediment that was deposited along a valley wall by streams that flowed from an adjacent melting glacier.

Slickensides: Polished and striated rock surface caused by one rock mass sliding past another.

Striae: Narrow parallel scratches cut into a rock surface by rock debris embedded in the bottom of a moving glacier.

Syncline: U-shaped downfold of rock layers.

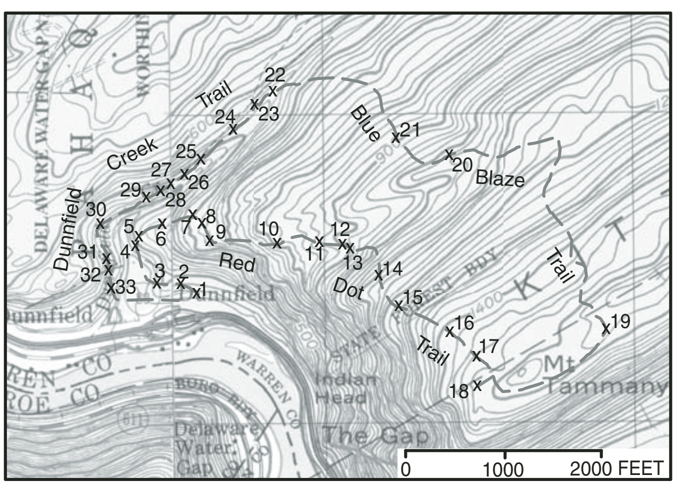

Figure 14. Trail map at Stop 5showing places of geologic interest and are keyed to the descriptions and pictures shown on the accompanying table. A colored version of this map will be handed out to the participants and is available in the GSA Data Repository (see footnote 1).

Talus: An apron of irregular rock fragments derived from and lying at the base of a cliff.

Till: Unsorted mixture of clay, sand, and boulders deposited beneath a glacier.

Miles *Int.*	*Cum.*	
0.1	11.0	Retrace route out of parking area, turning right along service road, carefully merging onto I-80 west.
0.7	11.7	Take Exit 1 to right toward Millbrook/Flatbrookville. At the offramp from I-80 to Old Mine Road there are splendid folds in the Bloomsburg Red Beds showing the relations of cleavage and bedding (Fig. 15). The southeast dip of cleavage in all limbs of the folds indicate that it was rotated by bedding slip after they formed.
0.1	11.8	Turn right at Stop sign onto Old Mine Road.
0.1	11.9	Pull off onto parking area to left before traffic light. Stop 6.

Stop 6. Guide to the Geology of the Karamac Trail

The trail begins in the parking area at the traffic light and barrier along the Old Mine Road 400 feet north of the I-80 overpass (Fig. 16). This a level trail, nearly one mile long, along an old railroad grade, and along which a few different types of rocks (sandstone, shale, siltstone and conglomerate), two different

TABLE 2. LOCALITIES OF GEOLOGIC INTEREST ALONG THE RED DOT–BLUE DOT–DUNNFIELD CREEK TRAILS AT STOP 5

1	Near contact between the Shawangunk Formation and Bloomsburg Red Beds.
2	Eight-foot-long boulder with slickensides.
3	Glacial kame terrace on silt, sand and gravel.
4	Glacial striae.
5	Rotted limestone glacial erratic.
6	Rib of Bloomsburg bedrock.
7	Series of greenish-gray and red siltstone, sandstone and shale of the Bloomsburg.
8	Large erratic, Schoharie Formation.
9	Overlook of the Delaware Water Gap.
10	Red sandstone and siltstone of the Bloomsburg have been polished by the last glacier (20,000 years ago), producing glacial striae.
11	Springs.
12	Beginning of Shawangunk Formation on steep slope.
13	Talus.
14	Rib of quartzite with joints.
15	Glacial cobbles and glacial striae on Shawangunk.
16	Gentle slope underlain by some shale.
17	Forest fire.
18	Overlook, many sedimentary structures in the Shawangunk.
19	Blue Blaze Trail descends slope through laurel and blueberries.
20	Exposure of Bloomsburg bedrock with glacial striae.
21	Soil erosion by boots and rain exposing Bloomsburg bedrock with glacial striae.
22	Erosion has removed about three feet of glacial till.
23	Dunnfield Creek falls over flat beds of the Bloomsburg in bottom of syncline.
24	Three large erratic boulders of slightly cherty limestone.
25	Intersection with Appalachian trail. Several more boulders in creek.
26	Plunge pool formed where the creek drops over hard sandstone and gouges out a rounded pool in softer shale below.
27	The creek erodes along a joint surface here forming a 30-foot sluiceway.
28	Large boulders fallen from adjacent Bloomsburg outcrop have sharp edges compared to the rounded and eroded edges of erratics.
29	Cleavage present in horizontal shale layers but not in sandstone. Erratic in creek.
30	Beginning of the terrace deposit that was first seen at locality 3.
31	25-foot-long limestone erratic limestone.
32	Bridge. Flat alluvial fan towards parking lot made up of rounded cobbles.
33	Parking lot. Note 6-foot boulder 40 feet above the creek in terrace to right.

geologic formations of Silurian age (Bloomsburg Red Beds and Shawangunk Formation), a landslide retained by a concrete structure (gabion), a few folds, joints, rock cleavage, and glacial boulders (erratics) can be seen. Terms in italics should be fully explained to students. The distance along the trail north from the parking area is shown in feet.

Locality	*Description*
–350	On the east side of the road is an excellent example of a small *thrust fault* and *ramp* in the Bloomsburg Red Beds (Fig. 17). The floor of the thrust is at the base of a thick sandstone bed lying on top of shale and siltstone that are less resistant to erosion.
0	Parking area. Looking to the right up the steep slope are *joints,* the result of the tectonic stress that folded the rocks in the Delaware Water Gap area. Similar vertical fractures can be seen along the trail for the next 400 feet.
400	The smooth face in a 6-foot-high bed of sandstone ahead is an excellent example of a *joint* (Fig. 18). Note the cleavage in the silty beds.
500	The closely spaced fractures in some of the greenish and reddish beds are tilted into the hill in a much gentle angle than are the joints (Fig. 19). This is *cleavage* which forms in shale and siltstone by reorientation of the mineral grains in the rock.
600	The interlaced segments of concrete is a 100-foot-long *gabion* (Fig. 20) which was constructed at this site to hold back a landslide that removed part of the Old Mine Road above the trail. Because of the slide, the road is now a single lane with a three-minute traffic light to control traffic along this stretch, and it is unwise to walk along it. The concrete blocks are filled with cobbles to stabilize the road. Immediately above this site along the Old Mine Road there is the potential for another rockfall because blocks of rock are being separated along irregular joints (Fig. 21).
1000	The islands in the middle of the Delaware River and terraces along its banks are made of sand that was deposited when the river flowed at a slightly higher level after retreat of the *Wisconsinan glacier* which left this area ~14,000 years ago. The sand islands are mute testimony to a former higher level of the river.
1075	Rivulet tumbling down over dark red rocks. This is the *Bloomsburg Red Beds.* Note that the rock layers are nearly flat at this spot. These rocks were deposited by rivers flowing to the sea. The soft sediment, composed of mud and sand, was hardened or *lithified* into rock and the layers are termed *bedding*. The process of *lithification* results from a variety of causes, including *cementation* (the rock is cemented by minerals that precipitated out from ground water) and *compaction* (due to the weight

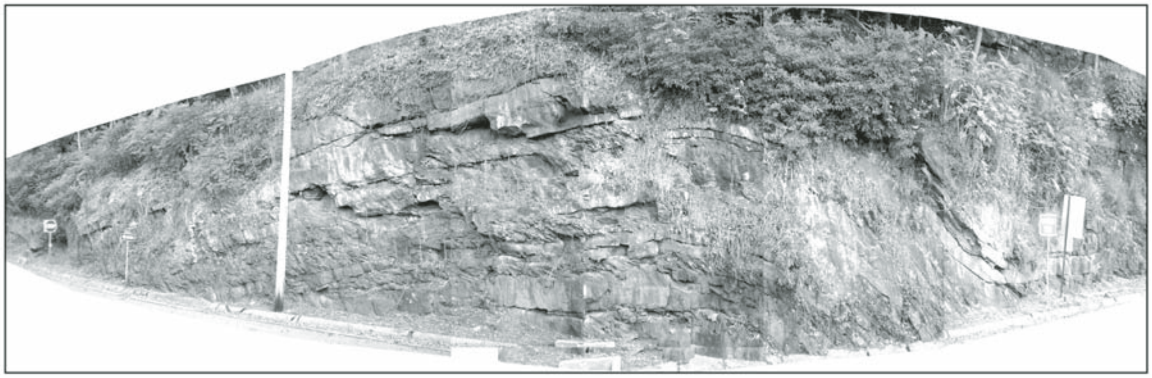

Figure 15. Panoramic view of folds in alternating sandstone, siltstone, and shale in the Bloomsburg Red Beds showing prominent southeast-dipping cleavage.

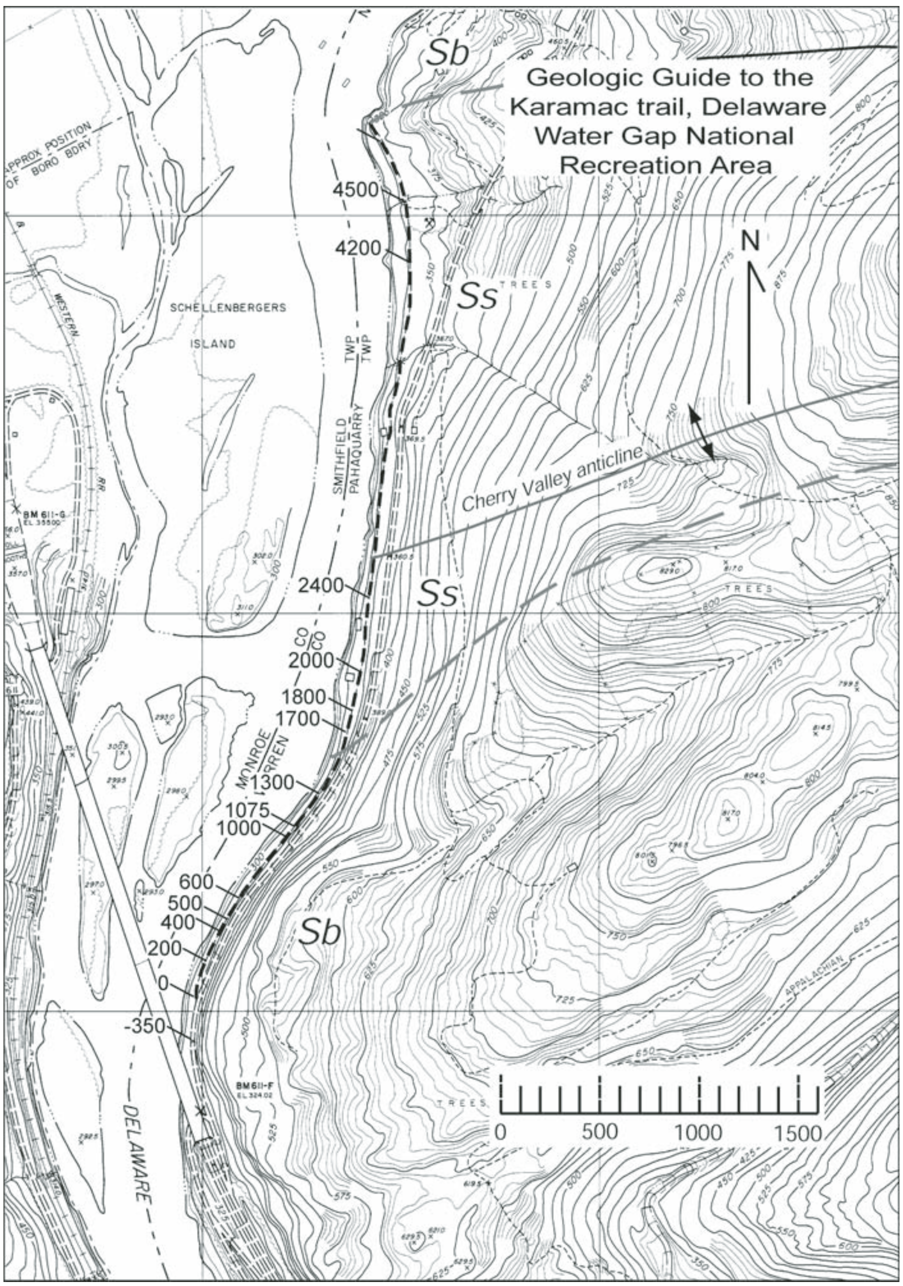

Figure 16. Detailed topographic map (contour interval: 5 feet) of the Karamac trail and distances from the parking area, keyed to descriptions in the text. Ss—Shawangunk Formation; Sb—Bloomsburg Red Beds. Consecutive figure numbers are for this guide only. A few sections of the trail are overgrown, but access to outcrops is generally good.

Figure 17. Bedding thrust and ramp at base of sandstone in the Bloomsburg Red Beds along Old Mine Road in New Jersey.

Figure 18. Smooth joint surfaces in sandstones of the Bloomsburg Red Beds.

Figure 19. Cleavage (dashed line) in shale and siltstone dipping more steeply than bedding (solid line). Be careful of the plant with leaves of three…"let it be."

Figure 20. Concrete gabion along abandoned railroad grade below the Old Mine Road in Worthington State Park.

Figure 21. Irregular joints, trending along the Old Mine Road above the Karamac Trail. Boulders in the fractures are wedging the block apart, creating the potential for toppling.

of thousands of feet of overlying sediments that were deposited on top).

1300 Water emitting from a drain pipe. Just beyond a rivulet, the bedding is tilted much more steeply to the south than previously (Fig. 22), showing that rocks have been *folded*. The rocks here are no longer red, but shades of gray. Thus, we have left the Bloomsburg Red Beds and are into another rock unit, the *Shawangunk Formation*. It would be worthwhile to discuss the fact that the Bloomsburg overlies and is younger than the Shawangunk based on the dip of the beds here.

1700 Outcrop of interbedded sandstone and some conglomerate and siltstone. Some of the sandstones have *cross bedding* (see Fig. 24). Beds dip about 35° to southwest. The *sediment* that was compacted into the hard sandstone formed by rapidly flowing streams that came off mountains that existed to the south of us ~425 million years ago.

1800 This small *anticline* (Fig. 23) interrupts the general south dipping layers along this stretch of the trail.

2000 Note that the bedding layers are tilted back toward the south, indicating that there is a *syncline* between here and the previously seen northward dipping beds. This is the site of a *spring*, where water, flowing through cracks in the underground rock (termed *ground water*), appears at the surface. During the summer when rainfall is less plentiful, the spring may dry up.

2400 Bedding in the Shawangunk Formation *dips* (is tilted) gently to the south (Fig. 24). Farther north along the trail and to the end of the trail it will be dipping northward, a structural configuration which is termed an upfold or *anticline,* named the *Cherry Valley anticline* because it is a major anticline that extends for several miles to the northeast and southwest. This outcrop is also a good example of *cross-bedding*, which is defined by layers of rock that dip more steeply than the beds above and below and is caused by large *ripples* that formed in a rapidly moving stream during the Silurian Period.

Figure 22. Beds in the Shawangunk Formation dip ~40° to the southeast.

3400 100-foot-long *outcrop* through the Shawangunk Formation (Fig. 25). A close look at the different beds show that some have grains the size of sand (sandstone), in others the grains are very fine (shale and siltstone), and some of the beds contain pebbles,

Figure 23. Anticline in Shawangunk Formation. The northward-dipping beds are fairly steep.

Figure 24. Crossbedding in the Shawangunk Formation. The normal bedding dips fairly gently (solid line), whereas the cross beds (dashed line) dip more steeply to the south. The crossbeds were formed by ripples in a stream that flowed from left to right

perhaps ½-inch long, in a rock termed *conglomerate*. The beds here are tilted ~20° toward the north.

4200 The gray rocks of the Shawangunk Formation are more steeply dipping (33°) here than they are to the south.

4500 So far all the loose boulders we have seen are quite angular in shape, having been derived by breaking off from the adjacent bedrock. Notice the large rounded boulders here. That shape implies that they have been water worn. But water needs to be flowing very rapidly to move boulders of that size. Because these rounded boulders are made up of a variety of rock types, some of which are foreign to the immediate neighborhood, it implies that they have been carried here by *glaciers* which invaded this area ~20,000 years ago. Now, fortunately, the glaciers are gone. Could they return some time in our geologic future? This would be a good place to discuss *climate change*, both natural and anthropogenic. These boulders, because they have come from afar, perhaps several miles away, are termed *erratics*. In the ground underneath they are mixed with clay, a geologic deposit called *till*. Till forms much of the surface further northward along the trail.

4850 The rocks of the Shawangunk Formation are cut through here along this old railroad grade (Figs. 26 and 27). The beds are tilted more steeply than before; 62° at this spot. This is a good outcrop to show the different lithologies in the Shawangunk Formation and the cleavage in the shales that dip 85° northwest. It is also a good outcrop to illustrate the various orientations of joints. It would also be an excellent locality to demonstrate the use of a *Brunton compass* to acquire structural orientations.

4950 Trail ends at bridge abutment, part of the Lackawanna Railroad bridge that was removed during the flood of 1955. Excellent blocks of *conglomerate* at the abutment. Turn around and leave parking area heading south on River Road toward the Delaware Water Gap visitor's center.

Miles *Int.*	*Cum.*	
1.0	12.9	Pass the DEWA Visitor's Center (or stop for respite) and turn left under I-80.

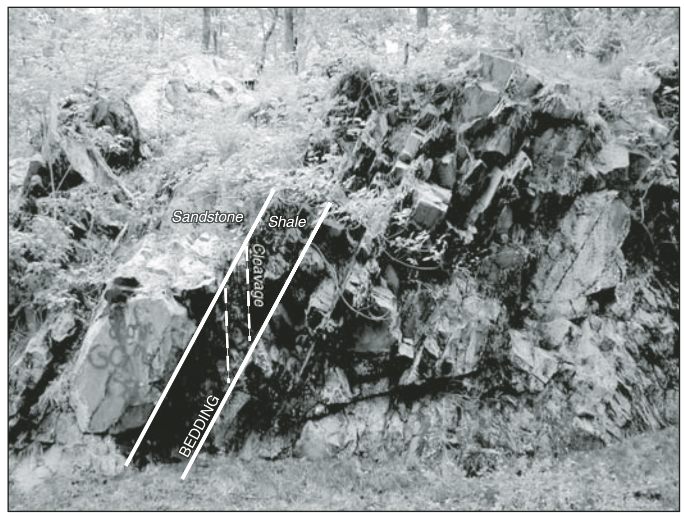

Figure 26. Steeply dipping beds in the Shawangunk Formation. Various joint orientations have developed in the sandstones and cleavage has formed in the shales. This would be a good outcrop to discuss the use of cleavage and bedding orientations to determine the surrounding structure (Fig. 27).

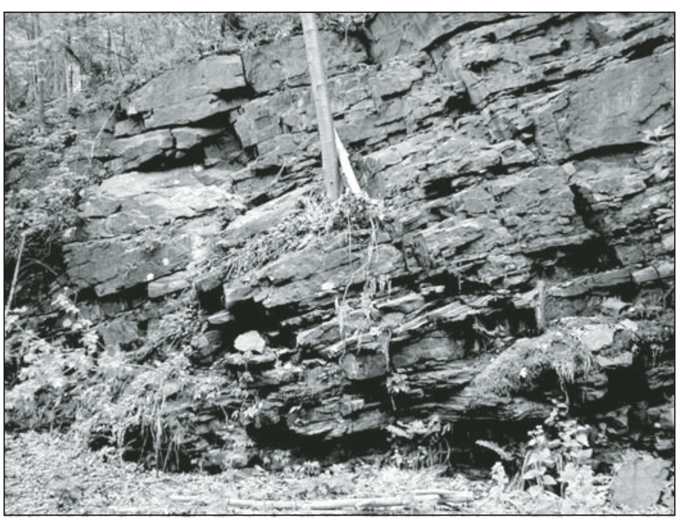

Figure 25. Moderately northwest-dipping beds in the Shawangunk Formation. There is an *anticlinal axis* between here and the rocks in Figure 24.

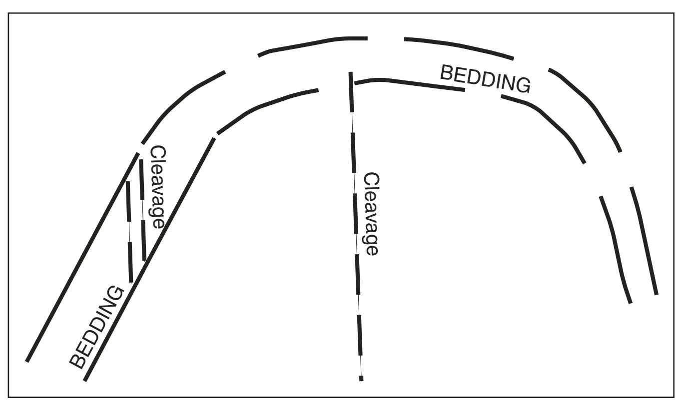

Figure 27. Using bedding-cleavage relations to show that where bedding is gentler than cleavage, the beds are right-side-up and that there should be an anticlinal axis to the right.

0.1	13.0	Turn left on ramp, carefully merging onto I-80W.
1.4	14.4	Tollbooth. Pay toll.
0.3	14.9	Bear right on Exit 310 toward Pa 611-Delaware Water Gap.
0.6	15.5	Merge onto Foxtown Hill Road.
0.6	16.1	Turn left onto Main Street.
0.2	16.3	Turn left onto Broad Street.
0.2	16.5	Turn right in motel parking lot.

End of trip. Have a safe journey home.

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