National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

Delaware Water Gap National Recreation Area

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2013/717

ON THE COVER
The Delaware River flows through a dramatic gap in tilted Paleozoic-age rocks within Delaware Water Gap National Recreation Area. This photograph is from the Appalachian Trail on Mt. Minsi. Photograph by Nicholas A Tonelli (Creative Commons Attribution 2.0 [CC by 2.0] Generic License).

THIS PAGE
Upper portion of Dingmans Falls cascades over Devonian rocks of the Mahantango Formation. Photograph by Ron Karpilo (Colorado State University).

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public..

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The Geologic Resources Division held a Geologic Resources Inventory (GRI) scoping meeting for Delaware Water Gap National Recreation Area in New Jersey and Pennsylvania on 3 October 2001 and a follow-up conference call on 11 November 2011 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.

Delaware Water Gap National Recreation Area encompasses the namesake gap and upstream valley of the Delaware River in northeastern Pennsylvania and northwestern New Jersey. From American Indians to the resort community of the late 1800s to the modern-day transportation corridor, Delaware Water Gap has funneled humans through the otherwise-imposing Kittatinny Mountain for centuries. Today the park also provides a natural area for outdoor recreation that is accessible from New York City and Philadelphia. Approximately 5 million people visit the park annually.

The park's 27,009 ha (66,740 ac) of rolling hills, ridges, and valleys lies along 64 km (40 mi) of the Middle Delaware National Scenic and Recreational River—the longest free-flowing river in the eastern United States. The valley lies between Kittatinny Mountain to the east and the Pocono (Allegheny) Plateau to the west. The 1.6-km- (1-mi-) wide, 370-m- (1,200-ft-) deep water gap cuts through Kittatinny Mountain, located in the Valley and Ridge province of the Appalachian Mountains. Mount Minsi (in Pennsylvania) and Mount Tammany (in New Jersey) flank the Gap. The Gap has been called "the most attractive in the United States."

The bedrock underlying Delaware Water Gap National Recreation Area was deposited during the Ordovician, Silurian, and Devonian periods, about 450 to 359 million years ago. The rocks were originally sediments (lime, mud, sand, and gravel) deposited in a basin west of the highlands that formed during Appalachian mountain-building events along the eastern margin of North America. Much more recently, during the past 2 million years, ice age glaciers beveled highlands, carved troughs, and deposited outwash, till, and moraines. Younger surficial units consist of unconsolidated alluvium (gravel, sand, silt, and clay) deposited by streams, colluvium collecting at the bases of slopes, and swamp and marsh deposits. These rocks and unconsolidated deposits underlie the landforms that influence ecosystems and historical development at Delaware Water Gap National Recreation Area.

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report. The report discusses distinctive geologic features and processes within the park, geologic issues facing resource managers at the park, the geologic history leading to the park's present-day landscape, and provides information about the GRI geologic map data produced for the park. Geologic Map Graphics (in pocket) illustrate the geologic data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit. This report also contains a glossary and a geologic time scale.

Geologic features of particular significance for resource management at Delaware Water Gap National Recreation Area include the following:

- Delaware Water Gap. The Delaware River flows through the spectacular Delaware Water Gap near the southern boundary of the park. The approximately 370-m- (1,200-ft-) deep, 1.6-km- (1-mi-) wide V-shaped notch in the narrow ridgeline of Kittatinny Mountain displays deformed erosion-resistant bedrock. Delaware Water Gap formed through a process of headward erosion and stream capture. Deformation of the bedrock during Appalachian mountain-building episodes hundreds of millions of years ago created an area of structural weakness in the rock. Erosion was concentrated at this weaker area, leading to the formation of the Gap. Other gaps in the region formed in a similar manner but lack the scale and grandeur of the park's namesake feature.
- Glacial Deposits and Features. The park's landscape reflects the massive amounts of ice that moved across and covered the park during Pleistocene ice age glaciations. During the most recent glaciation, ice sheets reached their maximum extent about 4 km (2 mi) south of the park. Glacial deposits and features in the park and surrounding area were deposited by glaciers, carved by moving ice, deposited by rivers flowing out of the glacier, or deposited in lakes near the glacier.
- Paleontological Resources. The bedrock in the park contains a rich Paleozoic marine invertebrate fossil record. There is also potential for a Pleistocene (ice age) terrestrial vertebrate fossil record. Paleozoic marine invertebrates, such as brachiopods, crinoids,

bryozoans, gastropods, trilobites, and corals, occur in several bedrock geologic units. Regional museums contain many fossils from the park.

- Type Sections. The extensive exposures of rocks within and surrounding the park have long been studied by geologists. Geologists designate type sections at the location where layers of rock (strata) were originally described or particularly well exposed. A type section is the standard for which exposures of the same strata in other locations may be compared. At least 24 type sections exist within or around Delaware Water Gap National Recreation Area.
- Folds and Faults. Hundreds of millions of years of mountain-building events deformed rocks in the park into folds or fractured them along faults. Folds in the park and surrounding area include both anticlines ("A"-shaped folds) and synclines ("U"-shaped folds). All three major types of faults (normal, reverse, and thrust) are documented in the area. Limbs of major folds support the high ridges of Kittatinny Mountain and are visible in the Gap. Folds and faults from later mountain-building events "overprint" folds and faults from earlier events.
- Sedimentary Features. The sedimentary rocks of the park contain evidence of the environments in which they were deposited. Examples of such features include turbidites from submarine landslides, mudcracks, soft sediment deformation, and concretions.
- Taconic Unconformity. Unconformities mark breaks in the stratigraphic record. The Taconic Unconformity is a regionally significant break marking the boundary between Ordovician and Silurian-aged rocks and the uplift and erosion of an ancient mountain range.
- Waterfalls. The park's high relief hosts many scenic waterfalls including the two tallest in Pennsylvania and one of the tallest in New Jersey. The falls along Dingmans Creek were not carved directly by ice although successive notches record periods of high meltwater flow when ice was melting during deglaciations.
- Cave and Karst. Karst topography—characterized by dissolution features such as sinkholes, caves, and springs—is not widespread in the park. However dozens of relatively small-scale features exist in the park. No formal, systematic inventory has yet been completed. Cold Air Cave is not a karst feature. It is an open space created between large blocks of rock that tumbled from the cliffs above. All caves (and mines) are closed to minimize the spread of white-nose syndrome, a disease that has devastated bat populations.
- Geologic Connections to Park Stories and Resources. The park's geology influences its human history, as well as its ecosystems and habitats. American Indians long used the Gap as a transportation corridor and utilized local chert for tool-making. Europeans also used the Gap for transportation and targeted many geologic exposures for mineral extraction. The spectacular scenery of the area fostered a resort community. The diverse topography in the park supports varied habitats from dry ridge-top communities with prickly pear cactus to wetlands and bogs. The park is an important migratory corridor for raptors.

Geologic issues of particular significance for resource management at Delaware Water Gap National Recreation Area were identified during the GRI scoping meeting and follow-up conference call. They include the following:

- Slope Movements. Slope movements in the park occur in four primary contexts: 1) landslides of soil and glacial till on glaciated and polished bedrock surfaces, 2) rockfalls and rockslides originating along fractures that parallel roads, 3) debris flows in glacial till, and 4) slumps. These are natural processes to be expected on the park's often steeply sloped landscape. Geological, morphological, physical, and anthropogenic factors contribute to slope instability. Many roads within the park are undercut by erosion, particularly along rivers. The mitigation of slope hazards often involves the construction of stabilizing structures.
- River Channel Migration and Flooding. The Delaware River and its tributaries naturally meander across the landscape within the park. Flooding undercuts and erodes roads, damages infrastructure, and alters river channel morphology and sedimentation patterns. Increased precipitation over the past decade (approximately 2000–2010), compared with the long term mean, exacerbated these impacts.
- Marcellus Shale Gas Extraction. The park is located near the eastern edge of the Marcellus Shale, a Devonian-aged rock unit that hosts considerable natural gas accessed via hydraulic fracturing, or "fracking." Natural gas–producing shale units do not occur in a geologic setting that would be viable for gas extraction within the park. Park resource management concerns include water quality impacts, degraded viewshed and air quality, increased noise, and visitor safety.
- Corridor Construction Projects. Large scale construction projects such as the Susquehanna to Roseland transmission line have the potential to impact geologic features directly or indirectly by increasing access to those features. Such projects may affect slope stability and the potential for slope movements along the corridor. An Environmental Impact Statement completed for the Susquehanna to Roseland project outlines impacts to geologic resources and specifically mentions the need to minimize impacts to geologic resources, including fossils, unique or rare geologic features, and different habitats associated with various geologic features. Restoration of disturbed lands can take decades.
- Micro-Hydro Power and Geothermal Development. Streams within the park have been deemed appropriate for micro-hydro power (generating hydroelectric power without dams or reservoirs) although the Delaware River's wild and scenic status should protect streams within the park from energy

development. Natural geothermal energy may be a future energy source for park infrastructure.

- Abandoned Mineral Lands. Centuries of mining within and surrounding what would become Delaware Water Gap National Recreation Area created a legacy of at least 56 abandoned mineral lands features at 38 sites. Environmental quality, habitat, and visitor safety concerns surround these features. The history of mining in the park includes the historically significant, but never economically viable, Pahaquarry Copper Mine, as well as extensive sand and gravel extraction and building stone (slate) quarries.
- Farm Ponds and Dams. Small-scale stream impoundments, locally referred to as "farm ponds," are found in the park and attest to human alteration of the landscape for agricultural and recreational needs. Some dams are maintained by the park, others have been removed or are slated for removal.
- Paleontological Resource Management. The park's rich fossil record has been studied for decades. Potential impacts include slope movements affecting localities, as well as public access and unauthorized collecting. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations beyond the scope of this report.
- Recreational Use. With nearly 5 million visitors annually, Delaware Water Gap National Recreation Area was the tenth most-visited park in the National Park System in 2012. High visitation may create visitor safety issues associated with geologic resource management issues described in the report. Resource management concerns also include soil and vegetation trampling associated with camping, as well as development of "social trails."
- Seismic Hazards. Earthquakes that are noticeable by humans are uncommon in Pennsylvania and New Jersey although the August 2011 earthquake in central Virginia was felt in the park. Earthquakes may damage infrastructure via shaking or trigger slope movements.
- Surface Water and Groundwater Quality and Quantity. Water chemistry in the park is influenced by the types of bedrock in the park. Surrounding development alters water quality in the park. Aquifers are subject to contamination from anthropogenic sources. Groundwater quantity may become an issue if regional droughts occur. A GIS-based watershed model could support resource management.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting and history of Delaware Water Gap National Recreation Area.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents. Appendix B lists laws, policies, and regulations relevant to geologic resource management.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: 1) conduct a scoping meeting and provide a scoping summary, 2) provide digital geologic map data in a geographic information system (GIS) format, and 3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Regional and Park Information

Encompassing 27,009 ha (66,740 ac) of rolling hills, ridges, valleys, and river ways, Delaware Water Gap National Recreation Area protects 64 km (40 mi) of the Middle Delaware River between northeastern Pennsylvania and northwestern New Jersey (fig. 1 and plate 1). Delaware Water Gap National Recreation Area is the largest natural area in the National Park System between Virginia and Maine and one of the largest protected natural areas in the metropolitan corridor extending from Washington, D.C. to Boston (National Park Service 2013). The middle Delaware River valley is the dominant landform within the park. The park's namesake water gap cuts through Kittatinny Mountain, located in the Valley and Ridge province of the Appalachian Mountains (fig. 2). There, the river is nearly 17 m (55 ft) deep. Immediately flanking the 1.6-km- (1-mi-) wide and approximately 370-m- (1,200-ft-) deep gap are Pennsylvania's Mount Minsi (to the south) at an elevation of 446 m (1,463 ft), and New Jersey's Mount Tammany (to the north) at an elevation of 465 m (1,527 ft). The Gap formed through a combination of headward erosion and stream capture. Upstream of the Gap, the river flows between Kittatinny Mountain to the southeast and the edge of the Pocono (also called

Figure 1. Regional map for Delaware Water Gap National Recreation Area. The park is located along the Pennsylvania–New Jersey border. A detailed, fold-out park map (plate 1) is provided in the map pocket of this report. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto.cfm (accessed 29 January 2013).

Figure 2. Physiographic map of eastern Pennsylvania and New Jersey showing the location of Delaware Water Gap National Recreation Area (circled in green) along their border. Red lines indicate boundaries between major physiographic provinces. The park straddles the boundary between the Appalachian Plateaus and the Valley and Ridge provinces. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Sevon (2000) and Dalton (2003).

Allegheny) Plateau to the northwest. The Pocono Plateau is part of the Appalachian Plateau province, the sharp, eastern edge of which is locally referred to as the Pocono Front.

The headwaters of the Delaware River are on the western slopes of the Catskill Mountains in eastern New York. Near the headwaters, the river flows in East and West branches, which merge in Hancock, New York. From that point, the Delaware River flows south to the mouth of the Delaware Bay, a total distance of more than 530 km (330 mi). The travel time from the confluence of the East and West branches to Delaware Water Gap is approximately 70 hours during moderate flow (White and Kratzer 1994). The Delaware is the longest free-flowing river in the eastern United States. According to the Delaware River Basin Commission, the river drains just 0.4% of the United States' land area, but provides almost 10% of the nation's population with potable and industrial water supplies. More than half of this watercourse is protected within various public lands, including five NPS units: Upper Delaware Scenic and Recreational River, Delaware Water Gap National Recreation Area, Middle Delaware National Scenic and Recreational River, Delaware and Lehigh National Heritage Corridor, and Lower Delaware National Wild and Scenic River.

The Paleozoic Era bedrock formations underpinning the landscape of the park and its surrounding area are primarily sedimentary rocks (limestone, shale, and sandstone) of Cambrian, Ordovician, Silurian, and Devonian ages. Together, they range in age from about 540 to 360 million years old (figs. 3 and 4). Most of these layers are tilted ("dip") to the northwest. Older, Middle Proterozoic (1.6 billion to 900 million years ago) metamorphic rocks occur in New Jersey, southeast of the park boundary. Rocks from the Mesozoic Era and much of the Cenozoic Era are missing from the park. They either eroded away or were never deposited. The geologic record within the park picks up again much more recently. Ice age glaciers deposited abundant material, mantling the park's landscape during the Pleistocene Epoch (2.6 million to 11,700 years ago). After the glaciers receded from their maximum extent 4 km (2 mi) south of the Gap, geologic processes of erosion and weathering continued to shape the landscape. Deposits of alluvium, colluvium, and peat continue to accumulate within Delaware Water Gap National Recreation Area (see Geologic Map Graphics).

The Gap and landscape strongly influenced the history of the area. Gaps, or passable breaks, through the steep mountain ridges of the Appalachians have long been used for navigation and transportation. American Indians such as the Lenni-Lenapes (or Delaware Indians) were the first humans to use the Gap to expand hunting and commerce. Antoine Dutot was an early European settler who played a large role in the future development of the Delaware Water Gap area. In 1793, seeing the incredible natural beauty of the river flowing through the gap in the bedrock, Dutot established Dutotsburg, which eventually became the borough of Delaware Water Gap. When roads and railways reached the area in the late 1800s, the Gap became a premier resort destination; it retained this function well into the early 20th century. Farms, some of which remain active, were established on the broad, fertile floodplains of the upstream river valley. The rugged, rocky upland and ridge areas posed challenges to permanent settlement. Many cultural resources, from historic transportation routes (ferry, automobile, and rail) to settlements, are preserved within the park. Today, the Delaware Water Gap continues to be a major transportation thoroughfare. In addition to the river, Interstate 80 (I-80) and Pennsylvania Route 611 cross Kittatinny Mountain at the Gap.

Delaware Water Gap National Recreation Area was authorized 1 September 1965. The federal government acquired the lands that would eventually become the park with the intent that the land would surround a reservoir. The proposed dam at Tocks Island was never constructed and the park is now extremely popular with hikers (about 40 km of the Appalachian Trail traverses the park), bikers, boaters, and travellers along I-80. Approximately 5 million visitors recreate in the park each year—Delaware Water Gap National Recreation Area was the 10th most visited park in the National Park System in 2012.

Connecting Visitors to Geologic Resources, Features, and Processes

Because the landforms of the park record and illustrate many geologic processes from mountain building to ice age glaciation, the park is an excellent setting for geoscience-themed interpretation and educational programs. A number of publications and resources are available to facilitate those opportunities. Epstein (2000), Witte (2000), and Witte and Epstein (2005) underscored the need for interpretive field and trail guides in addition to geological educational outreach programs based on parkwide geologic mapping. Ferrence et al. (2003) developed a curriculum-based guide to the geology of the park for grades 3 through 6. Epstein (2010a, 2010b) prepared a teacher's guide to geologic trails in Delaware Water Gap National Recreation Area. Various stops of geologic significance are described in detail with respect to geologic history, units, structures, and processes that resulted in the present landscape. Stops include: 1) Point of Gap Overlook, 2) Cold Air Cave, 3) Arrow Island Overlook and Trail, 4) Lake Lenape, 5) Red Dot-Blue Blaze-Dunnfield Creek trails, and 6) Karamac Trail. The scale of features described is comprehensive, ranging from the largest elements of the landscape, including the Delaware Water Gap and Kittatinny Mountain, to small-scale features such as glacial erratics and sedimentary structures. Geologic map units described and visited include the Martinsburg Formation (Omp, Omhp, Omr, Omrg, and Omb), Shawangunk Formation (Ss, Sst, Ssl, and Ssm), and Bloomsburg Red Beds (Sbcu and Sb). In addition to the park's existing geology trail, such a teacher's guide is invaluable for the development of interpretive programs focusing on making geology understandable and relevant to visitors. Two other geology trails have been "developed" in the park: 1) a geologic podcast for the Red Dot Trail and 2) a not-yet-completed geologic trip along the river by a Geoscientist-in-the-Park (Leslie Morlock, GIS coordinator, Delaware Water Gap NRA, written communication, 24 August 2012). Detailed field guidebooks prepared for two field conferences of Pennsylvania geologists feature sites within and surrounding Delaware Water Gap National Recreation Area (Inners and Fleeger 2001; Harper 2012).

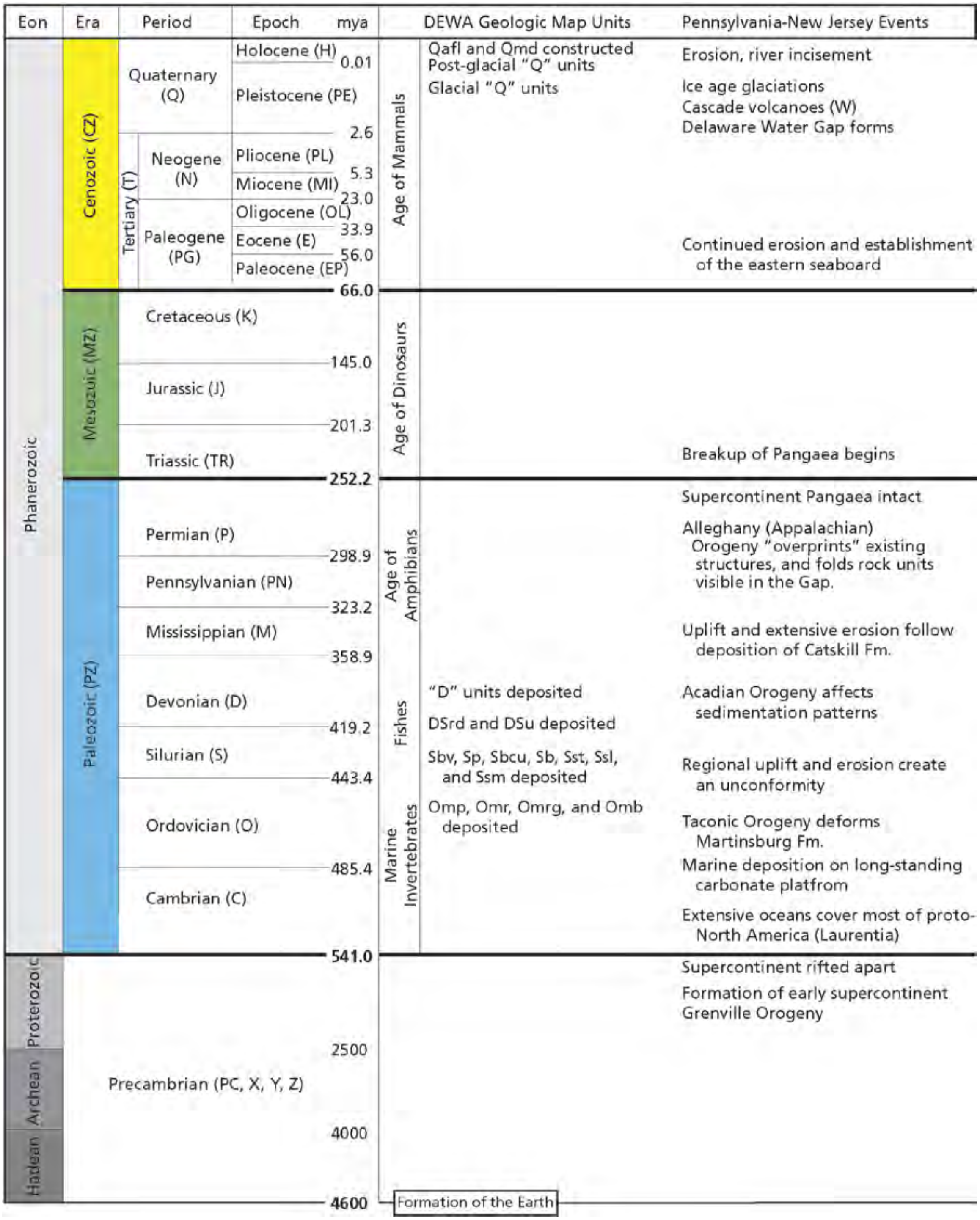

Figure 3. Geologic time scale. Geologic events occurring in the Delaware Water Gap National Recreation Area are included with an emphasis on units appearing within the park ("DEWA Geologic Map Units"; see also fig. 4). The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Bold horizontal lines indicate major boundaries between eras; boundary ages are millions of years ago (mya). Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), ages from the International Commission on Stratigraphy time scale (http://www.stratigraphy.org/ICSchart/ChronostratChart2012.pdf).

Era	Period	Epoch	Rock Unit		General Description
CENOZOIC	QUATERNARY		Younger alluvial and colluvial deposits ("Q" units)		Unconsolidated clay, silt, sand, and gravel; peat; talus
			Older glacial deposits ("Q" units)		Unconsolidated glacial outwash, till, and eolian deposits
PALEOZOIC	DEVONIAN	Late	Trimmers Rock Formation	Millrift Member (Dtm)	Dark gray, fossiliferous siltstone, shale, and sandstone
				Sloat Brook Member (Dtsb)	Gray siltstone and silty shale
		Middle	Hamilton Group Mahantango Formation	Mahantango Formation, undivided (Dmh)	Dark gray, fossiliferous siltstone and shale
				Lower Member (Dml)	Dark gray, siltstone and silty shale
			Hamilton Group Marcellus Shale	Marcellus Shale (Dm)	Dark gray, fossiliferous shale and limestone
				Broadhead Creek Member (Dmb)	Dark gray silty shale
				Stony Hollow and Union Springs Shale members (Dmsu)	Dark gray sand, silty, and limey shale
			Onondaga Limestone Buttermilk Falls Limestone (Db)		Gray fossiliferous limestone, chert, argillite, and siltstone
		Early	Schoharie Formation (Ds)		Gray fossiliferous siltstone
			Esopus Formation (De)		Gray shale and siltstone
			Oriskany Group, undivided (Do)		Dark gray, conglomeratic sandstone and quartzose limestone
			Helderberg Group	Port Ewen Shale (Dph, Dp)	Gray shale and siltstone, some fossils
				Minisink Limestone (Dph, Dmn)	Gray fossiliferous limestone
				New Scotland Formation (Dmn, Dph)	Gray fossiliferous shale and limestone
				Coeymans Formation (Dc)	Gray fossiliferous limestone and sandstone
	SILURIAN and DEVONIAN		Rondout Formation (DSrd)		Gray shale, limestone, and dolomite
			Decker Formation (DSrd)		Conglomerate, sandstone, siltstone, limestone, and dolomite
			Undifferentiated Devonian and Silurian rocks (DSu)		Mixed carbonates, shales, and siltstones
	SILURIAN	Late	Bossardville Limestone (Sbv)		Gray limestone
			Poxono Island Formation (Sp)		Gray to green shale, dolomite, sandstone, and siltstone
		Late and Middle	Bloomsburg Red Beds (Sbcu, Sb)		Red, green, and gray siltstone, shale, sandstone, and conglomerate
		Middle and Early	Shawangunk Formation (Ss)	Tammany Member (Sst)	Gray conglomerate and quartzite
				Lizard Creek Member (Ssl)	Gray quartzite and argillite
				Minsi Member (Ssm)	Gray quartzite and conglomerate
	ORDOVICIAN	Late and Middle	Martinsburg Formation	Pen Argyll Member (Omp)	Gray slate
				Ramseyburg Member (Omr, Omrg)	Gray slate, graywacke, and siltstone
				Bushkill Member (Omb)	Gray slate and siltstone

Figure 4. General stratigraphic column of the Paleozoic geologic units mapped within Delaware Water Gap National Recreation Area. Geologic map unit symbols appear in parentheses. A list of all geologic units, including Quaternary and Precambrian, in the digital map data, as well as detailed descriptions and resource management information, is available in the Map Unit Properties Table. Colors are standard U.S. Geological Survey designations. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Delaware Water Gap National Recreation Area.

Delaware Water Gap National Recreation Area is in a formerly glaciated area of the eastern Valley and Ridge province of the Appalachian Mountains in eastern Pennsylvania and northwestern New Jersey. Thick Pleistocene (2.6 million to 11,700 years ago) glacial deposits cover many bedrock exposures, as illustrated on the Geologic Map Graphics (in pocket). In addition to its namesake geologic feature, the Delaware Water Gap, the park contains glacial deposits and features, paleontological resources, geologic type sections, folds and faults, sedimentary features, the Taconic Unconformity, waterfalls, as well as cave and karst resources. Geologic connections to park stories and other resources are also discussed in this section. Plate 2 (in pocket) notes the locations of many features discussed in this section.

Delaware Water Gap

The Delaware Water Gap is a prominent feature in the Appalachian Mountains of eastern Pennsylvania and northwestern New Jersey (fig. 5 and cover). This magnificent gorge is often referred to as the classic water gap, to which all other gaps in the Appalachian Mountains have been compared (Epstein 2006). It is an "Outstanding Scenic Geological Feature" of Pennsylvania and described as "a highly scenic water gap…the most attractive in the United States" (Geyer and Bolles 1979, p. 248). At the southern end of the park, a river cut through bedrock to form this approximately 370 m (1,200 ft) deep, V-shaped notch 1.6 km (1 mi) wide in the ridgeline of Kittatinny Mountain (Epstein 2006). The depth to which the Delaware River has cut through Kittatinny Mountain is remarkable, creating spectacular exposures of steeply inclined Silurian (more than 416 million years old) rocks (Shawangunk Formation [geologic map units Ss, Sst, Ssl, and Ssm] and Bloomsburg Red Beds [Sb]) that are visible from the Gap overlooks.

Figure 5. Photograph of Delaware Water Gap and flanking mountains, Mt Minsi (Pennsylvania) and Mt Tammany (New Jersey). National Park Service photograph.

Formation of the Gap

Throughout the Appalachian Mountains, hard rocks such as quartzites, sandstones, and conglomerates form ridges where adjacent less-resistant rocks have been eroded away. Gaps through these ridges form slowly where weathering exploits zones of weakness. Many conditions may create a zone of weakness. Tectonic forces can fracture rocks, create faults, and fold and deform rocks.

Another well-known Appalachian gap is Cumberland Gap within Cumberland Gap National Historical Park (at the intersection of Tennessee, Kentucky, and Virginia). That gap formed along a fault that cut through Cumberland Mountain (Thornberry-Ehrlich 2011). However, faulting did not cause the zone of weakness at Delaware Water Gap. Chance (1875) was among the first to notice "warping of the formations" in the immediate vicinity of the Gap, rather than obvious linear faulting as at Cumberland Gap. At Delaware Water Gap, erosion focused on a flexure or kink in the bedrock—identified by the different orientations of bedrock units on either side of the Gap—(fig. 6). Evidence that a local zone of weakness exists around the flexure includes:

- A change in rock inclination. On the New Jersey side of the Gap, the bedding inclination (dip) increases to 45° toward the top of Kittatinny Mountain, whereas on the Pennsylvania side, bedding dip decreases to 25° about halfway up the mountain(Epstein 2001b).
- A change in ridge crest orientation. The ridgeline trend lies approximately 210 m (700 ft) further southeast on the Pennsylvania side than in New Jersey (Epstein 2006). A bend in the rocks would have been present at the site now occupied by the water gap.
- A change in the extent of bedrock deformation. The Bloomsburg Red Beds (Sbcu and Sb) are complexly folded immediately northwest of Delaware Water Gap. Similar tight folding is not seen elsewhere in the red beds beyond the Gap site. Thus, the beds were presumably more highly deformed within and near the Gap (Epstein 2001b).
- A change in the amount or thickness of erosion-resistant bedrock. The erosion-resistant Shawangunk Formation outcrop at the Gap site is narrower than in exposures to the northeast (where the Cherry Valley anticline and Dunnfield Creek syncline widen the exposure; see "Folds and Faults" section). Thus, less rock was present at the Gap site for the river to cut through (Epstein 1966, 2001b).

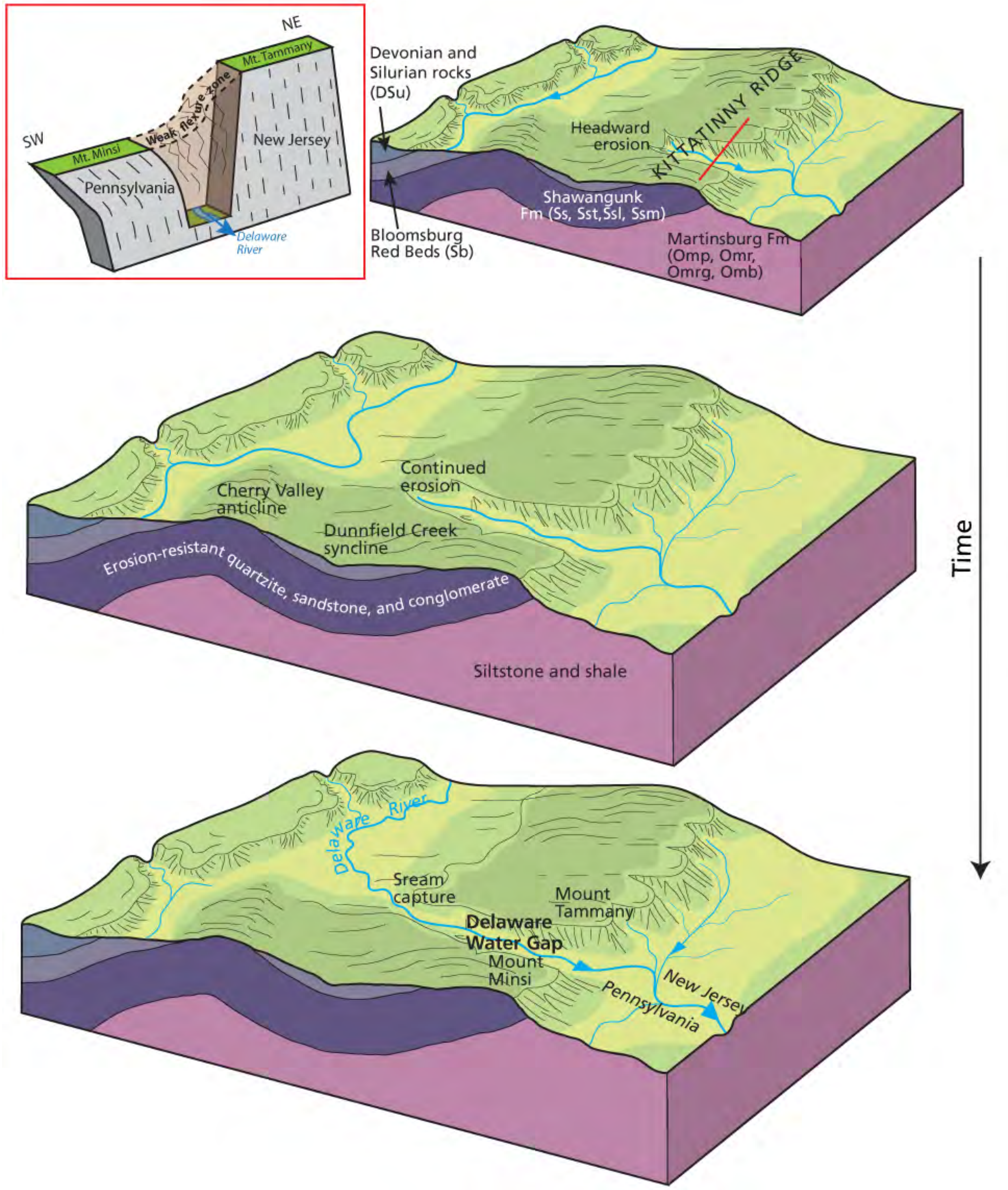

Figure 6. Schematic graphics illustrating gap formation at the landscape scale. The Gap formed via headward erosion, concentrated erosion at a zone of bedrock weakness, and stream capture. A bedrock "flexure" (inset; red line indicates approximate location of cross section) whose inherent weakness (fractures) focused erosion, ultimately forming the Delaware Water Gap. The flexure also explains the offset of the Kittatinny Mountain ridge between the two sides of the Gap. The underlying layers were tilted and deformed during Appalachian mountain-building events (orogenies) in the Paleozoic Era (refer to the "Geologic History" section). Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 7 in Epstein (2010b) and figure 9 in Epstein (2006).

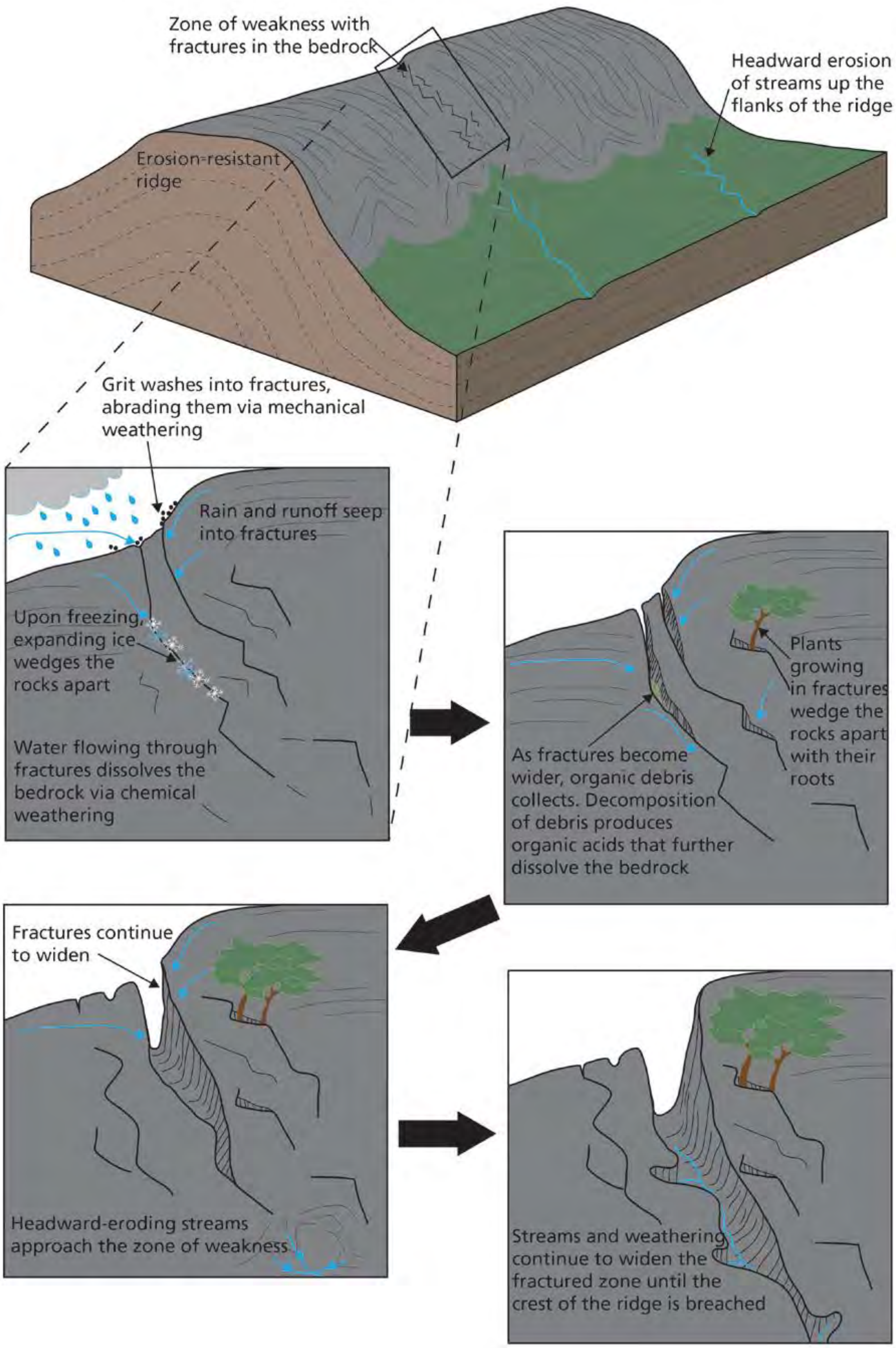

Figure 7. Schematic graphic of gap formation at the outcrop scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Following the development of a zone of weakness across Kittatinny Mountain, a large river was able to cut through. After the most recent ice age, rivers drained the flanks of Kittatinny Mountain to the east and west (fig. 6). As headward erosion, the process by which a stream cuts progressively further upslope, cut the stream ravines, a notch formed on the east side of the ridge crest. The river exploited the highly deformed zone of weakness when forming the notch. A combination of weathering processes, such as frost wedging, dissolution (chemical weathering), abrasion (mechanical weathering), and tree-root wedging, further broke down the rocks (fig. 7). Frost-wedging occurs when water seeping into very narrow fractures freezes and expands, forcing the rock apart. Dissolution involves the chemical removal of rock material as water flows through the fracture. As cracks widen, runoff water transports grit into them that scratches the sides, slowly enlarging them. Similar to frost-wedging, tree roots exert significant force, breaking rocks apart. Trees and plants also deposit organic debris into enlarging fractures. When this material decomposes, organic acids dissolve away more of the rock surface.

Through time, the notch deepened through Kittatinny Mountain, eroding a gap. Eventually, an eastern stream captured the flow of a western stream and a through-flowing water gap formed, creating the channel for the modern Delaware River system (fig. 6). The course of the Delaware River curves in a loop pattern that roughly parallels the curve of bedding exposed in the Cherry Valley anticline (an "A"-shaped fold that plunges to the north). This pattern was likely a function of the river's contact with erosion-resistant Shawangunk quartzites and conglomerates ("Ss" map units) in addition to river migration down the plunge of the anticline (Epstein 1997, 2001b).

Other Gaps

Delaware Water Gap is a classic and nationally significant example of a gap formed in an area of deformation (flexure). Other regional gaps formed in a similar manner but lack the scale and grandeur of Delaware Water Gap. Epstein (1997) studied 16 smaller gaps—including Fox, Totts, and Wind gaps—in the Blue, Kittatinny, and Shawangunk mountains between Lehigh Gap in eastern Pennsylvania and Ellenville, New York. Each of these gaps feature one or more of the following examples of rock deformation leading to a zone of weakness: 1) "dying out" of folds, 2) narrow outcrops of resistant beds due to steep dips (inclinations), 3) intense folding, 4) abrupt change in trend (strike) due to "kinking," and 5) intense overturning of beds. Some of these gaps formed at faults, particularly where multiple faults intersected at nearly right angles (termed "cross faulting").

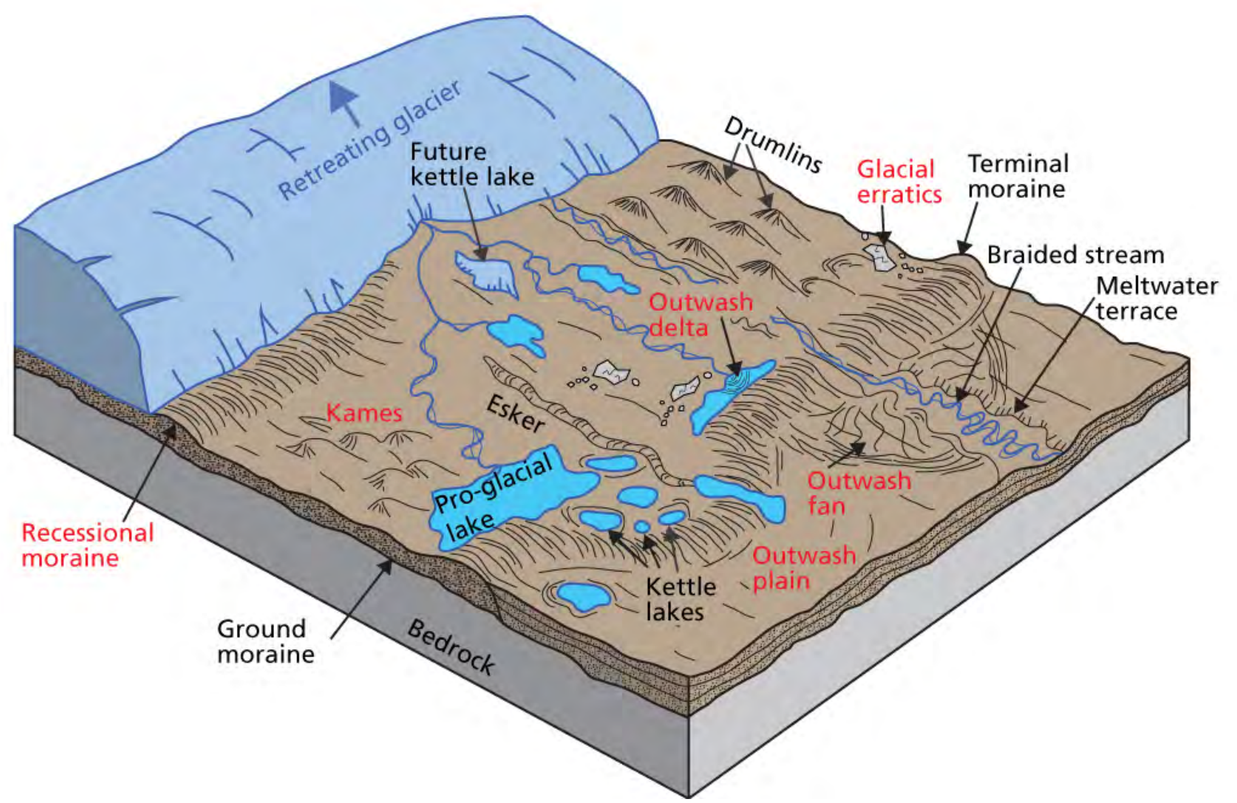

Figure 8. Schematic illustration of glacial features and deposits. Not every glacially altered landscape contains all of these features or deposits. Prominent features and deposits within the park are labeled in red and include outwash deposits, recessional moraines, outwash fans, glacial erratics, glacial grooves (see fig. 11), and kames. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Glacial Deposits and Features

Repeated glaciations (ice ages) during the Pleistocene Epoch (2 million to approximately 20,000 years ago) scoured and reshaped the landscape of northeastern United States, including Delaware Water Gap National Recreation Area. Thick sheets of ice advanced and retreated over the park throughout the Pleistocene, culminating in the most recent "Wisconsinan" glaciation when the Laurentide Ice Sheet covered northern North America. During this event, the Kittatinny and Minisink Valley lobes of the Laurentide Ice Sheet reached their maximum extents just 4 km (2 mi) south of the park's southern boundary. Glacial deposits and features within and surrounding the park are well exposed and well-studied. They include those deposited or carved by moving ice, those deposited by rivers flowing out of the glacier (termed "glaciofluvial") or deposited in lakes near the glacier (termed "glaciolacustrine") (fig. 8). Following the most recent glacial retreat, the area's geomorphology changed considerably.

Features Deposited or Formed by Moving Ice

Glacial till, a mixed assortment of sediments dumped in place when a glacier melts, mantles much of the local bedrock (Qtq, Qtk, and Qit) (Epstein 1973, 1990; Witte 2001). Some till forms moraines (Qwmrk, Qdfm, Qom, and Qm) or drumlins. Moraines are ridges of material that mark the edges of a glacier. Terminal moraines mark the farthest advance of a glacier and were used to determine the maximum extent of ice age glaciations (fig. 9). The massive size of Pleistocene ice sheets created massive moraines. The terminal moraine is more than 33 m (100 ft) high in places such as Belvidere, New Jersey (Epstein 2010b). A series of recessional moraines (Qwmrk, Qdfm, Qom, and Qm) records the stepped (rather than continuous) glacial retreat. The Zion Church, Sand Hill Church, Dingmans Ferry, Montague, Millville, and Tristates margins delineate systematic major recessional positions during northeasterly retreat of the Minisink Valley and Kittatinny ice lobes (fig. 9) (Epstein 1969; Witte 2001; Stone et al. 2005). Drumlins are elongated, linear hills formed when a glacier flowed over a mass of sediment and indicate the direction of glacial flow (Witte 2001; Pristas 2007) (fig. 10). Moraine crests and "drumlinoid" features are included for portions of the geologic map area in the "Glacial Line Features" layer of the GRI GIS data. Locations and orientations of glacial striations are also included in the GRI GIS data as part of the "Glacial Feature Points" layer.

Bedrock also contains information about glacial ice flow. Grooves and striations record the direction of glacial movement (fig. 11). They formed when rocks and grit entrained in the glacial ice cut into the underlying bedrock as the glacier flowed. On a larger scale, a roche moutonnée is a knob of bedrock whose long axis is oriented in the direction of ice movement, formed by glacial erosion directly on bedrock. The profile of a roche moutonnée and its relation to glacial ice movement are opposite to those of a drumlin (fig. 10).

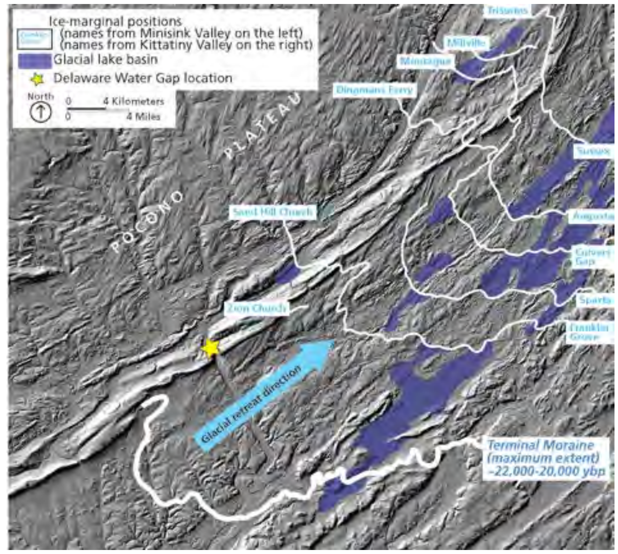

Figure 9. Map of ice-margin positions in Minisink Valley and upper Kittatinny Valley. These positions illustrate the step-wise retreat of ice during following the most recent glaciation. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 61 in Witte (2001).

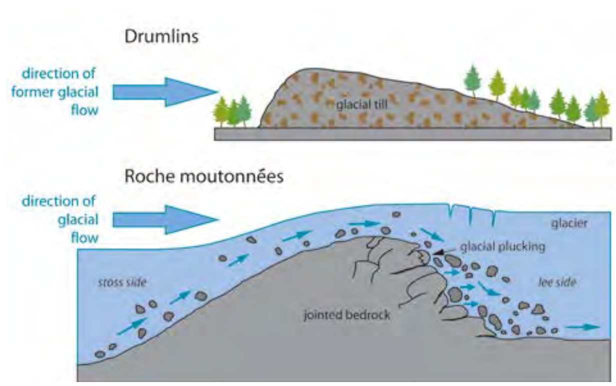

Figure 10. Schematic graphic of drumlin and roche moutonnée formation. Note the difference in glacial flow direction versus resulting topography. Glacial plucking creates a steep lee side of the roche moutonnée. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from the Brooklyn College (http://depthome.brooklyn.cuny.edu/geology/core332/central.htm; accessed 17 January 2011).

Figure 11. Photograph of glacial grooves. These grooves are in bedrock at Table Rock within Delaware Water Gap National Recreation Area. U.S. Geological Survey photograph by E. B Hardin (no date), available at: http://libraryphoto.cr.usgs.gov/parks.htm (accessed 16 September 2013).

These features are found along the Red Dot-Blue Blaze-Dunnfield Creek trails (Epstein 2010b).

Glacial erratics are large rocks that fell onto the glacier's surface, were transported some distance, and then were dumped on the landscape as the glacier retreated. They occur throughout the park, and are visible along the Arrow Island Trail (Epstein 2010b).

Glaciofluvial and Glaciolacustrine Features

Kames are glaciofluvial or glaciolacustrine deposits of sand and gravel. They typically collect as sediments deposited in hollows or depressions atop a retreating glacier. Kettles are low areas (now typically filled with a lake or swamp) that formed when a large block of glacial ice that was partially or totally buried by glacial sediment melts, leaving a depression. Ice-contact deposits (Qwic) are primarily sand and gravel deposits that form knolls and ridges higher than adjacent glacial-lake levels or glaciofluvial plains. They were deposited in ice-walled basins. Kames and kame terraces (Qk and Qokt), kettle lakes, ice-contact slopes (Qwic), and perched terraces (Qwfv and Qmt) formed atop or adjacent to the glaciers (Fisher et al. 1970; Davis 1989; Witte 2001; Witte and Epstein 2005; Pristas 2007). Kettle lakes throughout the Poconos are particularly scenic tourist attractions (Epstein 2010b).

As glacial ice retreated from the Delaware Water Gap area, meltwater was dammed by the terminal moraine, surrounding mountains, and ice front. The meltwater formed what is now termed Lake Sciota. Deltaic and varved (layered in annual upward-fining sequences of Qod and Qd) glaciolacustrine deposits collected there. Water levels reached depths of about 60 m (200 ft) and the initial lake outlet passed over the terminal moraine at Saylorsburg, allowing water to flow west toward the Lehigh River. As the glacier continued to retreat northeastward, the Gap superseded the former outlet and drained the lake (Epstein 2001b). Subsequent glacial lakes formed between the ice lobe and older glacial deposits down valley or in large depressions scoured in bedrock. As retreat continued, Lake Sciota ultimately drained out of the Gap. Meltwater deposits formed at and beyond the various margins of the Minisink Valley and Kittatinny ice lobes, often atop the glaciolacustrine deposits. They consist of valley-train (Qv), outwash-fan (Qfd, Qf, Qfdb, and Qdfm), and meltwater (Qwft and Qmt) terraces that formed along braided streams flowing away from the glacier (Witte 2001; Witte and Epstein 2005; Pristas 2007). A concentration of glacial deposits occurs at the intersection of Brodhead Creek, Cherry Creek, and the Delaware River at the southern end of the park, just before the river flows through the Gap (Delaware Water Gap National Recreation Area natural resource staff, conference call, 16 November 2011).

Post-glacial Geomorphology

After the glaciers retreated from the landscape and prior to the re-establishment of plant communities, rivers incised glacial deposits, creating myriad landforms such as terraces, channels, and floodplains. Winds swept across the bare earth and entrained fine-grained sand and silt, depositing them in drift and dunes (Qe and Qed) (Witte and Epstein 2005; Pristas 2007). Loess (winnowed silt) deposits and sand sheets occur on the eastern side of the Delaware River valley toward the southern end of the park (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Some alluvial fan deposits (Qaf) are associated with postglacial and outwash terraces. Modern streams dissect some older fans, reflecting the evolution of the modern fluvial system (Witte and Epstein 2005). Boulder fields reflect the colder climates associated with glacial and periglacial (influenced by glacial ice) conditions, when accelerated freeze–thaw action wedged the bedrock apart and large rockfalls accumulated (Qba and Qsr) (Witte and Epstein 2005).

Paleontological Resources

Delaware Water Gap National Recreation Area contains a rich Paleozoic fossil record from Ordovician, Silurian, and Devonian rocks. These fossils range in age from more than 480 million to about 360 million years old. There is also the potential for much younger Pleistocene fossils (tens to hundreds of thousands of years old) in surficial deposits, although none have been formally documented in the park. As part of the Eastern Rivers and Mountains Inventory and Monitoring Network paleontology summary, Koch and Santucci (2004) presented a brief summary of fossils within the park and surrounding area, as well as a fossil resource bibliography. A park-specific, field-based paleontological resource survey would provide important resource management information beyond the scope of this report (see "Paleontological Resource Management" section).

More than a century of fossil resource investigation has taken place within and surrounding what is now the park. In 1903, paleontologist Stuart B. Weller of the New Jersey Geological Survey discovered, collected, and described fossils from many localities in the area (Parris et al. 1990). Weller's specimens are curated at the New Jersey State Museum in Trenton, as part of more than 1,300 paleontological specimens from park collections housed there. Subsequent investigations have been conducted by Parris and others (Parris and Albright 1979a, 1979b; Parris et al. 1990; Parris and Cruikshank 1984). A non-technical guide to the fossils of New Jersey was published by Pallis et al. (2012). Common fossils of Pennsylvania are described and illustrated in Hoskins (1999).

Paleozoic (Bedrock Map Units) Paleontological Resources

Fossils in the Paleozoic clastic (claystone, siltstone, and sandstone, and conglomerate) and carbonate (limestone and dolomite) rocks of the park are primarily marine invertebrates. The Map Unit Properties Table includes additional detail about common fossils for each geologic map unit. Common marine invertebrate fossils are listed in Table 1. Vertebrate fossils—mostly fish scales—are occasionally found. Plant fossils are very rare and are restricted to Devonian-aged rocks. Trace fossils record the activities of organisms without preserving any parts

Table 1. Common types of Paleozoic marine invertebrate fossils in Delaware Water Gap National Recreation Area. Some are illustrated in figure 12.

Group		Common Name	Description
Chlorophyta		calcareous algae	large, single-celled algae that construct "shells" of calcium carbonate
Porifera		sponges	simple multicellular animals with bodies full of pores.
Anthozoa		corals	colonial or solitary, often reef-forming
Conulariida		conulariids	Enigmatic group of animals with ice cream cone shaped exoskeleton. May be related to corals. They are extinct.
Foraminifera		forams	small, amoeba-like single-celled organism that makes a "shell" called a "test." Useful for correlating rocks (biostratigraphy).
Arthropoda		insects and crustaceans	
	Trilobita	trilobites	well-known Paleozoic fossil group characterized by three longitudinal (parallel to body length) lobes. They are extinct.
	Eurypterida	sea scorpions	among the largest arthropods, eurypterids were fearsome predators. They are extinct.
	Ostracoda	seed shrimp	small bean-shaped crustaceans with bivalve-like "shells."
Mollusca		molluscs	
	Bivalvia	bivalves	Clams are a common bivalve. Their shells are symmetrical.
	Cephalopoda	nautiloids and ammonites	Squid-like animals with coiled or conical shells.
	Gastropoda	snails	Marine snails have a variety of shell types from coils to spired.
Bryozoa		moss animals	colonial animals can encrust surfaces or form fronds
Brachiopoda		brachiopods	Like bivalves, brachiopods are filter-feeders with two shells. Unlike bivalves, their shells are not symmetrical. The plane of symmetry is perpendicular to the shell opening.
Graptolithina		graptolites	colonial animals that often resemble saw blades. Useful for correlating rocks (biostratigraphy; e.g., Parris et al. 1998).
Echinodermata			
	Crinoidea	sea lillies	filter-feeding echinoderms, attached by stalks (resembling stacks of Checkers) to the sea floor.
	Asteroidea	sea star/starfish	Echinoderm with 5 arms.

For more information refer to the Map Unit Properties Table, Parris and Albright (1979a, 1979b), Parris et al. (1990), Parris and Cruikshank (1984), and Koch and Santucci (2004).

of the actual organism. They include burrows such as *Skolithos* (worm burrows) and horseshoe crab traces.

Of particular interest are type specimens collected within Delaware Water Gap National Recreation Area (compiled by Justin Tweet, paleontologist, Tweet Paleo-Consulting, written communication, 11 September 2012). Cramer (1959) described the sea star *Hudsonaster wardi* from the Mahantango Formation ("Dm" map units) near Milford. The enigmatic jellyfish-like (but of unclear taxonomy) *Rutgersella truexi*, *R. delawarensis*, and *R. kittatinnyensis* were originally named by Johnson and Fox (1968) for discoveries in the Silurian Shawangunk Formation ("Ss" map units) near the Gap. Although they are not considered type specimens, Metz (1998, 2000, 2003, 2006, 2009a, 2009b) described a number of trace fossils from many locations in the park including near the Gap, Wallpack Center, Conashaugh, and Buttermilk Falls. In the immediate vicinity of the park, worm-like *Rectogloma problematicum* was described near Henryville, Pennsylvania (Van Tuyl and Berkhemer 1914); the conulariid *Conularia sussexensis* from near Montague, New Jersey (Herpers 1949), and the horn coral *Nalivkinella echoense* from the vicinity of Stroudsburg, Pennsylvania (Oliver 1964).

Classic exposures of the Silurian Bloomsburg Red Beds (Silurian fish, map units Sb and Sbcu) exist within the park (Parris et al. 1990). There are several notable Devonian fossil bearing formations. An ancient reef is preserved in the Coeymans Formation (Dc) north of Tocks Island (Epstein and Epstein 1969a, 1969b; Alvord and Drake 1971). The Esopus Formation (De) yielded important Paleozoic fossils which are now housed in the New Jersey State Museum's collection (Parris et al. 1990; Koch and Santucci 2004). The Centerfield Member of the Mahantango Formation (Dmhc) consists of horizontal layers of fossils called a biostrome. It is often referred to as the "Centerfield Reef" due to abundant horn corals and other shells (Alvord and Drake 1971; Epstein 1973, 1990). This unit is popular for fossil collecting along Pennsylvania State Route 115 near Saylorsburg, and excellent exposures occur along I-80 in the park (Epstein 1990).

Pleistocene (Surficial Map Units) Paleontological Resources

In contrast to the marine invertebrate fossils that characterize the Paleozoic rocks, Pleistocene fossils in the area are primarily terrestrial vertebrates. Although none have yet been documented in the park, fossils discovered in neighboring sites include remains of

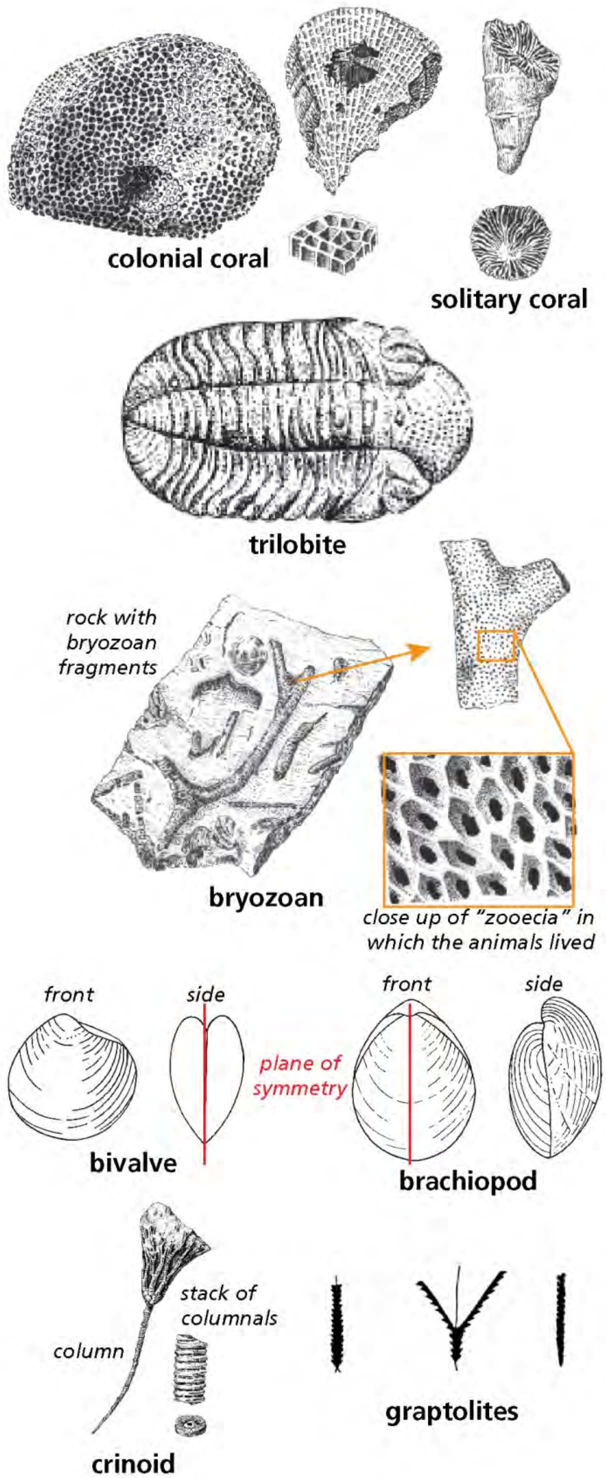

Figure 12. Sketches of representative Paleozoic marine invertebrate fossils in Pennsylvania. See also table 1. Illustrations by Albert E. Van Olden and John G. Kuchinski, extracted from Hoskins (1999).

freshwater mollusks, turtles, turkeys, woodchuck, chipmunk, squirrel, mouse, wood rat, vole, beaver, mole, raccoon, weasel, skunk, mastodons, stag-moose, deer, peccary, horse, bison, bat, gray fox, wolf, and lynx (Parris et al. 1990; Koch and Santucci 2004). Two significant mastodon discoveries were made near the park. The Marshalls Creek Mastodon is 90% complete and on display at the State Museum of Pennsylvania (Hoff 2001). Several mastodon teeth and bones were discovered west of Stony Lake in Stokes State Forest (New Jersey) and are now on display in the state forest visitor center. Quaternary peat and swamp deposits may contain pollen and other organic remains (Alvord and Drake 1971; Davis 1989).

Type Sections

Geologists often study the extensive exposures of diverse rock types within and surrounding Delaware Water Gap National Recreation Area. The spectacular exposures of sedimentary rocks within and near the park have yielded at least 24 type sections (table 2 and plate 2) (Jack Epstein, geologist, U.S. Geological Survey, written communication, 6 June 2012). A type section is the location where layers of rock (strata) were originally described. A type section is the standard for which exposures of the same strata in other locations may be compared.

Type sections are typically selected for layers of sedimentary rocks which share similar characteristics, such as rock type (e.g., sandstone, shale, siltstone), color, or distinctive features. Such a rock group is called a "formation." Geologists usually name formations to reflect a geographic feature (e.g., river, mountain, city) where the layers are best seen. Formations can be lumped together into "groups" (e.g., Helderburg Group) or subdivided into "members" (e.g., Brodhead Creek Member).

Folds and Faults

As expected for an area that experienced hundreds of millions of years of tectonic forces from major Appalachian mountain-building events (called orogenies, detailed in "Geologic History" section), bedrock throughout the park is deformed into folds or fractured by faults. The GRI GIS data locates hundreds of folds and faults. The vast majority are oriented northeast-southwest, parallel to the ancient continental margins involved in the orogenies (plate 2).

There are two primary types of folds: anticlines which are "A-shaped" (convex) and synclines which are "U-shaped" (concave). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently "plunge" meaning the fold axis tilts. As bedrock is compressed, anticlines and synclines form adjacent to each other, as in the southern end of the park. There are two dozen major named, and many dozens more unnamed, folds identified in the GRI GIS data. The Cherry Valley anticline and Dunnfield Creek syncline are prominent folds visible near the Gap. Limbs of the Dunnfield Creek syncline and the axis of the Cherry Valley anticline support the high ridges of Kittatinny Mountain (fig. 13). The geologic map (in pocket) shows the many tightly spaced folds west of the Gap. Such deformation contributed to the areas of weakness later exploited to form the Gap as described in the "Formation of the Gap" section.

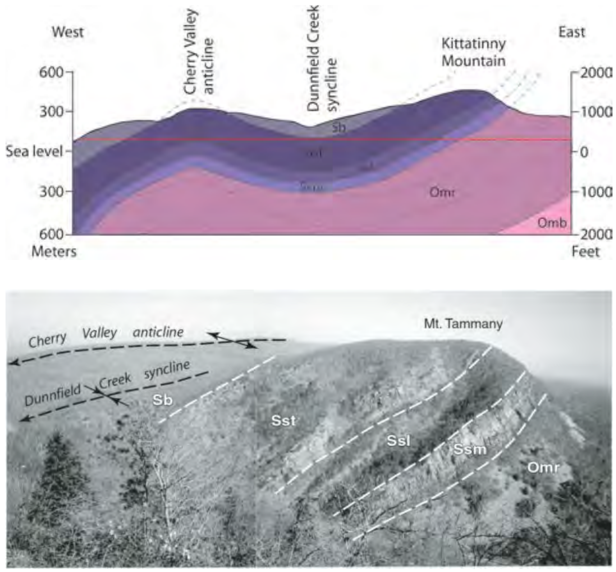

Figure 13. Schematic cross section and photograph of folds at Delaware Water Gap. Red line indicates approximate level of exposures along Interstate 80 through the Gap. Geologic map units are abbreviated as follows: Sb, Bloomsburg Red Beds;, Sst, Tammany Member of Shawangunk Formation, Ssl, Lizard Creek Member of Shawangunk Formation; Ssm, Minsi Member of Shawangunk Formation; Omr, Ramseyburg Member of Martinsburg Formation; and Omb, Bushkill Member of Martinsburg Formation. Cross section graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 from Epstein (2010b).Photograph is figure 2 in Epstein (2010b).

There are three primary types of faults: normal faults, reverse faults, and strike-slip faults (fig. 14). All three are mapped within GRI GIS data. Faults are classified based on motion of rocks on either side of the fault plane as described in fig. 14. Thrust faults are reverse faults with a low angle (<45°) fault plane. Decollements or detachment faults are very low angle (subhorizontal) reverse faults with large displacement (kilometers to tens of kilometers). There are nine major, named faults in the GRI GIS data. Two decollements, the Blue Mountain and Godfrey Ridge are mapped within the southern end of the park near the Gap.

Because multiple orogenies deformed or fractured the rocks of the park and surrounding area, unraveling their geologic history is a challenge. For example, the Alleghany Orogeny created folds and slaty cleavage (tendency for rocks to break apart in thin sheets) in rocks of the park and surrounding area. These structures were superimposed on ("overprinted") older, structures in the pre-Silurian rocks created during the Taconic Orogeny (Epstein and Epstein 1967; Epstein 2010b). In the Dunnfield Creek syncline, the Bloomsburg Red Beds display many small folds not seen on adjacent structures, such as the Cherry Valley anticline. Bedding plane faults have also developed within this unit and display slickensides (directional grooves on fault surfaces). Bedding plane faults likely predate folding (Epstein 2010b).

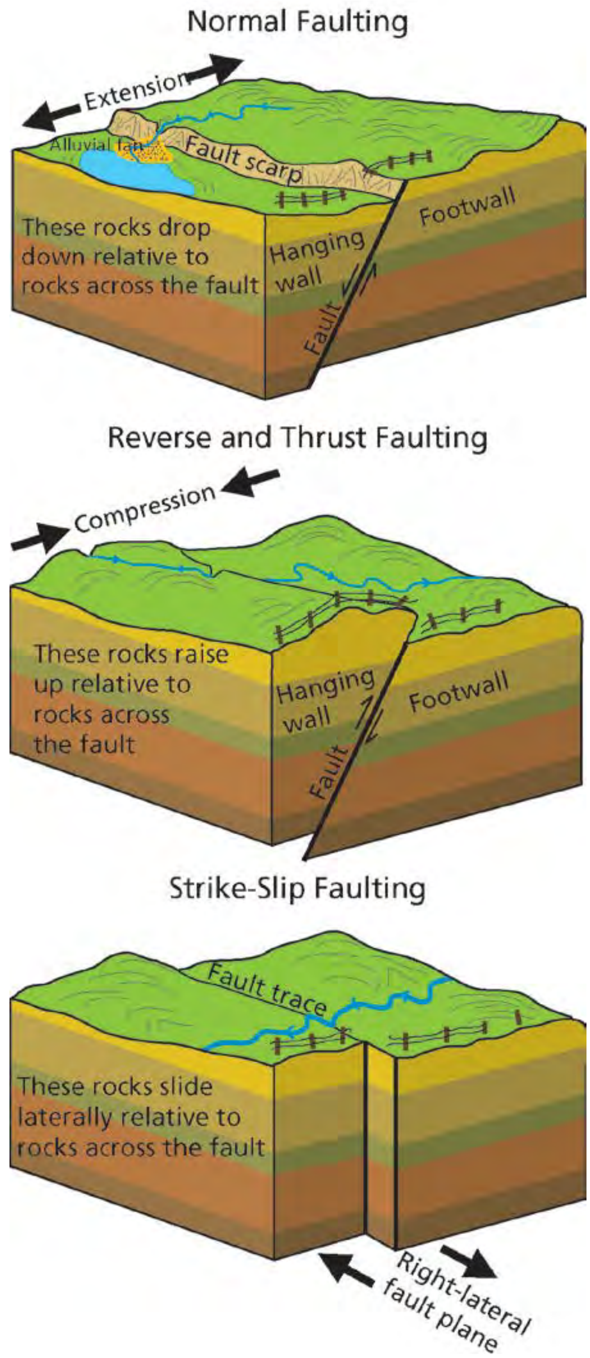

Figure 14. Schematic illustrations of fault types. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. Decollements are very low angle reverse faults with large displacement. In a strike-slip fault, the relative direction of movement of rocks across the fault is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Sedimentary Features

Sedimentary features in rocks preserve a record of conditions during their deposition and the processes by which they were deposited. These features are described in detail in the Map Unit Properties Table. Of interest are turbidites, features that indicate terrestrial fluvial (river) settings, soft sediment deformation, as well as concretions and nodules.

Layers of rocks in the park called turbidites are evidence of deposition by submarine landslides. Sole marks, scoured shale remnants, rip-up clasts, graded bases, parallel laminated tops, and load casts record offshore locations where submarine landslides were common. The intense energy of a landslide rips up the existing submarine slope, forming a turbidity current (sediment slurry) which tumbles downslope and is deposited on the edge of the continental shelf. Stacks of turbidites are prominent in the greywacke found in the park. Greywacke is generally gray, compact, fine- to coarse-grained sandstone that consists of poorly sorted, angular to subangular grains of quartz, mica, and feldspar, with a variety of dark rock and mineral fragments embedded in a compact clay-rich matrix. Turbidites occur in the oldest rocks exposed in the park: the Martinsburg formation (Omp, Omr, Omrg, and Omb) (Epstein 1990; Drake 1992).

Sedimentary features also indicate some rocks in the park were deposited in terrestrial, fluvial, and deltaic environments. Coarse-grained deposits characterized by rounded quartz pebbles are evidence of deposition in a high-energy environment such as a fast flowing mountain stream. Red beds (e.g., Bloomsburg Red Beds, Sbcu or Sb) which formed when sediments or rocks containing iron were exposed to oxygen, can also indicate terrestrial deposition. Like today, mudcracks formed in desiccated mud puddles and clearly indicate that the rock was once exposed to dry air (fig. 15). Geologists have used these clues in addition to sedimentary features such as crossbeds, cut-and-fill structures, planar bedding, and channels to infer a nearshore, fluvial to deltaic depositional setting for some rock units in the park. In contrast to the largely marine Martinsburg Formation (Omp, Omr, Omrg, and Omb), the aforementioned features occur in the Shawangunk Formation (Ss, Sst, Ssl, and Ssm), the Bloomsburg Red Beds (Sbcu and Sb), the Rondout and Decker formations (DSrp, DSrd, and Sd), and the Catskill Formation (Dclr, Dcbr, Dcw, Dcs, Dca, Dcd, and Dct), among others, indicating at least intermittent periods of subaerial exposure (Epstein 1973, 1990; Drake et al. 1985; Drake 1992).

In contrast to the coarse-grained, high energy deposits; fine-grained mud and clay settle in lower-energy depositional environments. Prior to the hardening that turns sediment into rock (lithification), soft-sediment deformation can produce load casts, where one layer sinks downward into a less dense layer. In a similar setting, soft sediments may be bioturbated, or churned up by burrowing or benthic marine organisms. Load casts and bioturbated beds appear in the Catskill Formation (Dcbr, Dcs, and Dcd).

Some sedimentary rocks within Delaware Water Gap contain concretions and nodules. A concretion is a hard, compact mass of material formed by the precipitation of "cement" between grains surrounding a nucleus of different material (typically a fossil or other material of different composition). Concretions form within water-saturated, unlithified sediments. They differ from nodules, which replace the bodies of some preexisting substance. Both are often spherical or ovoid, but irregular morphologies can occur. The fine-grained nature of the cement of a nodule or concretion often makes these masses more resistant to weathering than the surrounding sedimentary rock. Concretions and nodules found within Delaware Water Gap include dark iron-rich dolomite nodules in the Catskill Formation (Dclr) and Bloomsburg Red Beds (Sb), quartz-chlorite (chert) nodules and shaly limestone concretions in the Marcellus Shale (Dm and Dmb), brown ironstone concretions in the Palmerton Sandstone (Dpt), and rare collophane (carbonate fluorapatite) nodules in the Shawangunk Formation (Ssl) (Alvord and Drake 1971; Epstein 1973, 1990; Davis et al. 1989). As described in the "Geologic Connections to Park Stories and Resources" section, chert nodules factored prominently in the American Indian history of the area and often contain minerals of economic interest.

Figure 15. Photograph of mudcracks. These polygonal mudcracks are on the Silurian Bossardville Limestone (Sbv), near Haneys Mill (New Jersey). They indicate subaerial exposure on tidal flats. Photograph is figure 132 in Inners and Fleeger (2001).

Taconic Unconformity

An unconformity is a break in the stratigraphic record, where a portion of time is not represented by a layer of rock. Either rocks were never deposited or the rocks have been eroded away. The Taconic Unconformity is a significant break in the stratigraphic record, marking the boundary between Ordovician and Silurian rocks in the Delaware Water Gap area. It is present in the park, but is difficult to see as it is buried beneath a thick pile of boulders (talus) shed from the overlying cliffs of the Shawangunk Formation. The 2012 Field Conference of Pennsylvania Geologists focused on the Taconic

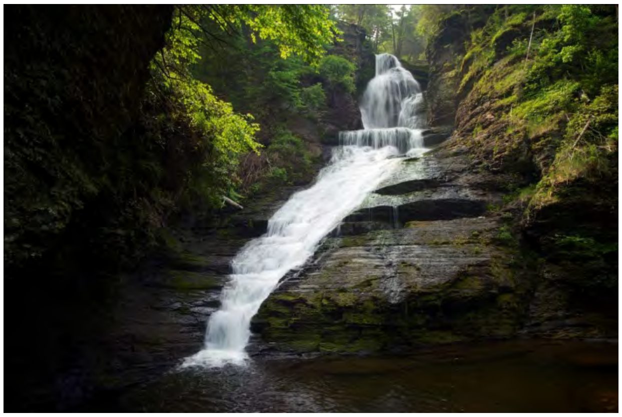

Figure 16. Photograph of Dingmans Falls. Dingmans Falls, the second tallest waterfall in Pennsylvania cascades over siltstone bedrock of the Devonian Mahantango Formation (Dmh). Photograph by Ron Karpilo (Colorado State University).

Unconformity, highlighting associated rocks and features within and surrounding the park (Harper 2012).

The rocks below the unconformity are the Ordovician Martinsburg Formation (Omp, Omr, Omrg, and Omb). They were deposited in a basin just west of the mountain range formed during the Taconic Orogeny, a major mountain-building event of the Paleozoic Era (see "Geologic History" section). During the orogeny, the basin was uplifted, deposition of the Martinsburg Formation ended, and the exposed Martinsburg sediments were eroded. The "Taconic mountains" were also eroding away, creating a thick wedge of sediments deposited at the base of the highlands, as well as off shore. These units consist of coarse-grained, terrestrial deposits of the Shawangunk Formation (Ss, Sst, Ssl, and Ssm). They were deposited unconformably on top of the deformed Martinsburg Formation, forming the distinctive Taconic unconformity (Epstein and Epstein 1969a, 1969b; Epstein 1973; Drake and Monteverde 1992; Epstein 2001c; Epstein and Lyttle 2001).

Waterfalls

The high relief of the park hosts many waterfalls, including the particularly scenic Raymondskill and Dingmans falls (fig. 16)—the two tallest waterfalls in Pennsylvania—and Buttermilk Falls, which is among the tallest in New Jersey. Other waterfalls, including Bushkill Falls (the "Niagara of Pennsylvania") are located near the park. Waterfalls are indicators of geologic change. They record where rock types change from more resistant to less resistant. They also record a river's adjustment to a change in base level or major increase in flow. Over time, waterfalls recede upstream, forming a canyon or gorge, while carving deeper into the resistant bedrock ridge.

Factory, Fulmer (fig. 17), Deer Leap, and Dingmans falls are successive "knickpoints" (sharp changes in channel slope) within the park along Dingmans Creek, west of Dingmans Ferry, Pennsylvania. They were created not by glacial ice but by meltwater erosion during deglaciations (Sevon and Inners 2001). Via quarrying and plucking, the creek cut distinctive and successive notched patterns into the bedrock at the lips of the falls. The "faces" of the falls represent pre ice age knickpoints (Sevon and Inners 2001). The successive notches in the lips formed during high meltwater flow following three or four deglaciations during the Pleistocene.

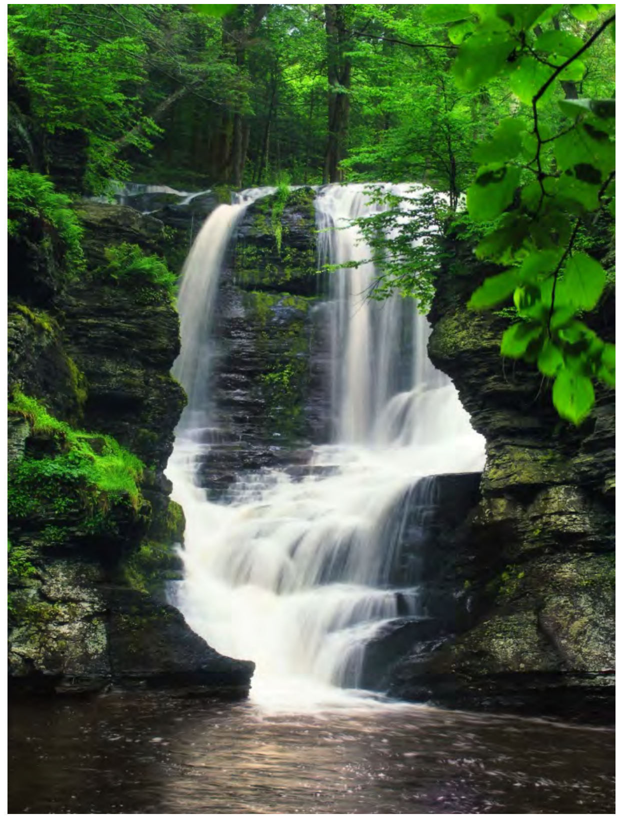

Figure 17. Photograph of Fulmer Falls. At Fulmer Falls, Dingmans Creek flows over sandstones of the Devonian Millrift Member of the Trimmers Rock Formation (Dtm). Photograph by Nicholas A Tonelli (Creative Commons Attribution 2.0 [CC by 2.0] Generic License).

Pinchot, Raymondskill, and Bushkill falls formed in a similar manner (Sevon and Inners 2001). Water exploited a narrow rock fracture (joint) to form Silverthread Falls, also near Dingmans Creek.

Cave and Karst

A cave is an underground open space (natural or artificial), usually with a connection to the surface that is sufficiently large to permit human entry and sufficiently long to extend into darkness. Karst is a type of topography formed on limestone and other soluble rocks, primarily through dissolution. Karst dissolution features include caves and sinkholes. Dissolution occurs when acidic groundwater reacts with carbonate rocks, such as limestone and dolomite, along subterranean cracks and fractures (Toomey 2009). Most meteoric water is slightly acidic (relatively low pH) due to the reaction between atmospheric carbon dioxide (CO_2) and water (H_2O). The product of this reaction is carbonic acid (H_2CO_3). Groundwater may become even more acidic as it flows through decaying plant debris and soils. The acid reacts with calcium carbonate ($CaCO_3$) in the rocks to produce soluble calcium (Ca^{2+}) and bicarbonate (HCO_3^-). The result is the dissolution of limestone rocks, which are considered to be "in solution." Over hundreds of thousands of years, dissolution has occurred between the intergranular pores and along fractures in the limestones of the park, creating increasingly larger voids. Although caves are characteristic of karst topography, Cold Air Cave, described below, is a talus not solutional cave.

Karst is not widespread within Delaware Water Gap National Recreation Area. It is limited to limestone-bearing Silurian to Ordovician bedrock units as well as other rock units containing carbonate minerals or carbonate-cemented sandstone (see Map Unit Properties Table). On the New Jersey side of the park, Witte and Monteverde (2006) described dozens of small sinkholes, sinking streams, springs, and small caves along Wallpack Ridge, mostly within the Devonian Onandaga Limestone (Dou and Db). Dingmans Ferry Spring and Brau Kettle are two springs typical of karst landscape (Witte and Monteverde 2006). All caves and mines are currently (September 2013) closed to public access to minimize the spread of white-nose syndrome (WNS; http://nature.nps.gov/biology/WNS/index.cfm).

No formal karst feature survey or inventory has been completed for the park, although Soto (2013) presents a brief summary of cave and karst resources for the park. A geologist with the Geoscientists-in-the-Parks program revisited previously mapped karst features at 12 sites in the New Jersey portion of the park, including sinkholes, caves, and disappearing streams (Ortiz 2009). A similar survey in the Pennsylvania portion of the park would provide a useful resource management dataset. Potential exists for future discovery of rock shelters and caves, particularly on Kittatinny Mountain and on the park's western side, the Pocono Front.

Toomey (2009) described caves and karst landscapes, as well as methods to inventory and monitor cave-related vital signs. Vital signs are measurable parameters of the overall condition of the cave system and include: 1) cave meteorology (microclimate and cave air composition), 2) airborne sedimentation (dust and lint), 3) direct visitor impacts (breakage of cave formations, trail use in caves, graffiti, cave lighting, etc.), 4) permanent or seasonal ice, 5) cave drip and pool water (drip locations, rate, volume, and water chemistry; microbiology; and temperature), 6) microbiology, 7) stability (breakdown, rockfall, and partings), 8) mineral growth (speleothems such as stalagmites and stalactites), 9) surface expressions and processes (karst processes link the surface to caves through springs, sinkholes, cracks, etc.), 10) regional groundwater levels and quantity, and 11) fluvial processes (underground streams and rivers) (Toomey 2009).

Cold Air Cave

Cold Air Cave is a talus cave, rather than a solution (karst) cave (fig. 18). The cave is an open space formed by large, jumbled sandstone boulders of the Shawangunk Formation ("Ss" map units) that fell from overlying slopes (see the "Slope Movements" section for more information about this process). The cave is capped by large blocks approaching 9 m (30 ft) long and misleadingly appears stable (Epstein 2001b). Talus deposits (Qta) above and around the cave attest to the potential for rockfall during freeze–thaw cycles (Witte and Epstein 2005; Pristas 2007; Epstein 2010b).

Figure 18. Photograph of Cold Air Cave. Cold Air Cave is a talus (not solutional) cave formed by collapsed blocks of Silurian Shawangunk Formation ("Ss" map units). Like all caves and mines in the park, it is closed to minimize spread of white-nose syndrome. Photograph is figure 121 in Inners and Fleeger (2001).

The cave was discovered and named around 1870, when very cold air (temperatures approaching –1°C, approximately 30°F) was reported from an opening in rocks along present-day State Highway 611 (Snyder 1989). The opening, became a tourist attraction during the late 19th and early 20th centuries. The cave may reach up to 21 m (70 ft) in length, although only about 9 m (30 ft) is accessible to adults (Snyder 1989; Epstein 2001b). The cave temperature fluctuates significantly, depending on the direction of air flow. Wind blowing out of the cave is cooler than air blowing in the opposite direction, suggesting that a supply of cold air exists in void spaces throughout the scree system and potentially the bedrock above the cave (Epstein 2010b).

Geologic Connections to Park Stories and Resources

American Indian History

The geology of the Delaware Water Gap area played a significant role in the lives of local American Indian groups. Following the most recent Pleistocene ice-age glacial advance and retreat, American Indians created pathways that followed natural corridors across the landscape (Thompson and Wilshusen 1999). The Gap through rugged Kittatinny Mountain facilitated travel, hunting, and commerce, and provided a strategic path during times of war. The record of human habitation in and surrounding Delaware Water Gap National Recreation Area extends back more than 10,000 years. Habitation sites in the park are found in a variety of settings, including river terraces, islands, and moraines.

Many archeological sites in the valley date to the Late Terminal/Archaic, late Middle Woodland, and Late Woodland cultural periods, such as the Shawnee-Minisink site (charcoal dated at 10,590 and 10,750 years before present) and the upper Shawnee Island site (McNett et al. 1977; McNett 1985; Stewart 1991; Witte 2001). Some of these sites contain fragments of stone tools. Reviews of local stratigraphy and accurate geochemical identification of chert used to make the tools revealed that it was obtained from local sources—the Devonian Helderberg and Oriskany groups (Dhg, Dph, Dp, Dmn, and Dc; and Do, Dr, and Drs, respectively). In addition to other local, chert-bearing units, these two units provided a seemingly inexhaustible supply of chert. They are found in linear exposures oriented along the axis of the Delaware River valley (La Porta 2000; see Geologic Map Graphics).

The word Minisink may be translated as "the land from which water is gone" (Happ 1938) or "stony country" (personal communication from James Rementer in 1989 cited in Grumet 1991; Witte 2001). Archeological studies provide invaluable paleoenvironmental information about the park and surrounding area, including river course history. Stewart (1991) noted that sedimentary sequences representing habitable landforms do not predate 10,000 to 9,000 years before present.

European Settlement and Development

Geologic features and processes gave rise to the modern physiographic features of eastern Pennsylvania that strongly influenced the historical development of the state's culture, economy, and society (Thompson and Wilshusen 1999). Ridges such as Kittatinny Mountain were natural barriers to travel, as evidenced by modern highway patterns throughout the state. As it had for thousands of years previously, the Delaware Water Gap focused the movement of people and goods as European-Americans explored and settled in the area.

Exploration for mineral wealth raised early geologic interest in the area. The Pahaquarry Copper mine, among the earliest in the country, was mined sporadically from the 1750s to the early 20th century, although it was never a profitable enterprise (Monteverde 2001). Today, remnants of the milling plants, boarding house, power house, and two adits (horizontal shafts) are still present in the park (Kopczynski 2004). The disseminated chalcocite (copper sulfide) beds (Sbcu) of the Bloomberg Red Beds were the target of mining activities (Parris et al. 1990). A variety of local legends surround the mine and associated Old Mine Road. Despite a lack of supporting archeological evidence, the most prominent story credits the Dutch with starting mining operations as early as 1614 and constructing the Old Mine Road to haul copper ore from Pahaquarry to Esopus for shipment to Holland (Kopczynski 2004). Old Mine Road features prominently in Revolutionary War history. General Horatio Gates used the road to march his troops to meet General George Washington prior to the crossing of the Delaware River and subsequent victory at Trenton in 1777 (Kopczynski 2004).

Other mineral resources have attracted attention, including sandstone flagstones, red clay, fill material, and sand and gravel deposits. Limestone of the Rondout Formation (DSrd and DSrp) was quarried and burned for agricultural lime, particularly at a lime kiln near Flatbrookville (Parris et al. 1990). Slate quarries and associated mine tailing piles are visible within park boundaries (see "Abandoned Mineral Lands" section; Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Artificial fill and mine dump deposits (Qafl and Qmd) are mapped within the park (Epstein 1990; Witte and Epstein 2005). Although slate is found in many formations (refer to the Map Unit Properties Table), Epstein (1974, 2010b) identified the Ramseyburg Member of the Martinsburg Formation (Omr) as the source targeted in the slate quarries. According the GRI GIS data, gravel pits and borrow pits within the park targeted various glacial gravel deposits (Qtq, Qod, Qoic, and Qg), and shale-chip rubble deposits (Qsr) of the Mahantango Formation (Dmh). Sand and gravel resource potential is summarized on the Map Unit Properties Table. Peat from swamp and marsh deposits (Qs) was mined to a depth of 12 m (40 ft) near Oak Grove (Alvord and Drake 1971).

The spectacular landscape of the Delaware Water Gap and its surrounding natural resources provided an ideal setting for the establishment of a resort community, particularly as people sought respite from the increasingly crowded and industrialized eastern cities in the late 1800s and early 1900s. In 1832, the famous Kittatinny Hotel opened to tourists. By 1856, the Delaware, Lackawanna and Western Railway forged through the Gap, leading to the establishment of 16 other hotels in the village of Delaware Water Gap. The spread of automobile travel and the Great Depression led to the decline of the resort industry surrounding the Gap. Various streams, springs, and seeps also influenced settlement patterns within the Delaware River valley upstream of the Gap. Farmers took advantage of natural water sources, constructing earthen dams and other impoundments to ensure a steady supply of water for agriculture. Many modern ponds within the park date to this period.

Tocks Island Dam

Proposals to build a dam at Tocks Island, less than 10 km (6 mi) upstream of the Gap within what is now the park, began in the 1930s. By 1960, the U.S. Army Corps of Engineers (ACOE) had planned the construction of a dam that would provide flood control, water supply, hydroelectric power, and recreation. In fact, the park's establishment was originally intended to enable the management of recreational opportunities along the reservoir created by the dam. This dam would have impounded a 64-km- (40-mi-) long reservoir, with depths reaching 45 m (150 ft) and a water storage capacity of 950 billion L (250 billion gallons). Congress approved the project in 1962. However, the geologic setting was ultimately deemed unsatisfactory for such a dam due to factors such as the presence of bedding-plane faults and fractures in the Bloomsburg Red Beds (Sb and Sbcu). This assessment and a massive conservationist effort led to the abandonment of the project. Congress finally de-authorized the Tocks Island Dam in 1992. The 1-m- (3- to 4-ft-) diameter cores extracted by the ACOE for geologic study of the site remain visible today near the boreholes.

Ecology and Biodiversity

The park and surrounding area form a transition between the mountainous terrain to the northwest and the more subdued topography of the Piedmont to the southeast; the park lies on the extreme eastern extent of the Pocono (also called Allegheny) Front. The Pocono Front is a geologic boundary between the Valley and Ridge and Appalachian Plateau physiographic provinces (fig. 2). In the Valley and Ridge province, highly deformed bedrock is faulted and folded into long, linear ridges separated by valleys (see "Geologic Map Graphics"). These linear features trend northeast–southwest and are more-or-less parallel to each other. By contrast, the Appalachian Plateaus province is far less deformed, the rocks are gently tilted, and mountain trends are not strongly linear. This transition in geology and landforms is associated with many ecological changes—an excellent interpretive program theme (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

The ecological transitions manifest as myriad habitat types within and surrounding the park. Habitats within the park vary in diversity from dry ridge-top communities supporting prickly pear cactus to wetlands and bogs. In particular, hemlock benches and ravines within the park provide habitat for bird species such as the Acadian flycatcher (*Empidonax virescens*), blue-headed vireo (*Vireo solitarius*), black-throated green warbler (*Dendroica virens*), and Blackburnian warbler (*Dendroica fusca*). Stands of eastern hemlock (*Tsuga canadensis*) thrive in cool, moist, hillside and ravine environments in Delaware Water Gap National Recreation Area (Ross et al. 2001; NPS 2011a. This species thrived in the cooler climates of the Pleistocene ice ages and still exist in isolated areas of the eastern United States where local conditions mimic cooler climates, such as shadowed ravines and north-facing slopes. Hemlock is a forest climax species that has been in decline for the past several decades, likely due to several factors including changing climate and the hemlock woolly adelgid (*Adelges tsugae*) (Ross et al. 2001). The loss of this habitat will affect bird populations in the area; effects on the other terrestrial components of hemlock ecosystems remain to be identified (Ross et al. 2001).

The heights of Kittatinny Mountain are part of a migratory corridor for hawks and other raptors. Neighboring Hawk Mountain, located 72 km (45 mi) southwest of Delaware Water Gap along Kittatinny-Blue Mountain, is part of the proposed Kittatinny-Shawangunk National Raptor Migration Corridor (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). The 400-km- (250-mi-) long corridor, one of the largest migration flyways east of the Mississippi River, crosses parts of New York, Pennsylvania, and New Jersey. Because it crosses through the Valley and Ridge province, it trends northwest–southeast. Ridges along the corridor are supported by erosion-resistant sandstone, quartzite and conglomerate (including Ss, Sst, Ssl, and Ssm). The ridges create strong updrafts and thermal air currents, which enable birds of prey, as well as butterflies and other migrating species, to travel more efficiently. According to the Kittatinny-Shawangunk National Raptor Migration Corridor Project (2011), between 15,000 and 20,000 or more individuals from 16 raptor species are spotted from lookouts atop the forested ridges every autumn. Protected lands along the corridor also serve as breeding areas for migratory songbirds, and cliffs and ridges provide nesting habitats for raptors and owls. The mountain ridges and caves are also habitat for other fauna (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

About 2,600 ha (6,400 ac) of wetland are located within park boundaries. Wetlands occur throughout the park in uplands and valley bottoms, particularly at the bases of slopes and benches (Qp and Qs). Upland wetlands occur on Kittatinny Mountain where glaciers carved hollows and depressions in the bedrock on ridges and side slopes (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Kettle ponds, formed by the melting of isolated blocks of ice after glacial retreat, occur in glacial outwash deposits of the park. These ponds naturally collect organic-rich deposits.

Sheehan and Master (2010) studied the wetlands as part of a 2-year survey of wetland bird species within the park. Wetlands frequently form in depressions and areas underlain by poorly drained soils. Clay-rich tills often form aquitards (layers of poor hydrologic permeability) upon which a wetland may develop. Natural depressions in bedrock may also support wetland development. An investigation of local landscape influences on ambystomatid salamander populations included approximately 90 bodies of water within the park. Factors surveyed included vegetative cover, topography, hydroperiod, and habitat patch isolation (Julian et al. 2001). Vernal pools and other amphibian habitats are located in peat units and swamp and marsh deposits (Qp and Qs, respectively) within the park.

The clay-rich nature of the glacial deposits located throughout the park has likely contributed to an abundance of thin, clay-rich, relatively nutrient-poor soils called fragipans (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

Fragipans are altered horizons or subsurface soil layers that restrict water flow and root penetration, affecting vegetation distribution and land-use history in the park. Refer to the Delaware Water Gap National Recreation Area soil resources inventory (NPS 2011c) for additional details. Units such as alluvium and alluvial fans (Qal and Qaf) are currently accumulating in river and stream corridors and associated riparian zones.

Table 2. Type sections within or near Delaware Water Gap National Recreation Area (continued on next page).

Unit Name (symbol)	Age	Location(s)	Within Park?	Namesake	Reference
Brodhead Creek Member of Marcellus Shale (Dmb)	Middle Devonian	Quarry on north side of Stroudsburg, Hwy 90 along west bank of Brodhead Creek, Monroe County, Pennsylvania	No	Brodhead Creek valley	Willard 1938
Buttermilk Falls Limestone (Db)	Early and Middle Devonian	North side of Godfrey Ridge; various places in vicinity of Stroudsburg; along railroads south of Stroudsburg and nearby quarries	No	Buttermilk Falls on Marshall Creek	Willard 1938 Gray et al. 1960 Rickard 1964 Epstein 1966 Epstein et al. 1974 Monteverde 1992 Repetski et al. 1995 Drake et al. 1996
Foxtown Member of Buttermilk Falls Limestone (Db)	Middle Devonian	Exposures in railroad cut of Erie-Lackawanna Railroad, nearly 1.6 km (1 mi) south of East Stroudsburg Post Office	No	Foxtown Hill on Godfrey Ridge	Epstein 1984
McMichael Member of Buttermilk Falls Limestone (Db)	Middle Devonian	Exposures in railroad cut of Erie-Lackawanna Railroad, nearly 1.6 km (1 mi) south of East Stroudsburg Post Office	No	McMichael Creek north of Godfrey Ridge	Epstein 1984
Stroudsburg Member of Buttermilk Falls Limestone (Db)	Middle Devonian	Exposures in railroad cut of Erie-Lackawanna Railroad, nearly 1.6 km (1 mi) south of East Stroudsburg Post Office	No	Stroudsburg, Pennsylvania	Epstein 1984
Minisink Limestone of Helderberg Group (Dmn, Dph)	Early Devonian	Road cut on southwest side of Interstate 80, 0.3 km (0.4 mi) south of Minisink Hills, Pennsylvania	No	Minisink Hills, Pennsylvania	Epstein and Epstein 1967 Monteverde 1992
Flatbrookville Member of New Scotland Formation (Dmn, Dph)	Early Devonian	In woods and along northeast side of Flatbrookville-Wallpack Center Road, 5.1 km (3.2 mi) from intersection with Trans-Kittatinny Road	Yes	Flatbrookville, New Jersey	Epstein and Epstein 1967
Maskenozha Member of New Scotland Formation (Dmn, Dph)	Early Devonian	In woods and along northeast side of Flatbrookville-Wallpack Center Road, 5.1 km (3.2 mi) from intersection with Trans-Kittatinny Road	Yes	Lake Maskenozha, Pennsylvania	Epstein and Epstein 1967
Depue Limestone Member of Coeymans Formation (Dc)	Early Devonian	Road cut along northwest side of road, 1 km (0.6 mi) southwest of Shawnee on Delaware	No	Island in Delaware River	Epstein and Epstein 1967 Monteverde 1992

Table 2. Type sections within or near Delaware Water Gap National Recreation Area (continued).

Unit Name (symbol)	Age	Location(s)	Within Park?	Namesake	Reference
Peters Valley Member of Coeymans Formation (Dc)	Early Devonian	Road cut along southwest side of Wallpack Ridge, 2.4 km (1.5 mi) northwest of Flatbrookville, New Jersey	Yes	Peters Valley	Epstein and Epstein 1967 Epstein 1987
Shawnee Island Member of Coeymans Formation (Dc)	Early Devonian	Road cut along northwest side of road, 1 km (0.6 mi) southwest of Shawnee, Pennsylvania, on Delaware River	No	Shawnee, Pennsylvania	Epstein and Epstein 1967 Monteverde 1992
Stormville Member of Coeymans Formation (Dc)	Early Devonian	Hartmans Cave near top of Godfrey Ridge, less than 2 km (1 mi) northeast of Stormville, Pennsylvania	No	Stormville, Pennsylvania	White 1882 Epstein 1987
Duttonville Member of Rondout Formation (DSohr, DShr, DSrp, DSrd)	Early Devonian	Abandoned William Nearpass quarry, 2.9 km (1.8 mi) southwest of Duttonville, New Jersey, and 0.8 km (0.5 mi) west of Clove School	No	Duttonville, New Jersey	Epstein and Epstein 1967
Mashipacong Member of Rondout Formation (DSohr, DShr, DSrp, DSrd)	Early Devonian	Abandoned William Nearpass quarry, 2.9 km (1.8 mi) southwest of Duttonville, New Jersey	No	Island in Delaware River	Epstein and Epstein 1967
Poxono Island Formation (Sp)	Late Silurian	Exposures in bluff of Delaware River in Middle Smithfield Township, opposite Poxono Island, Pennsylvania	Yes	Poxono Island	White 1882; Swartz and Swartz 1941 Epstein and Epstein 1967 Epstein 1993
Clove Brook Member of Decker Formation (Sd, DSrd)	Late Silurian	Abandoned William Nearpass quarry, 2.9 km (1.8 mi) southwest of Duttonville, New Jersey	No	Clove Brook	Epstein and Epstein 1967
Wallpack Center Member of Decker Formation (Sd, DSrd)	Late Silurian	Exposures 2 km (1 mi) northeast of Wallpack Center, Sussex County, New Jersey	Yes	Wallpack Center, New Jersey	Epstein and Epstein 1967
Tammany Member of Shawangunk Formation (Sst)	Middle Silurian	Road cut along Interstate 80 in Delaware Water Gap	Yes	Mount Tammany	Epstein and Epstein 1972
Lizard Creek Member of Shawangunk Formation (Ssl)	Middle Silurian	Exposures along abandoned Lehigh and New England Railroad in Lehigh Gap, Pennsylvania	No	Lizard Creek	Epstein and Epstein 1972 Anastasio and Myers 1993
Minsi Member of Shawangunk Formation (Ssm)	Early Silurian	Road cut along Interstate 80 in Delaware Water Gap	Yes	Mount Minsi	Epstein and Epstein 1972; Epstein 1990; Anastasio and Myers 1993

Table 2. Type sections within or near Delaware Water Gap National Recreation Area (continued).

Unit Name (symbol)	Age	Location(s)	Within Park?	Namesake	Reference
Bushkill Member of Martinsburg Formation (Omb)	Middle and Late Ordovician	Outcrops along Bushkill and Little Bushkill creeks in Northampton County, Pennsylvania	Yes	Bushkill and Little Bushkill creeks	Drake and Epstein 1967 Epstein and Lyttle 1987 Parris et al. 1987
Ramseyburg Member of Martinsburg Formation (Omr)	Middle and Late Ordovician	Outcrops along U.S. Highway 46 and Erie-Lackawanna Railroad near Ramseyburg, Warren County, New Jersey	No	Ramseyburg, New Jersey	Drake and Epstein 1967 Epstein and Lyttle 1987 Parris et al 1987
Pen Argyl Member of Martinsburg Formation (Omp)	Late Ordovician	Slate quarries in and near Pen Argyl, Northampton County, Pennsylvania	No	Pen Argyl, Pennsylvania	Behre 1926; Drake and Epstein 1967 Fisher 1977; Parris et al. 1987
High Point Member of Martinsburg Formation (Omhp)	Late Ordovician	Exposures at High Point State Park and south along New Jersey Route 23 to Colesville, Sussex County, New Jersey	No	High Point State Park	Drake 1991

Geologic Issues

Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical or policy assistance.

During the 2001 scoping meeting and 2011 conference call, the following geologic resource management issues were identified:

- Slope movements
- River channel migration and flooding
- Marcellus Shale gas extraction
- Corridor construction projects
- Micro-hydro power and geothermal development
- Abandoned mineral lands
- Farm ponds and dams
- Paleontological resource management
- Recreational use
- Seismic hazards
- Surface water and groundwater quality and quantity

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Slope Movements

Slope movement (or "mass wasting") refers to any downslope movement of rock, weathered rock material (regolith), or soil (fig. 19) under the influence of gravity. Steep slopes, which are particularly susceptible to mass-wasting events, characterize the valley along the Delaware River and throughout the park. Slope movements are a natural process to be expected in the park's landscape. However they are of particular concern where steep slopes intersect park roads or trails. Such infrastructure may also increase the likelihood for slope movements where construction has altered the natural slope.

According to Epstein (2001a) and park staff, four types of slope movement occur in the Delaware Water Gap National Recreation Area: 1) landslides of soil and glacial till on glaciated and polished bedrock surfaces, 2) rockfalls and rockslides originating along fractures that parallel roads, and 3) debris flows in glacial till. Park staff identified 4) slumps as an additional issue. Some rockfalls, rockslides, and debris flows are indicated in the digital geologic (GIS) data for the park (see the "Geologic Map Data" section), as extracted from Pallis and Marzulli (2006). Slope movement potential for different map units is detailed on the Map Unit Properties Table. Refer to Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), and http://landslides.usgs.gov/ for detailed information regarding slope movements, monitoring, and mitigation options.

Landslides

Landslides (also called landslips or soil slips) occur in the park where soil, glacial till, blocks of sandstone or a combination of these materials overlie glacially polished bedrock (Epstein 2001a). A good example of this type of failure occurred as a soil slip along the south bank of the Delaware River near Sambo Island in October 1995 (fig. 20). A thin veneer of soil and glacial till on top of the northwest tilted Bloomsburg Red Beds (geologic map units Sbcu and Sb) became saturated following heavy rains and slid downhill. The slide covered a total length of 180 m (600 ft) and extended an additional 18 m (60 ft) into the Delaware River.

Epstein (2001a) identified the factors that made this area prone to instability:

- Slopes steeper than 30 degrees
- Soil or glacial till on top of glacially polished bedrock
- Tree roots that do not penetrate bedrock
- Water seeping along the soil-bedrock boundary
- Toe removal by natural processes (e.g., cut-bank erosion along the outer bend of stream meanders) or human activities (e.g., road construction at the base of steep slopes)
- The presence of tension cracks.

Similar geologic settings occur throughout the park and could indicate areas susceptible to landslides (Epstein 2001a).

Rockfalls and Rockslides

Rockfalls and rockslides have occurred in the park where fractured bedrock is exposed on slopes. Fractures are cracks in rock and can be classified as joints or faults. Joints are fractures where the rock has cracked but not moved along the fracture surface. Faults are fractures where rocks have moved (a few millimeters to many kilometers) along the fracture surface. Joints and faults are both planes of weakness and may act as failure surfaces during rockfalls and rockslides. Rockfalls and rockslides have caused roadway and vehicular damage in the park (Pallis and Marzulli 2006). Cold Air Cave (see "Cave and Karst" section) is actually a void between large sandstone boulders that fell from the cliffs above.

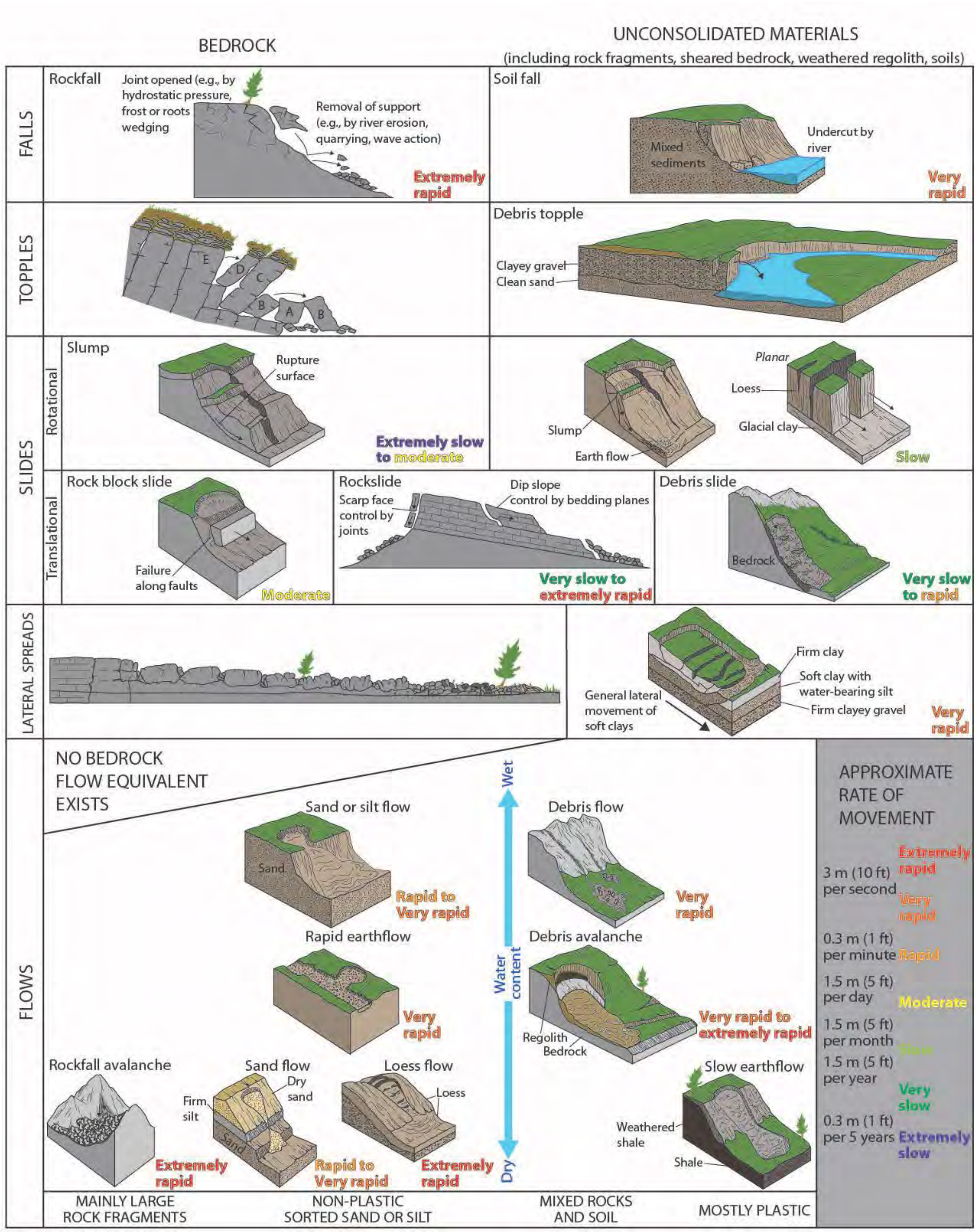

Figure 19. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978).

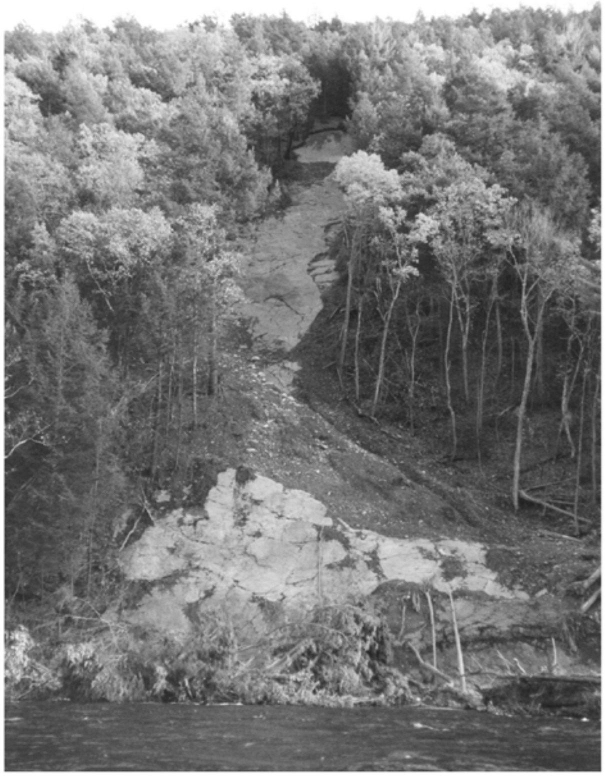

Figure 20. Photograph of Sambo Island landslide. This slide is typical for areas where occur in the park where relatively unconsolidated soil, glacial till, blocks of sandstone or a combination of these materials overlie glacially polished ("slippery") bedrock. Epstein (2001a) mapped an area southwest of this slide where future slides could occur. Photograph is figure 68 from Epstein (2001a).

This section examines the nature of the joints and faults in the Delaware Water Gap area, identifies how they contribute to rockfall and rockslide susceptibility, and discusses recommendations to avoid and mitigate these hazards.

Joints are a type of brittle deformation where the rock masses on either side of the fracture have not been displaced relative to one another. They frequently occur in sets within solid, hard, folded rocks as a result of compression and tension associated with movements of the earth's crust. They are widespread in the anticlines and synclines of Valley and Ridge bedrock. Joints may also form as a result of exfoliation. Exfoliation occurs where rivers (or other processes) have eroded or removed surface material, reducing pressure on the previously buried rocks, which subsequently crack. There are two types of joints common in the park (Epstein 2001a), cross joints and longitudinal joints ("sheeting") (fig. 21).

Cross joints cut across mountain ridges at right angles. In the park they are steep and irregular surfaces oriented northwest to southeast. Water gaps can develop where streams flow into cross joints and carve valleys. Gap formation by eroding streams reduces the confining pressure on cross joints which allows the rock masses to move outward and become a rockfall hazard (Epstein 2001a). This process also occurs where roads are

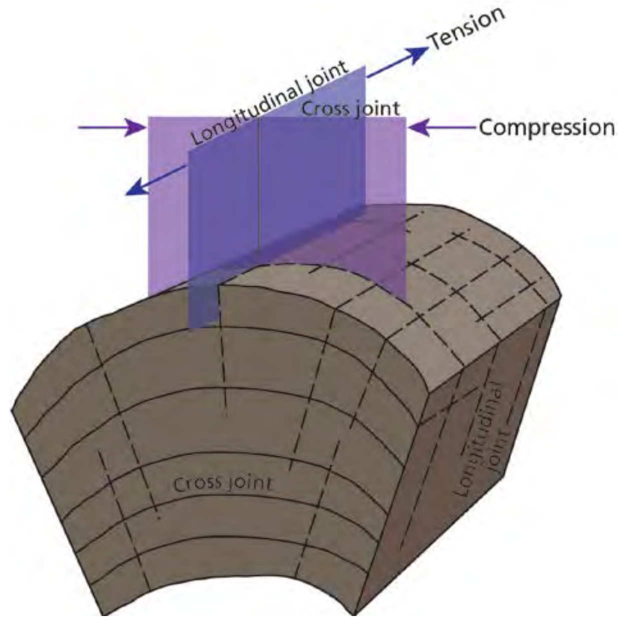

Figure 21. Schematic illustration of cross joints and longitudinal joints (also called "sheeting") in a fold. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted from Epstein (2001a).

constructed perpendicular to mountain ridges. A rockfall of this nature in the Bloomsburg Red Beds occurred 300 m (1,000 ft) north of Delaware Water Gap (Epstein 2001a).

The same setting of cross joints is encountered at Lehigh Gap, 47 km (29 mi) southwest of Delaware Water Gap. A geotechnical evaluation conducted by the U.S. Geological Survey determined that there was potential for rapid failure of large amounts of rock (Epstein 2001a). The rockfall hazard was mitigated by removal of large blocks from the fractured Shawangunk rocks and by construction of a gabion to prevent erosion and spalling (Epstein 2001a). Similar strategies could be employed to mitigate rockfall hazards elsewhere within the park. The Bloomsburg Red Beds and the Shawangunk Formation, which are both present in the park, have the potential to produce rockfalls (Epstein 2001a).

Longitudinal joints form parallel to mountain ridges. In the park they are steep, planar surfaces oriented perpendicular to cross joints. Longitudinal joints may act as failure surfaces for rockslides where the Delaware River or a road runs parallel to the mountain ridges (Epstein 2001a). If the longitudinal joints are steeply inclined toward the river or roadway any activity which removes the toe of the slope may trigger a rockslide (Epstein 2001a) (fig. 22). Removal of the toe of the slope may occur naturally from river erosion or by excavation related to construction projects. Rockslides have occurred where the Old Mine Road parallels longitudinal joints near the crest of an anticline opposite Tocks Island (fig. 23) (Epstein 2001a).

Faults along bedding planes may also act as failure surfaces for rockslides in much the same way as

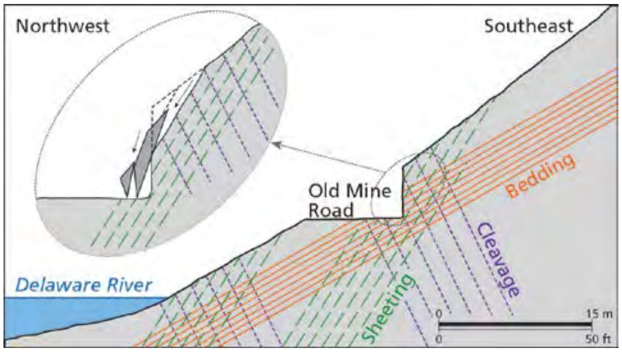

Figure 22. Schematic illustration of rockslide potential along longitudinal joints triggered by removal of the toe of the slope. The road cut along Old Mine Road across from Tocks Island is steeper than the dip of the joints making the areas susceptible to rock falls along the joints. Note that closer to the river the slope is shallower than the dip of the joints, meaning there is little likelihood for rock fall in that area. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted from Epstein (2001a).

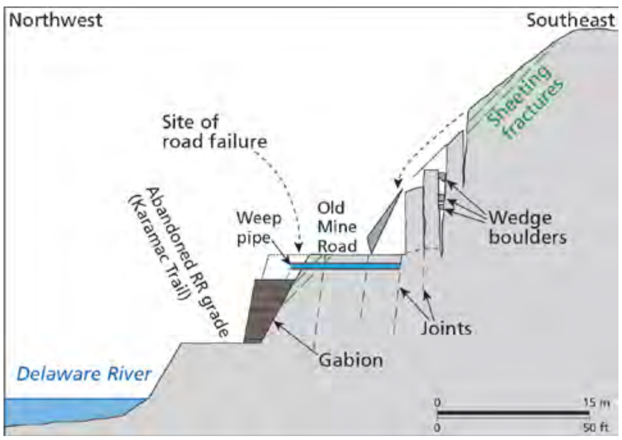

Figure 23. Schematic illustration of rockfall hazards produced by exposed cross joint surfaces along Old Mine Road in Worthington State Park (New Jersey). Sheeting fractures are longitudinal joints (fig. 21). Joints and sheeting fractures beneath the road probably contributed to the collapse in the middle 20th century. A gabion (a retaining wall constructed of stacked wire mesh or concrete berm "baskets" filled with rock aggregate) was installed to support the road after the collapse. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted from Epstein (2001a).

longitudinal joints. However, bedding plane faults are even more likely to produce rockslides because they are also zones of weathering and groundwater flow. During evaluation for the proposed dam near Tocks Island, the Army Corps of Engineers (ACOE) conducted stress tests on bedding plane faults exposed along Old Mine Road. They concluded that there was little to no strength across the faults and if the toe of the slope were to be removed during dam construction the entire uphill mass of uphill rock would slide downhill along the fault plane. There are many of these zones in the Bloomsburg Red Beds within the park and sites should be analyzed for their presence prior to initiation of construction activities.

Debris Flows

Debris flows are moving masses of mud, sand, soil, rock, water, and air that travel or "flow" downslope under the influence of gravity. Debris flows are very fast moving, particularly on steep slopes, where they can reach speeds of more than 160 km (100 mi) per hour. Areas of glacial till (primarily surficial Qot, Qtq, Qtk, and Qit) are particularly prone to debris flows as those deposits are commonly unconsolidated (Epstein 2001a). Because glacial till occurs throughout much of the park, debris flows are possible wherever the base of a steep slope is excavated (Epstein 2001a). Debris flows can be triggered by heavy rain and flooding, and can threaten bridges and other infrastructure near rivers within the park (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). One debris flow mapped in till (Qtk) underlain by Bloomsburg Red Beds (Sb) bedrock along Sambo Island Brook moved nearly 1,400 m^3 (1,800 yd^3) of material in October 1995 due to "weathering." In 1996, in a narrow tributary valley in the Pocono Plateau on the east side of Brodhead Road, a debris flow formed in rain-saturated glacial till along a road cut.

Slumps

A slump occurs when material moves and rotates downslope along a curved (concave up) failure surface. Slumps can occur slowly (moving over years) or quickly (minutes). Areas of steep topography and unconsolidated deposits (Qac, Qsr, Qokt, and Qmt are just a few examples) are susceptible to slumping. Toward the southern end of the park, near the Gap, fine-grained deposits within tributary valleys are being eroded away, undercutting the river banks and causing slumps (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). At least one fossil locality, part of a shale-rich geologic unit, is threatened by slumping in the park (see the "Paleontological Resource Management" section).

Heavy precipitation events can exacerbate slumping. In August and September 2011, Hurricane Irene and Tropical Storm Lee caused slumping and significant damage to many park roadways and visitor-use areas. A dirt section of Old Mine Road in New Jersey near Van Campen Inn was closed after the collapse of a historic stone culvert due to a slump and a landslide in highly erodible material.

Slope Movements and Rivers

Slope movements along the park's rivers and tributaries are a common and typically natural process, which becomes a concern for resource managers when park infrastructure or visitor safety is threatened. As described in the "River Channel Migration and Flooding" section, many roads—the park contains more than 320 km (200 mi) of maintained roads—are undercut by eroding streams. Streams have flooded more often in the past decade due to increased precipitation and severe storms. The undercutting of roads is more commonly an issue than rockfall on top of them (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). For example, heavy rains associated with Hurricane Irene and Tropical Storm Lee in 2011 undermined the asphalt surface and eroded the shoulders of Blue Mountain Lakes Road by up to 1 m (4 ft) in some stretches. A section of U.S. Route 209 (between mileposts 14.8 and 15.3) collapsed in October

Figure 24. Photograph of slump along U.S. 209. Near mile marker 15, portions of the road collapsed in October 2011 as the slope was undercut by the Delaware River. National Park Service photograph courtesy Leslie Morlock (Delaware Water Gap NRA).

2011 as a result of a landslide along a steep slope, which was caused by undercutting of the Delaware River (fig. 24). The slide may have been accelerated by erosion due to storms and earthquakes felt at the park in August 2011 (see "Seismic Hazards" section) (NPS 2012a). However some roads, including Interstate 80, are vulnerable to both.

Declining forest cover (particularly hemlock), coupled with high water events associated with an increase in storms, exacerbates erosion and increases susceptibility to slope movements. Landslides, in turn contribute to additional forest decline.

Monitoring and Mitigation

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: 1) types of landslide, 2) landslide causes and triggers, 3) geologic materials in landslides, 4) measurement of landslide movement, and 5) assessment of landslide hazards and risks. Their publication provides guidance in the use of vital signs and monitoring methodology.

Epstein (2001a) suggested that an adequate geologic database and understanding of the following factors could help to avoid or mitigate slope-failure hazards: slope declivity, shallow soils with tree roots that do not penetrate the underlying bedrock, polished glaciated bedrock surfaces beneath thin regolith, relation of joint and cleavage orientation to roads, and the presence of glacial till on steep slopes.

Park efforts to curb further slope scour and stabilize slopes include installation of limited shoreline armoring and revegetating slopes. Such efforts have been initiated along Dingmans Creek (Kara Deutsch, acting chief, Resource Management & Science Division, Delaware Water Gap NRA, written communication, 24 August 2012). In 2012, park staff submitted technical assistance

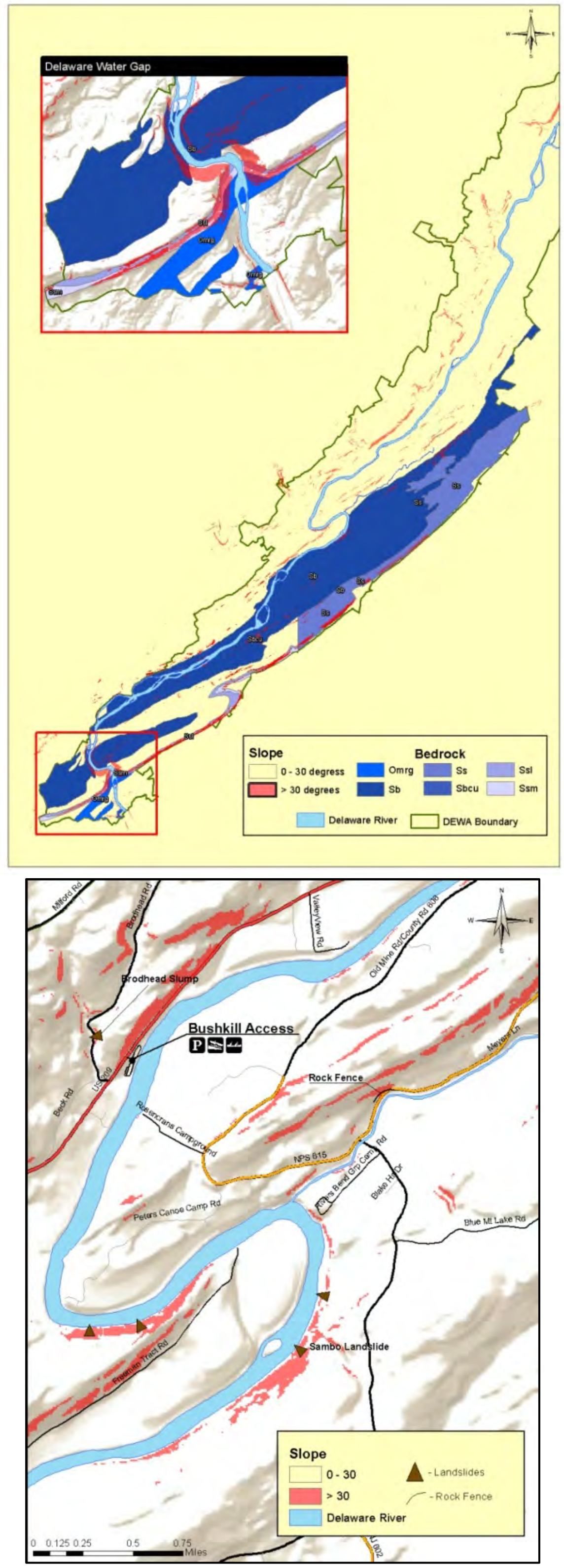

Figure 25. Maps of high slope areas indicating potential for slope movements. Slopes steeper than 30 degrees are particularly vulnerable to slope movements. The upper map shows such areas park-wide with an inset for the area around the Gap. The lower map is of the Walpack Bend area and shows the location of landslides and rock fencing. Maps by Alexander Colón (2012 Geoscientist-In-the-Park)

requests and a Geoscientist-in-the-Parks proposal to examine slope movements along valleys and tributaries. The mapping of hazard areas will be a component of these projects (fig. 25). Final products from the Geoscientist-in-the-Parks project are forthcoming as of March 2013. The GRD geologic hazards program is available to provide technical assistance and guidance regarding slope movements in the park.

The mitigation of slope hazards often involves stabilization with structures such as gabions (retaining walls constructed of stacked wire mesh or concrete berm "baskets" filled with rock aggregate), rock fences, or mesh. Gabions were emplaced at the site of an early-1980s rockfall that removed part of the west side of Old Mine Road (northeast of where I-80 crosses the Delaware River) and at a till debris flow on the east side of Brodhead Road northeast of Bushkill, Pennsylvania (Epstein 2001a).

The New Jersey Department of Transportation proposed a rockfall hazard mitigation project in Delaware Water Gap National Recreation Area to install fences, mesh, and other stabilization structures on slopes above I-80, an area of well-known rockfall hazards. This type of project could negatively impact park viewsheds. The project is a high priority for the state of New Jersey and park staff is closely monitoring the progress of the proposal and providing input during the comment period (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

River Channel Migration and Flooding

The Delaware Water Gap and the fluvial system, including the Delaware River and its tributaries, are major features of the park landscape. Channel migration and flooding are natural processes that have occurred throughout history at Delaware Water Gap National Recreation Area. The Delaware River flows between two topographic highs—Kittatinny Mountain and the Pocono Plateau. In the ridge and valley topography, typical of the region, travel was (and still is) easiest in valleys. Therefore, narrow valleys of many of the park's tributaries contain roads and streams in close proximity, increasing the potential for infrastructure damage when channels migrate or flood (fig. 26). Streams naturally migrate or meander across valley floors. Riparian zones and in-stream habitats, including tree islands, gravel bars, sand bars, and bedrock riffles, also shift. Forest decline and vegetation changes (due to invasive insects and climate change) are correlated strongly with channel instability (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

High gradients and high flow create high-energy streams. High energy streams are capable of increased erosion, deposition, debris jams, and gravel bars where slopes flatten upon meeting the valley floor (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Roads adjacent to high-flowing streams are undercut or become "asphalt river channels" (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). A variety of

Figure 26. Photograph of repairs to U.S. 209 bridge over Raymondskill Creek. River channel migration and flooding are natural processes that impact infrastructure along or crossing the rivers. Note eroded and slumped banks along the creek. National Park Service photograph courtesy Leslie Morlock (Delaware Water Gap NRA).

Flooding can occur on any river or stream in the park; although destructive to infrastructure, flooding also naturally enriches floodplain soils through the deposition of river silt. Major floods are a natural part of the river's history and have been recorded at the park since the 1950s. Flooding occurs seasonally and in response to massive storm events, such as hurricanes or tropical storms. Above-average precipitation has recently become "normal." According to the park website, three 100-year floods in 2004, 2005, and 2006 (called "Ivan the Terrible," "The Spring Flood," and "Strike Three," respectively) damaged archeological sites, undercut roads, caused rivers to abandon old channels, and eroded riverbank sites. Annual precipitation in 2010 (the most recent data available) averaged above the long-term mean for the 10th consecutive year at the Blue Mountain Lakes and Loch Lomond monitoring stations within park boundaries (Knight et al. 2011). Measured precipitation in 2010 at Matamoras, just upstream of the park, was on average 106% of the 30-year normal (Knight et al. 2011). In 2011, two major storm systems, Hurricane Irene and Tropical Storm Lee, caused major flooding along many of the park's waterways, washing away bridges, eroding roads and trails, and causing significant damage to visitor use facilities (subsequent slope movements and damage are described in the "Slope Movements" section).

Lord et al. (2009) provided an overview of river and stream dynamics, identified potential triggers of channel instability, and described methods for the monitoring of streams and rivers. Stream channel morphology is influenced by complex relationships between regional geology, climate, topographic gradient, drainage basin history, river history, and sediment load. Channel instability is manifested as significant changes in channel bed elevation, cross-sectional morphology, and channel patterns. Vital signs, a subset of fluvial system characteristics that can be monitored to provide information about the condition and trends of a system, include: 1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), 2) hydrology (frequency, magnitude, and duration of stream flow rates), 3) sediment transport (rates, modes, sources, and types of sediment), 4) channel cross section, 5) channel planform, and 6) channel longitudinal profile.

Marcellus Shale Gas Extraction

Approximately 35 units of the National Park System in New York, Pennsylvania, West Virginia, Ohio, Virginia, Maryland, and Tennessee contain or are near the Marcellus Shale (Dh, Dm, Dmb, and Dmsu) (fig. 27; Moss 2009). Delaware Water Gap National Recreation Area is near the eastern edge of the Marcellus. Hydraulic fracturing technology ("fracking") enables the extraction of natural gas from the Marcellus Shale. As of 2011, this Devonian, shale-rich unit may contain an estimated 2.4 trillion m^3 (84 trillion ft^3) of technically recoverable, undiscovered natural gas and 3.4 billion barrels of natural gas liquids (Coleman et al. 2011). Using those numbers, the Marcellus gas resource may be large enough to supply the natural gas needs of the United States for more than 3.5 years. Other estimates vary.

In the upper portions of the Upper Delaware Basin (surrounding the Upper Delaware Scenic and Recreational River upstream of Delaware Water Gap National Recreation Area) and the upper basins of some tributaries (upstream and upslope of the park), the Marcellus Shale is being test-well drilled for natural gas extraction. Current drilling surrounding the Upper Delaware Scenic and Recreational River was on hold at the time of report writing due to a moratorium until the finalization of drilling regulations set forth by the Delaware River Basin Commission (DRBC) (Leslie Morlock, GIS coordinator, Delaware Water Gap NRA, written communication, 24 August 2012). The DRBC website (http://www.nj.gov/drbc/programs/natural/) posts the most current information regarding regulation decisions.

Natural gas–producing shale units do not occur in a geologic setting that would be viable for gas extraction within the park. The main issue for the park is its proximity to potential extraction activities. Modern drilling methods require vast amounts of water to facilitate horizontal drilling. Extraction of water resources may eventually impact flow through the park. This "frac water" includes natural gas, brine, and chemicals added to facilitate extraction (DRBC 2012).

Distribution pipelines in various locations are being expanded toward the park. Speculation for high quantities of gas production has led to increased interest in the expansion of gas transmission projects in the area. Current projects that cross the park include the Columbia Gas pipeline upgrade project and the proposed Tennessee Gas Northeast Expansion project (under review) (Leslie Morlock, GIS coordinator, Delaware Water Gap NRA, written communication, 24 August 2012). Regional drilling and the accompanying human presence has the potential to impact water quality and quantity (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

Other proximity resource concerns include air quality degradation, increased noise, viewshed and scenic intrusions, and visitor safety.

Another shale unit, the Middle Ordovician Utica Shale, has potential for natural gas production. This unit is buried several hundred meters beneath the Marcellus Shale. According to the Ohio Division of Geological Survey (2012), the thickness and geographical extent of the Utica Shale indicate that it may have significant oil and gas potential. Drilling and permit activity for the Utica Shale have reached record highs in eastern Ohio. Interest is expected to spread into western and northwestern Pennsylvania.

The GRD is available to provide the park with policy and technical assistance regarding minerals and energy issues. Recommendations include remaining aware of public and private mineral ownership and speculation, exploration, or drilling activity on lands in the park's vicinity. Regulations and permit procedures vary among states. Moss (2009) provided a quick reference to key provisions from state drilling and production regulations governing the development of the Marcellus Shale. The GRD advises contacting state agencies regarding potential permits and other oil and gas activity (Moss 2009).

Figure 27. Map of National Park System units and approximate extent of Marcellus Shale (orange area). The dashed line indicates the extent of other Devonian-aged shales. NPS units atop or near the Marcellus Shale are labeled. Green dots and areas denote other NPS units. Map by Trista Thornberry-Ehrlich (Colorado State University) with information from Moss (2009) and Soeder and Kappel (2009). National Park Service base map available http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=nps (accessed 18 September 2013).

Large Scale Corridor Construction Projects

Energy transmission or other corridor construction projects have been initiated (and will likely continue to be proposed) within or adjacent to the park. A wide variety of natural resource concerns stem from the construction and associated increases in traffic and access which accompany such projects. If the proposed project is predicted to significantly affect the quality of the environment, an Environmental Impact Statement (EIS, such as NPS 2012b) must be completed to describe the environmental effects and list alternative actions.

Possible impacts include the loss or degradation of significant geologic resources and features, as well as slope destabilization. Significant geologic features (type sections, sedimentary structures, paleontological resources) could be impacted through direct damage from excavation or via increased access. Increased access facilitates vandalism or unauthorized collecting. Slope destabilization would exacerbate the potential for slope movements such as landslides, rockfall, and slumps (see "Slope Movements" section). If a proposed project requires blasting, the potential to trigger slope movements should be assessed.

In additional to direct impacts to geologic resources, habitat dependent on particular resource characteristics may also be affected. For example, blasting may alter bedrock fractures that are key habitat for species such as the timber rattlesnake, although the potential and extent of such alteration is not well understood. Additional concerns relate to habitats with particularly strong hydrogeologic connections, including acidic broadleaf swamps, acidic cliff habitats, calcareous fens, circumneutral-pH broadleaf swamps, forested wetlands, hemlock forests, palustrine emergent wetlands, rocky summit outcrops, scrub shrub wetlands, and talus slopes (e.g., NPS 2012b).

Floods are a major resource management issue within the park, and the location of access roads could impact floodplain processes. In addition, clearing of vegetation could increase erosion and sediment loads in local waterways, which in turn would alter stream channel morphology.

The Susquehanna to Roseland 500 kilovolt (kV) transmission line is one example of a major corridor construction project. The project will increase the capacity of an existing energy transmission corridor stretching 6.9 km (4.3 mi) through the park. The project calls for the existing right-of-way (created more than 85 years ago, prior to the establishment of the park) to be widened and new, taller towers to be installed. In order to support this installation, canopy vegetation will be cleared and access roads, culverts, concrete crane pads, and temporary staging areas will be constructed. Blasting, drilling, and large excavations will be required. The NPS released a Final Environmental Impact Statement (EIS) in August 2012 (NPS 2012b) for the Susquehanna to Roseland project. The EIS outlines impacts to geologic resources and specifically mentions the need to minimize impacts to geologic resources, including fossils, unique or rare geologic features, and different habitats associated with various geologic features.

Measures taken to restore disturbed lands, including those associated with proposed transmission line construction may not have substantial effects for decades. For example, based on reclamation activities following the establishment of the park, the restoration of roads prisms to natural conditions could take up to 50 years. Reduced rainfall interception and increased erosion resulting from clearing of woody vegetation to maintain the right-of-way, and the resultant adverse impacts on soils, geology, and geomorphology, will continue in perpetuity.

Micro-Hydro Power and Geothermal Development

The U.S. Department of Energy identified streams within Delaware Water Gap National Recreation Area appropriate for the development of micro-hydro power, the harnessing of hydropower to generate electricity without the use of large dams or reservoirs (Department of Energy 2011; Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). The streams have high flows and hydraulic heads, making them ideal for renewable hydroelectric power generation. The main change in elevation head occurs outside of the park, but the streams of interest do cross parklands. The Delaware River's wild and scenic status should protect streams within the boundary from energy development (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

Although no surficial geothermal feature occurs within the park or surrounding area, park staff is exploring geothermal energy development for infrastructure use. A ground-source heat pump is present at the Zimmerman Farm main house (a historic structure) (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

Abandoned Mineral Lands

Mining and quarrying in the area that would later become Delaware Water Gap National Recreation Area extends back at least to the 1750s. One mine in the park, the Pahaquarry mine, may have been the first copper mine in the United States. Several other quarries and sand and gravel pits are also located within what is now the park (e.g., Epstein 1974).

According to the NPS Abandoned Mineral Lands (AML) database (accessed 13 May 2013) and Burghardt et al. (2013), the park contains 56 AML features at 38 sites. The features within Delaware Water Gap NRA include adits, prospects, shafts, structures, surface mines, tunnels, waste rock piles, and a well.

AML features present a variety of resource management issues including: visitor/staff safety, environmental quality (air, water, soil), and habitat (NPS 2011b). AML features can also provide habitat for bats and other animals. Resource management of AML features first requires accurate inventory and reporting. All AML features should be recorded in the AML database (contact GRD for assistance). Human safety hazards may be mitigated and features may be closed, reclaimed, or restored as appropriate. AML features also present opportunities for interpretation as cultural resources. Three AML features within the park have already been mitigated and three additional features at two sites are in need of mitigation and classified as high priority (Burghardt et al. 2013). For additional information refer to the NPS AML Program website: http://nature.nps.gov/geology/aml/index.cfm.

Pahaquarry Copper Mine

The origins of the Pahaquarry copper mine are the subject of lore; one story credits a Dutch operation of the 1600s with the construction of the 167-km- (104-mi-) long Old Mine Road (Kopczynski 2004). Although the mine operated sporadically in three different centuries, it was never economically viable. The mine is located within the Bloomsburg Red Beds and targeted diffuse copper in the disseminated chalcocite beds (Sbcu) of that unit. Monteverde (2001) described the mine's geologic setting and mining history. According to the AML database, visitors occasionally access the site, and loose rocks at portals and rocks continue to scale off the adit walls. Wooden bulkheads have been compromised. During the 1990s, the NPS Geologic Resources Division conducted site visits to the mine and provided recommendations for resource management. Bat gates have been installed with assistance of the Bureau of Mines. In 2011, more secure gates were installed to prevent human access (Kara Deutsch, acting chief, Resource Management & Science Division, Delaware Water Gap NRA, written communication, 24 August 2012). No further reclamation is planned and the site is not interpreted (Leslie Morlock, GIS coordinator, Delaware Water Gap NRA, written communication, 24 August 2012).

Sand and Gravel Pits and Slate Quarries

Sand and gravel pits and slate quarries comprise the vast majority of AML features within the park, and some are listed on the Map Unit Properties Table. The building stone (slate) quarries have not been reclaimed or restored (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). These abandoned quarry areas are mostly isolated from the public and not interpreted at this time (Kara Deutsch, acting chief, Resource Management & Science Division, Delaware Water Gap NRA, written communication, 24 August 2012).

Farm Ponds and Dams

Disturbed lands within the park include several small-scale stream impoundments. Most of these "farm ponds" were constructed by homesteaders to provide reliable domestic and agricultural water supplies. Others were landscape enhancements to create lakefront property prior to the establishment of the park. The park maintains some of these dams and others will be deactivated and removed; some will not be actively managed. To date, most dam removal has been completed by park staff and the Bureau of Reclamation. Repairs to existing dams were contracted to experts (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011; Jeffrey Shreiner, biologist, Delaware Water Gap NRA, written communication, 24 August 2012).

Paleontological Resource Management

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act. Regulations associated with the Act are still (September 2013) being developed. The abundance, diversity, and significance of paleontological resources varies widely within Delaware Water Gap National Recreation Area. In turn, appropriate management techniques also vary widely from site-to-site. A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Contact the Geologic Resources Division for assistance.

Although a park-specific survey has not yet been completed, there are a variety of publications and resources that provide park-specific or NPS-general information and paleontological resource management guidance. See also Appendix B.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: 1) erosion (geologic factors), 2) erosion (climatic factors), 3) catastrophic geohazards, 4) hydrology/bathymetry, and 5) human access/public use. All of these are potential issues within Delaware Water Gap National Recreation Area.

Parris and Albright (1979a, 1979b), Parris et al. (1990), Parris and Cruikshank (1984) prepared reports and a road log for the Delaware Water Gap region which names specific areas in the park that provide excellent opportunities for paleontological interpretation.

A geologist with the Geoscientists-in-the-Parks program surveyed paleontological sites in the park, contrasting their current conditions to those detailed by Dave Parris in the 1970s. Monitoring involved evaluation of the degree of human disturbance, bedrock fragility, fossil abundance, and site accessibility (Ortiz 2009). Most sites were in good condition; however, mass wasting at one site along a road cut is washing fossil resources into the road. Samples from the wash are now housed in the park collection (Ortiz 2009). A technical assistance request has been submitted to the NPS Geologic Resources Division to evaluate the site. As of September 2013, the request is still pending. A fossil-site ranking study found no evidence of theft and only natural erosion of exposures (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Unauthorized fossil collecting is assumed to occur because knowledge of paleontological resources in the park and adjacent areas is widespread. However, collecting is difficult to identify and control on exposures such as talus deposits, slate quarries, and tailing piles.

There are opportunities to develop interpretive programs about the paleontological resources in the park. A strong starting point could be with the Pocono Environmental Education Center which maintains a 2 km (1.25 mi) "Fossil Trail" featuring fossiliferous bedrock exposures.

Recreational Use

Recreational use impacts soil and vegetation at Delaware Water Gap National Recreation Area. Marion and Cole (1996) studied the effects of camping on soils and vegetation. They found that trampling associated with camping results in the loss of organic soils, decreases vegetation diversity, and compacts soils. Lowland campsites were found to lose more ground vegetation, but retain more organic soil, than upland sites with similar levels of use. Low-elevation sites are frequently flooded, which renews their fertile soils. Marion and Cole (1996) suggested the location of campsites on durable sites (lowland areas under open forest canopy), the use of temporary closures to allow system recovery, and concentrating areas of use and impact to a small number of high-use campsites.

Erosion is exacerbated where thin glacial till can be entirely removed along steep hiking trails, thereby exposing glacially smoothed/slippery bedrock, especially on the slopes east of the Delaware River (Jack Epstein, geologist, U.S. Geological Survey, written communication, 6 June 2012). User-created trails, or "social trails" are another park concern. In many locations, visitors create trails (such as steps dug into riverbanks) to access the river. Off-trail use by hikers, off-road vehicles, bikers, and horses is another concern. These users damage vegetation and soils, particularly near the Delaware River and tributary streams (Kara Deutsch, acting chief, Resource Management & Science Division, Delaware Water Gap NRA, written communication, 24 August 2012).

Seismic Hazards

Earthquakes are not commonly felt in New Jersey and Pennsylvania. The largest earthquake on record in either state was approximately magnitude 5.3 in late 1783. Nevertheless, earthquakes centered elsewhere have been felt within the park and impacted park resources.

A magnitude 5.8 earthquake struck central Virginia on 23 August 2011. Shaking from this event was felt across the east coast, including Delaware Water Gap National Recreation Area. Although no park infrastructure was damaged during the 2011 earthquake, shaking associated with the event may have "hydrolyzed" a slump along Highway 209 near milepost 15. Prior to the earthquake, significant precipitation saturated the deposits on slopes above the road. Further precipitation from Hurricane Irene in the days following the earthquake exacerbated the slide. The road was closed and park staff worked with the Federal Highway Administration to determine the cause of the slump and possible stabilization actions (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011; NPS 2012a). Undercutting along the outside curve of the Delaware River was determined to be a major cause of the slumping (Jack Epstein, geologist, U.S. Geological Survey, written communication, 6 June 2012).

Seismic monitoring data can be used for many purposes, such as to determine the frequency of earthquake activity, evaluate earthquake risk, interpret the geologic and tectonic activity of an area, and provide an effective vehicle for public information and education (Braile 2009). In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: 1) monitoring earthquakes, 2) analysis and statistics of earthquake activity, 3) analysis of historical and prehistoric earthquake activity, 4) earthquake risk estimation, 5) geodetic monitoring and ground deformation, and 6) geomorphic and geologic indications of active tectonics.

Surface Water and Groundwater Quality and Quantity

In the moist climate of the eastern United States, abundant runoff water flows in streams, rivers, springs, and into ponds, eventually percolating down into surficial and bedrock aquifers, such as those in Delaware Water Gap National Recreation Area. A variety of resource management issues are associated with water quality, stream flow, channel morphology, sediment loading, ponds, lakes, streams, and wetlands. Those with geologic components are mentioned here. Park staff is interested in the creation of a GIS-based watershed model to gain an understanding of the amount and quality of existing groundwater, sites of emergence, and geologic controls on groundwater dynamics (GRI scoping notes 2001; Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Contact the NPS Water Resources Division (http://nature.nps.gov/water/) for guidance and technical assistance regarding water issues.

A U.S. Geological Survey study determined that geologic features and processes, land use, and the presence of wastewater facilities affect water quality in the park (Hickman and Fischer 2008). The study found correlations between acres of wetland within a basin to turbidity and concentrations of nitrogen and phosphorous in through-flowing streams (Hickman and Fischer 2008). Total nitrogen and phosphorous increased, and the water became more "colored," with increased wetland area and natural increases in organic debris. Types of bedrock can also play a role in water chemistry. Naturally, rainwater is mildly acidic; this acidity is exacerbated by air pollution and can be buffered by the neutralizing ability of soluble rocks. Limestone, a source of bicarbonate ions, is one such soluble rock. Rock types such as quartzite and granite lack this buffering capability. Buffering accounted for elevated pH, high specific conductance (ability to conduct an electric current), dissolved calcium, and acid-neutralizing capacity in Little Flat Brook, Sand Hill Creek, and Shimers Brook, all of which flow over or through carbonate rocks (e.g., Sbv, DSrd, Dmn, Do, and Db are particularly rich in limestone and/or dolomite) (Epstein 1973; Hickman and Fischer 2008).

Most of the drainage basin area for the park's many stream tributaries is located beyond park boundaries; only the lowermost portions of the basins are within the park. Thus, up-basin development and land cover patterns impact water quality and hydrology in the park. Population is increasing in surrounding counties, and growth is predicted to continue (Cho 1995; Hickman and Fischer 2008). As described in the "Marcellus Shale Gas Extraction" section, drilling for Marcellus Shale gas in adjacent lands poses a potential water quantity and/or quality threat (Moss 2009; Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Increased development could threaten water quality in the park, in part by impacting the hydrogeologic system of the up-drainage basins. Cho (1995) presented techniques for the application of GIS-based water quality system models to issues related to water quality in Delaware Water Gap National Recreation Area. The GRI digital geologic map data accompanying this report may provide geologic context to support hydrogeologic system research, modeling, and monitoring.

Aquifers within the park and surrounding area fall into two broad types: surficial aquifers and fractured bedrock aquifers (NJGS 2012). Surficial aquifers within unconsolidated glacial and fluvial deposits at the park can be valuable reservoirs for groundwater. Because of their high permeability and close proximity to the surface, they may be more susceptible to contamination and water quality issues than deeper, fractured bedrock aquifers. During the present regime of high precipitation, park resource managers are not significantly concerned about groundwater quantity, but that could change during future regional droughts, such as those in 1998, 1999, and 2003 (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

At the 2001 scoping meeting, park staff expressed the need for a watershed model and maps to quantify precipitation percolating through the ground and contributing to the regional aquifer. Scoping participants identified the following datasets as useful to this effort:

- Borehole or well-log data for stratigraphic correlation.
- Pump test analyses to determine hydraulic properties of aquifers, aquitards and aquicludes, specified in terms of horizontal and vertical conductivity and confined and unconfined storage coefficients.
- Lithological classification at several geo-referenced well sites to serve as a foundation for the geological interpretation of unsaturated and saturated zones.
- Geophysical data to help in deriving the electromagnetic resistance values of the local lithology.
- Groundwater abstraction data and groundwater head observations from monitoring wells collected on a monthly basis.

The New Jersey Geological Survey (NJGS) maintains a compilation database of hydrologic properties of geologic materials, located at: http://www.state.nj.us/dep/njgs/geodata/dgs02-1.htm. This effort is ongoing as further data are collected. Compiled data include analyses of aquifer pumping tests, in-situ hydrologic testing such as slug injection and removal tests, and lab permeameter tests. The NJGS also has GPS coordinates for municipal well locations in and near the park (GRI scoping notes 2001). Potential applications of a groundwater model include the prediction of hydrologic impacts of groundwater extraction, analysis of the sustainable yield of water supply wells, and determination of the rate of movement of groundwater contaminants through aquifers (NJGS 2012).

According to Martin (2009), a park-specific monitoring plan is not needed; local monitoring is probably sufficient where contamination is suspected.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Delaware Water Gap National Recreation Area, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history reflected in rocks in and around Delaware Water Gap National Recreation Area spans from between 1 and 1.6 billion years ago to the present (fig. 3). The oldest rocks on the geologic map are Proterozoic metamorphic rocks more than 1 billion years old associated with the Grenville Orogeny (mountain-building event) and the assembly of the supercontinent Rodinia. The history recorded in rocks of the park includes a series of orogenies that led to the formation of the Appalachian Mountains and the assembly of the supercontinent Pangaea hundreds of millions of years ago. Much more recently, during the ice ages (within the past 2 million years), glacial ice sculpted the landscape. Today rivers and streams continue to shape the land.

Proterozoic Eon (2,500 to 542 Million Years Ago): Ancient Mountain Building and Iapetus Ocean Formation

The Middle Proterozoic rocks of northwestern New Jersey were deformed and metamorphosed by tectonic forces responsible for the mountain-building event called the Grenville Orogeny. The Grenville Orogeny, which occurred more than 1 billion years ago, was part of a global series of events that lead to the assembly of the supercontinent Rodinia. Middle Proterozoic rocks are exposed in the Reading Prong-New Jersey Highlands outside of the park and include predominantly metasedimentary amphibolite, gneiss, marble, granite, and venite (geologic map units Ya, Ylo, Yk, Yg, Ymr, and Yv; Drake and Lyttle 1985; Hozik 1990). The granites of the Byram Intrusive Suite (Yba and Ybh) were emplaced during the metamorphism of the Grenville Orogeny (Drake and Lyttle 1985).

Approximately 590 million years ago, continental rifting in the area began to break up Rodinia, leaving behind the subcontinent Laurentia (proto-North America) on the western side of the rift. As rifting progressed, an ocean basin opened that eventually became the Iapetus Ocean.

Paleozoic Era (542 to 251 Million Years Ago): Appalachian Mountain Building and the Assembly of Pangaea

At the dawn of the Paleozoic Era, continued rifting and subsidence established a marine basin where sediments were deposited for approximately 100 million years (Hozik 1990; Doolan 1996). The ancient coastline of eastern Pennsylvania was blanketed with deposits of beach and tidal-flat sands (later metamorphosed into quartzite such as the Hardyston Quartzite [Ch]), which are not exposed within the park. This deposition coincided with the opening of the Iapetus Ocean adjacent to the North American continental margin (Drake and Lyttle 1985). Other marine deposits included carbonates (e.g., limestone and dolomite of the Leithsville Formation [Cl]) deposited in shallow- to deep-marine environments (Drake and Lyttle 1985). The deposition of carbonates continued into the Ordovician Period as part of a well-developed, east-facing, Cambrian–Ordovician shallow ocean platform adjacent to the continent that is recorded in carbonate rocks, including the Allentown Dolomite, Stonehenge Formation, Beekmantown Group, and Sequence at Wantage (OCa, Os, Obu, Obl, Oe, Or, and Ow) (Drake et al. 1985; Drake 1992; Drake and Monteverde 1992; Pristas 2004).

During the Cambrian and Ordovician, the Iapetus Ocean began to shrink as tectonic forces pushed continents together. Subduction zones within the basin fueled volcanic island arcs. The oldest rocks extensively exposed in the park, the Ramseyburg Member of the Middle Ordovician Martinsburg Formation (Omr; the older Bushkill Member [Omb] appears in two very small locations in the extreme southeastern corner of the park), were deposited in a rapidly subsiding foreland basin (figs. 28 and 29A) during the early stages of the Taconic Orogeny (Epstein 1973, 1990; Hozik 1990; Jack Epstein, geologist, U.S. Geological Survey, written communication, 6 June 2012). The Martinsburg sediments covered the muddy carbonate rocks of the Jacksonburg Limestone (Oj and Ojl), one of the last units deposited on the Cambrian–Ordovician carbonate bank (Drake and Monteverde 1992; Epstein 2001c). The source area for Martinsburg sediments was Appalachia to the southeast. As the basin deepened, deep-sea sediments and sediments from underwater mass-wasting events (turbidites) accumulated. The deepest part of the basin was located where northeastern Pennsylvania is today (Epstein 2001c).

The Taconic Orogeny began during the Ordovician Period, approximately 488 to 440 million years ago. In general, this orogeny involved the collision of one or more volcanic arcs with the eastern margin of the North American continent, the subduction of oceanic crust, and the eventual closing of the Iapetus Ocean, a predecessor to the Atlantic Ocean. The timing, extent, and exact nature of these collisions are actively debated and the subject of much study. Ocean basin sediments were disrupted and, in some cases, transported long distances (tens of kilometers) to the west by thrust faults. Volcanic arcs formed above subduction zones and fragments of crust that formed elsewhere (terranes) were accreted to the eastern margin of North America. As a result of accretion, the eastern margin of the continent

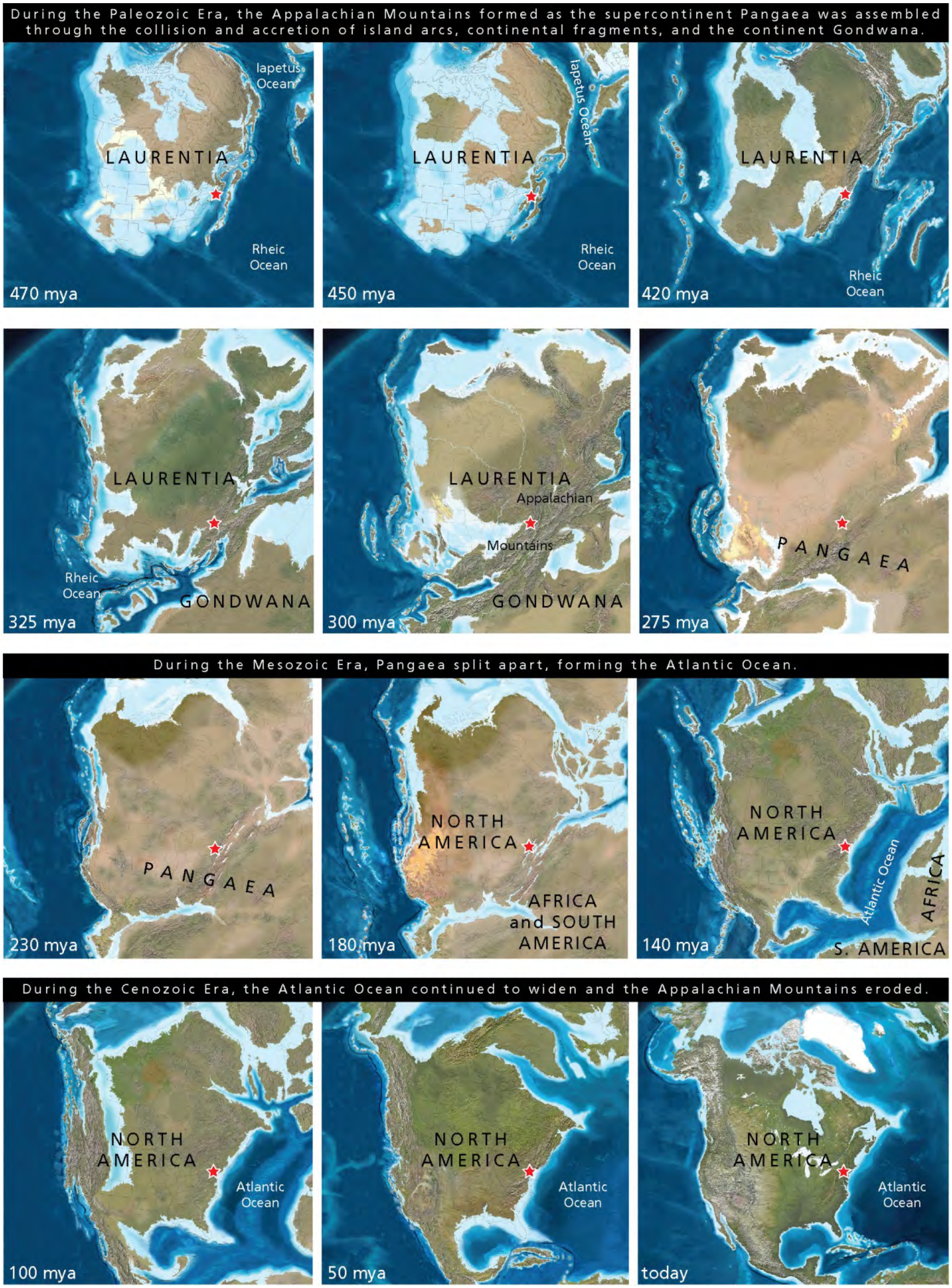

Figure 28. Paleogeographic maps of North America. The bedrock geologic units of Delaware Water Gap National Recreation Area and the surrounding area are tied to the intense deformation and intrusion of molten material during the formation of the Appalachian Mountains during several Paleozoic orogenies. Pangaea began to split apart during the Mesozoic and the Appalachian Mountains began to erode. Today, the Atlantic Ocean continues to widen and erosion has exposed the core of the Appalachian Mountains. Red stars indicate approximate location of Delaware Water Gap National Recreation Area. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/paleomaps.html (accessed 18 September 2013).

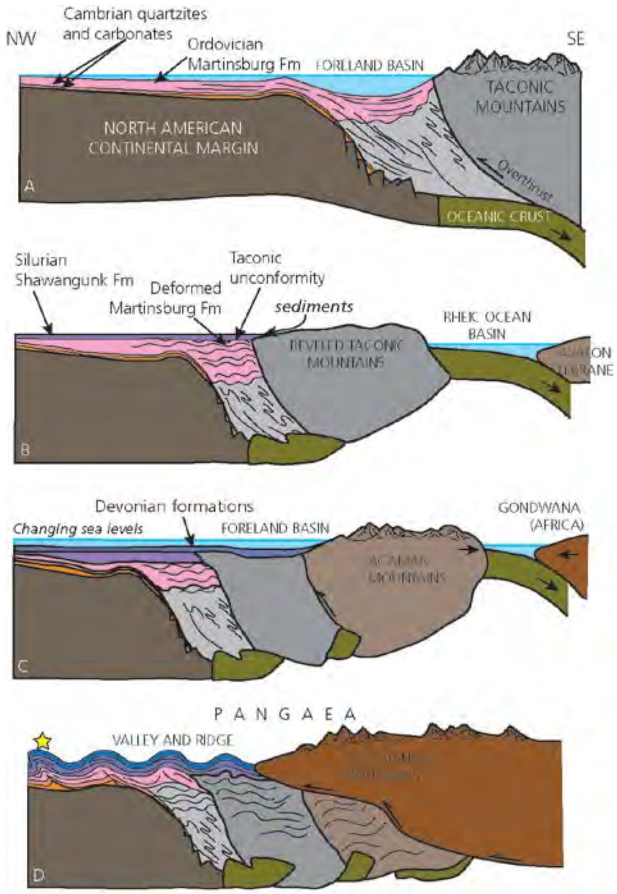

Figure 29. Schematic illustration of tectonic evolution during the Paleozoic. This graphic spans the time period from the Ordovician deposition of the Martinsburg Formation through the Alleghany Orogeny. Star represents the approximate location of the park on the western edge of the Valley and Ridge province. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Epstein (2010b) and after Fichter and Baedke (2000).

shifted further eastward and a mountain range developed.

Tectonic uplift and rapid deposition of the Martinsburg Formation (Omp, Omhp, Omr, Omrg, and Omb) in the Ordovician foreland basin reduced its depth. The Martinsburg Formation was folded and faulted during the complex deformation of the Taconic Orogeny (Epstein and Lyttle 2001). The former foreland basin area was lifted above sea level during the Late Ordovician and then eroded (Epstein 2001c).

At the end of the Taconic Orogeny around 440 million years ago, a range of mountains stood along the east coast of North America. As the range eroded, a thick wedge of sediments was deposited on land and offshore. These lowest Silurian sediments consisting of coarse-grained, terrestrial deposits became the Shawangunk Formation (Ss, Sst, Ssl, and Ssm). They were deposited unconformably (discontinuously) on top of the deformed Martinsburg Formation, marking the Taconic unconformity (fig. 29B) (Epstein and Epstein 1969a, 1969b; Epstein 1973, 2001c; Drake and Monteverde 1992; Epstein and Lyttle 2001). Quartz, chert, and quartzite pebbles in this formation indicate that the source material was older than the Martinsburg sediments, possibly comprising chert from the Beekmantown Group (Obu, Obl, Oe, and Or), quartzite from the Hardyston Quartzite (Ch), and/or vein quartz from Precambrian rocks (Epstein 2001c).

These deposits accumulated in a nearshore fluvial environment. As erosion of the highlands progressed and the mountains were lowered, the energy of the rivers diminished and sedimentation became finer grained. Thus, the high-energy braided streams which produced the Shawangunk Formation transitioned to lower-energy, meandering streams that deposited the Silurian Bloomsburg Red Beds (Sb) (Epstein 2001c, 2006). Invertebrate burrows in the Bloomsburg Red Beds support this hypothesis and mudcracks reveal periods of desiccation where, in some areas, water flow ceased completely (Alvord and Drake 1971; Epstein 1990, 2001c).

During the late Silurian and continuing into the Devonian, seas advanced over the land, as recorded by the clay-rich carbonate rocks of the Poxono Island Formation (Sp) and Bossardville Limestone (Sbv). Later in the Devonian, during the deposition of the Oriskany Group (Do), the area was near sea level and the depositional environments reflected in the rock units are a complex mix of supratidal and intertidal flats, barrier bars, and subtidal zones (Epstein 1990, 2001c).

Following the deposition of the Oriskany Group, as relative sea level lowered, the shoreline migrated to the northwest and the area was exposed and subjected to erosion. Subsequently, sea level rose and moderate to deep water conditions returned. This progression is recorded by the accumulation of the limestone, clay, and silt of the Esopus Formation (De and Dse) and lower Schoharie Formation (Ds and Dse) (Alvord and Drake 1971; Epstein 1973, 1990, 2001c). Marine shallowing (regression) followed, and the Onondaga Limestone (Dou and Db) was deposited (Epstein 1973, 2001c).

Black, pyritic shales of the Marcellus Shale (Dh, Dm, Dmb, and Dmsu) then accumulated in an anoxic (depleted of dissolved oxygen) basin below active wave base. The anoxic setting facilitated the burial of organic-rich sediments that would become the natural gas and petroleum products extracted throughout the northeast (Moss 2008). The Hamilton Group-Mahantango Formation (Dmhc, Dmhn, Dmu, and Dmh), deposited atop the Marcellus Shale, is coarser grained with diverse fossil fauna, indicating a return to shallow marine conditions and increased water circulation (Alvord and Drake 1971; Epstein 1973, 1990, 2001c). A series of volcanic tuffs in the Marcellus Shale and Onondaga Limestone signal the onset of the next episode of tectonic activity along the eastern margin of North America (Epstein 1990, 2001c).

By the Middle Devonian Period, about 375 million years ago, landmasses were converging again along the eastern seaboard of ancient North America and the Rheic oceanic basin was rapidly shrinking (Doolan 1996).

These processes marked the onset of the Acadian Orogeny. The Acadian orogeny produced folds, faults, and igneous intrusions to the northeast (Epstein and Lyttle 2001) and did not deform rocks as far southwest as the park. However, the Acadian Orogeny did uplift mountains in the area of the park and affected the sedimentary system recorded in the Devonian units. Siltstone and sandstone of the Trimmers Rock Formation (Dtr, Dtm, and Dtsb) record the transition between marine conditions and the advancing Catskill deltaic system (fig. 29C) (Alvord and Drake 1971; Davis et al. 1989; Epstein 1990, 2001c).

The Catskill Formation ("Dc" map units) was deposited in a delta that migrated northwestward with corresponding shoreline shifts as highlands rose to the southeast (Alvord and Drake 1971; Davis et al. 1989; Epstein 1990, 2001c). This Acadian mountain chain was similar to the source area that supplied sediments to the Shawangunk Formation during the Silurian following the Taconic Orogeny (Hozik 1990; Epstein 2001c). The Catskill Formation is the last Paleozoic unit preserved in the area surrounding the park. Younger Paleozoic rocks were eroded away from the Middle Delaware River valley region and adjacent Pocono Plateau (Epstein 2001c).

Later in the Paleozoic, approximately 315 to 295 million years ago, the African continent collided with the North American continent during the Alleghany Orogeny. This collision deformed rocks within and surrounding the park, including the Martinsburg Formation and underlying units, overprinting deformation that occurred in the earlier Taconic Orogeny. The structures that formed during the Alleghany Orogeny typically trend northeast, in contrast to the north-trending structures associated with the Taconic Orogeny (Epstein and Lyttle 2001). The folds visible in the Delaware Water Gap today formed during the Alleghany Orogeny and likely contributed to the creation of an area of weakness (kink) in the rocks that would become the Gap millions of years later as the result of river activity (Epstein 2010b). At the culmination of the Alleghany Orogeny, Pennsylvania and New Jersey were located in the core of the supercontinent Pangaea, comprised of nearly all continental crust in existence (figs. 28 and 29D). Extensional forces began to pull Pangaea apart at the dawn of the Mesozoic Era.

Mesozoic Era (251 to 65.5 Million Years Ago): Pangaea Separation, Atlantic Ocean Formation, and Appalachian Mountain Erosion

During the Triassic and Jurassic periods, rifting pulled what would become Africa and South America apart from North America, forming a basin that is now the still-widening Atlantic Ocean. The rifting created many fault-bounded extensional basins along eastern North America. Steeply dipping normal faults formed the boundaries of these basins, which quickly filled with sediment eroded from the surrounding highlands. Triassic "red beds" found throughout the northeast and mid-Atlantic indicate the presence of these basins.

Cenozoic Era (the Past 65.5 Million Years): Gap Formation, Ice Age Glaciation, and Appalachian Mountain Erosion

Following Mesozoic rifting, the area including Pennsylvania and New Jersey became relatively passive. Erosion began to wear away the massive Appalachian Mountains, which had reached their maximum elevation, possibly rivaling today's Himalayas. Erosion-resistant units such as the Shawangunk Formation (Ss, Sst, Ssl, and Ssm) formed high ridges, whereas softer, less-resistant units underlay adjacent valleys. High-energy, eastward-flowing streams carved valleys on the steep gradients of the new mountains and were responsible for more erosion than gentler-gradient streams (lower energy and erosion potential) that flowed toward the continental interior (Epstein 2006). As rifting and opening of the Atlantic Ocean continued, the original divide of the Appalachian Mountains, which was likely to the east of the park within the Piedmont or Valley and Ridge province, began to migrate westward towards its present position in the Appalachian Plateau (Epstein 2006).

As streams migrated further inland due to headward erosion, they encountered resistant mountain ridges, such as Kittatinny Mountain. Wind and water gaps formed through the Kittatinny and Blue mountains at sites of structural weakness (Epstein 2006). Over time, a south-flowing river whose headwaters were around the Trenton area eroded northward toward the Delaware Water Gap area. Simultaneously, southeastward-flowing streams across Kittatinny Mountain began eroding through the ridge. Through a process of stream capture, the two stream systems merged and began to flow through the Gap as described in the "Gap Formation" section (fig. 6).

During the Pleistocene Epoch (about 2 million to 20,000 years ago) thick sheets of ice repeatedly advanced (ice ages) and retreated over the park landscape, with long-lasting effects on the landscape. The maximum extent of ice during the most recent glacial advance occurred between about 26,000 and 18,000 years ago when the Laurentide Ice Sheet extended from the Arctic to 4 km (2 mi) south of the park boundary (fig. 9) (Witte 2001; Witte and Epstein 2005; Pristas 2007). Evidence of glaciation and ice movement is present as various glacial deposits, which reach up to 75 m (250 ft) thick and mantle much of the park's landscape. The "Surficial Units" GIS data layer for the park includes many glacial deposits and features and the "Glacial Deposits and Features" section of the report includes additional detail.

As glacial ice retreated from the Middle Delaware River valley area, massive amounts of meltwater were released and large lakes, including Lake Sciota, formed (geologic map units Qd and Qod; fig. 9) (Epstein 2006; Witte 2001; Witte and Epstein 2005). As the glacier retreated, glaciolacustrine deposits were covered with more valley-train sediments (figs. 30 and 31) (Witte 2001). Numerous lakes, many in kettles, formed as a result of glacial activity, making the Pocono area a remarkable attraction (Epstein 2006).

The park and surrounding area were devoid of stabilizing vegetation after the glacial ice receded. Wind sweeping across the landscape picked up fine particles and deposited them in dunes (Qed) and other eolian deposits (Qe) (Witte and Epstein 2005; Pristas 2007). Within the park, noted loess deposits and sand sheets occur on the eastern side of the river valley toward the southern end of the park (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011).

Pleistocene glaciers disrupted regional drainage of the Delaware River and its tributaries, displaced stream divides, and partly or completely buried stream valleys, forcing streams to forge new channels (Epstein 1969). After the glaciers melted away from eastern Pennsylvania and northwestern New Jersey, local rivers incised channels through the glacial sediments and the Delaware River system transitioned from a braided stream to a meandering river (Witte 2001; also see Bitting 2008). Alluvial terraces (exposed or buried; Qst, Qst2, and Qst3) perched above the modern floodplain record a postglacial history of incision and episodic floodplain deposition punctuated by periods of land stability and soil formation (figs. 31 and 32) (Witte 2001; Witte and Epstein 2005; Pristas 2007). Controls on the early development of the Delaware River system included 1) a decrease in overall flow due to the continued retreat of the Laurentide ice sheet from the area, 2) regional tilting of the landscape due to isostatic rebound (massive glaciers depressed the land surface; as they melted, the land “rebounded”), and 3) an overall reduction in sediment supply due to revegetation of the landscape (Witte 2001). The geomorphology of the park is still evolving. Erosion continually subdues the topography at Delaware Water Gap National Recreation Area. Peat (Qp), swamp and marsh deposits (Qs), alluvium (Qal, Qaoo, and Qac), and alluvial fan deposits (Qaf) accumulated throughout the Holocene and continue to develop within the fluvial and wetland systems of the park (Fisher et al. 1970; Davis 1989; Epstein 1990; Witte and Epstein 2005; Pristas 2007). Near the Gap, tributaries deposit fine-grained particles that can be windblown (Delaware Water Gap NRA natural resource staff, conference call, 16 November 2011). Active erosion and mass-wasting processes in steep areas result in slope-related deposits, including shale-chip rubble (Qsr), colluvium (Qac), boulder accumulations (Qba), and talus deposits (Qta) (Davis 1989; Witte and Epstein 2005). Soils continue to develop on the landscape and have been mapped as part of the NPS Soil Resources Inventory (NPS 2011c). Human activities have also affected the geologic landscape of the park and surrounding area. Mappable geologic units such as artificial fill and mine dump deposits (Qafl and Qmd) reflect extensive use (Epstein 1973, 1990; Davis 1989; Witte and Epstein 2005). Slate dumps may rise locally more than 30 m (100 ft) above surrounding surfaces near slate quarries in the Martinsburg Formation (Omp, Omhp, Omr, Omrg, and Omb) (Epstein 1969). The history of slate mining and location of slate quarries in the park may be obtained

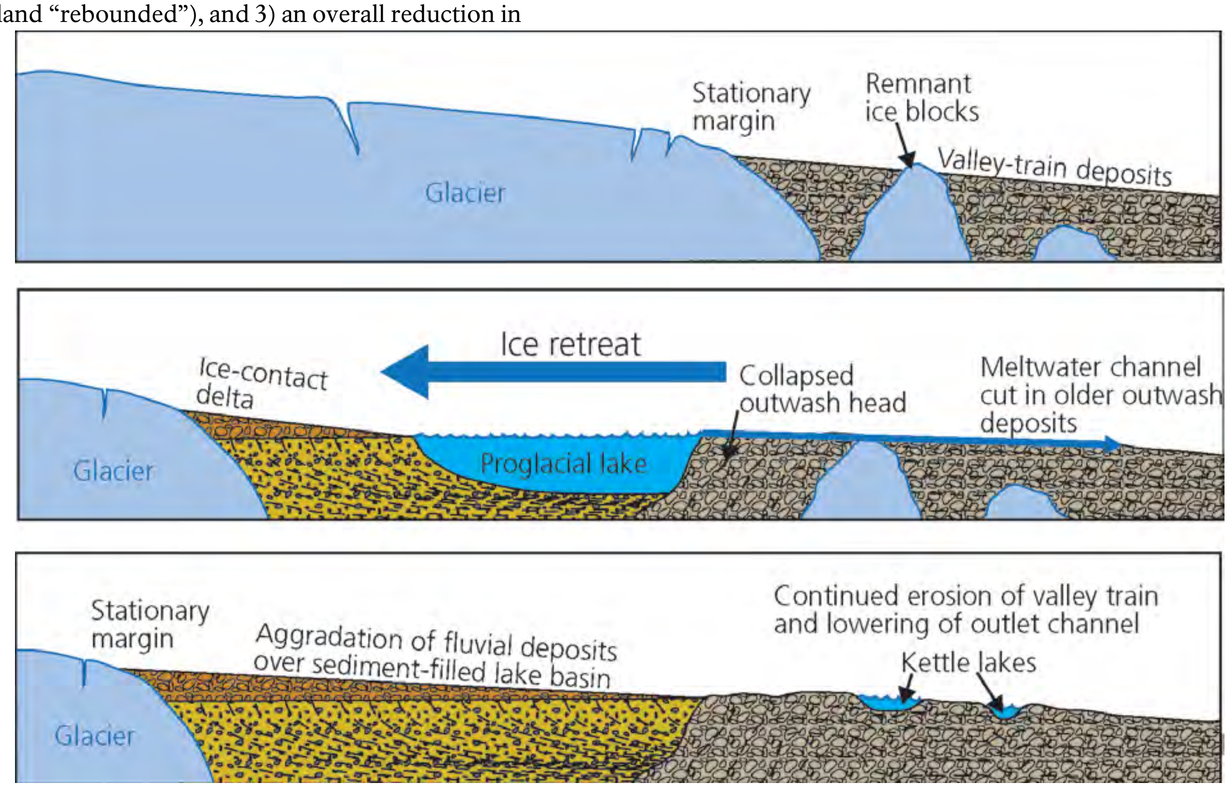

Figure 30. Schematic graphic of deglaciation and sedimentation in a narrow valley. Graphic shows the progression of glacial sediments deposited as the glacier continued to retreat. Adjacent valley-train (e.g., geologic map unit Qv), glaciolacustrine (Qod), and deltaic deposits (Qd) are typical in the rock record of the park. Numerous kettle lakes are also attractions throughout the Poconos region. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 125 in Epstein (2001b).

from Epstein (1974) and references therein. Abandoned sand and gravel quarry operations occur in a variety of sorted deposits throughout the park (Epstein 1969). A geologic history of colliding land masses, mountain building, ocean basin formation and destruction, and continental glaciation shaped a landscape that has long attracted people to its geologic resources and spectacular scenery.

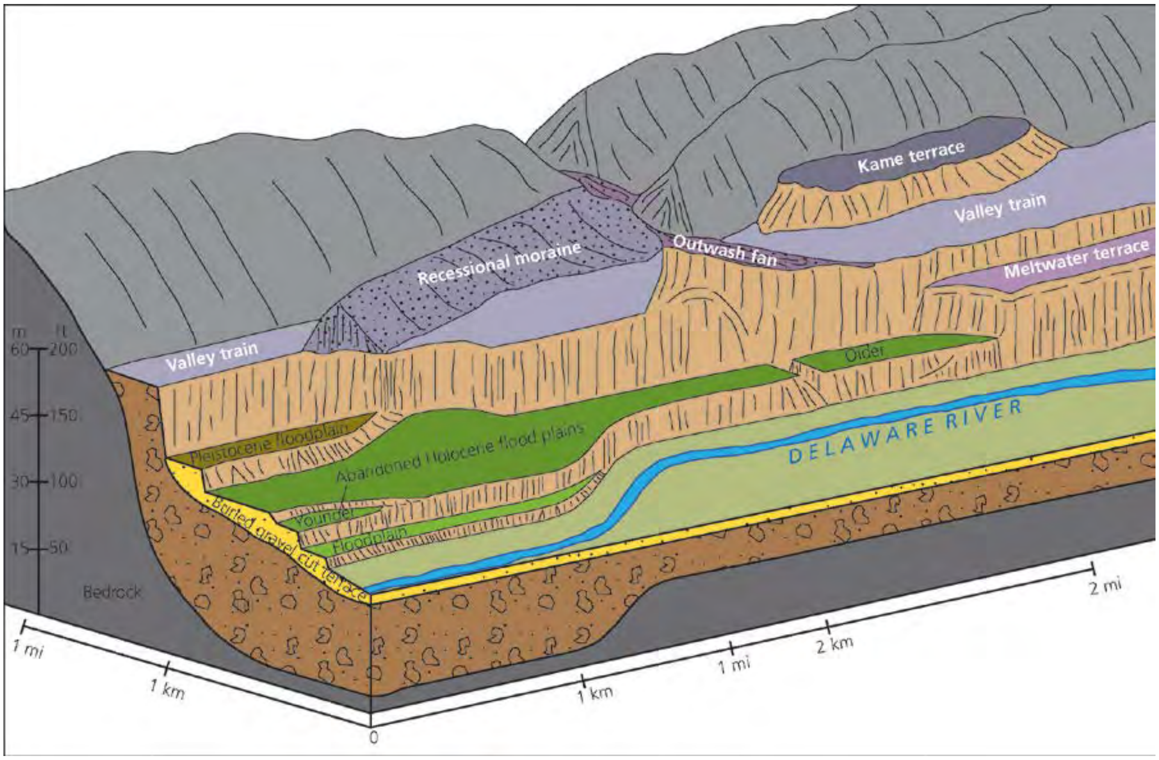

Figure 31. Schematic graphic of positions and assemblages of typical glacial and alluvial landforms in Minisink Valley along the Delaware River. Older, glacial deposits sit on terrace levels above the modern floodplain. Younger, abandoned floodplains step down in elevation to the modern floodplain and record past river elevations. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 62 in Witte (2001).

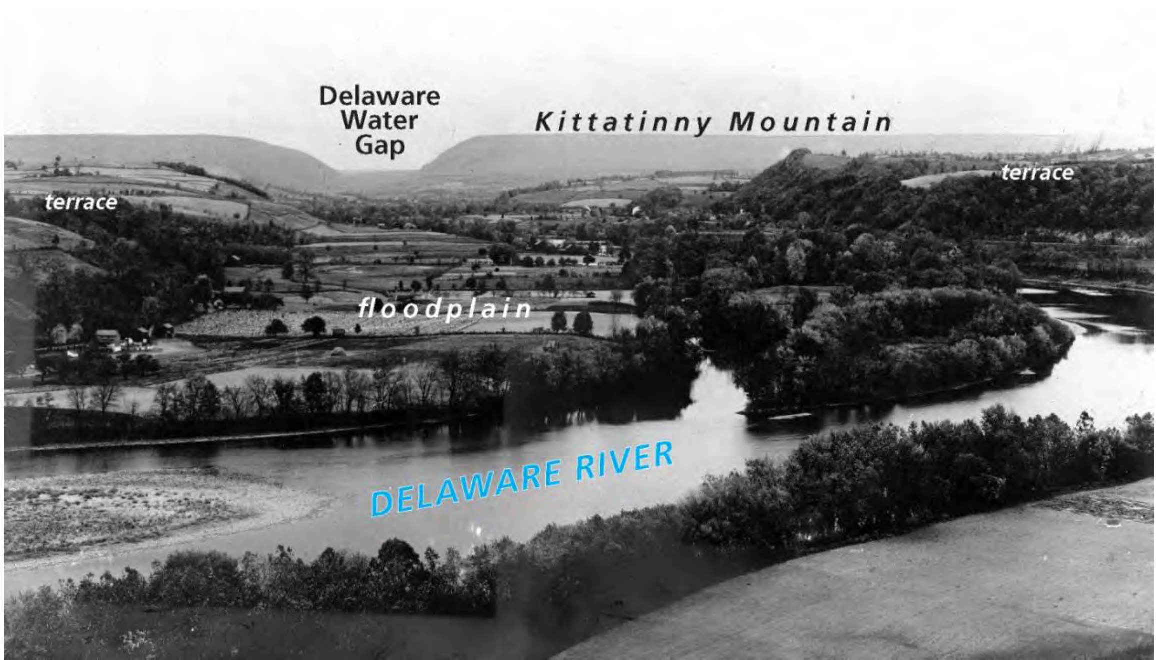

Figure 32. Photograph of Delaware Water Gap. This view of the Gap from the southeast shows the ridge of Kittatinny Mountain in the distance and the broad floodplain of the Delaware River in the foreground, flanked by higher terraces. U.S. Geological Survey photograph by G. W. Stose (no date), available online: http://libraryphoto.cr.usgs.gov/parks.htm (accessed 16 September 2013). Annotation by Jason Kenworthy (NPS Geologic Resources Division).

Geologic Map Data

This section summarizes the geologic map data available for Delaware Water Gap National Recreation Area. The Geologic Map Graphics (in pocket) display the geologic map data draped over a shaded relief image of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 3. Bedrock and surficial geologic map data are provided for Delaware Water Gap National Recreation Area.

Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to produce the digital geologic data for Delaware Water Gap National Recreation Area. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Alvord, D. C., and A. A. Drake, Jr. 1971. Geologic map of the Bushkill quadrangle, Pennsylvania and New Jersey (scale 1:24,000). Geologic quadrangle map GQ-908. U.S. Geological Survey, Reston, Virginia, USA.

Carswell, L. D., and O. B. Lloyd, Jr. 1979. Geology and groundwater resources of Monroe County, Pennsylvania (scale 1:48,000). Water resource report 47. Pennsylvania Geological Survey, Harrisburg, Pennsylvania, USA.

Davis, D. K., W. D. Sevon, T. M. Berg, and L. D. Schultz. 1989. Bedrock geologic map of Pike County, Pennsylvania, showing locations of selected wells (1:50,000 scale). Water Resources Report W 65. Pennsylvania Geological Survey, Harrisburg, Pennsylvania, USA.

Drake, A. A., Jr. 1992. Geologic map of the Newton West quadrangle, Sussex and Warren counties, New Jersey (scale 1:24,000). Geologic quadrangle map GQ-1703. U.S. Geological Survey, Reston, Virginia, USA.

Drake, A. A., Jr., J. B. Epstein, and J. M. Aaron. 1969. Geologic map and sections of parts of the Portland and Belvidere quadrangles, New Jersey-Pennsylvania (scale 1:24,000). IMAP I-552. U.S. Geological Survey, Reston, Virginia, USA.

Drake, A. A., R. L. Kastelic, and P. T. Lyttle. 1985. Geologic map of the eastern parts of the Belvidere and Portland quadrangles, Warren County New Jersey (scale 1:24,000). IMAP I-1530. U.S. Geological Survey, Reston, Virginia, USA.

Drake, A. A., and P. T. Lyttle. 1985. Geologic map of the Blairstown quadrangle, Warren County New Jersey (scale 1:24,000). Geologic quadrangle map GQ-1585. U.S. Geological Survey, Reston, Virginia, USA.

Drake, A. A., and D. H. Monteverde. 1992. Bedrock geologic map of the Branchville quadrangle, Sussex County, New Jersey (scale 1:24,000). Geologic quadrangle map GQ-1700. U.S. Geological Survey, Reston, Virginia, USA.

Epstein, J. B. 1973. Geologic map of the Stroudsburg quadrangle, Pennsylvania and New Jersey (scale 1:24,000). Geologic quadrangle map GQ-1047. U.S. Geological Survey, Reston, Virginia, USA.

Epstein, J. B. 1990. Geologic map of the Saylorsburg quadrangle, Monroe and Northampton counties, Pennsylvania (scale 1:24,000). Geologic quadrangle map GQ-1638. U.S. Geological Survey, Reston, Virginia, USA.

Fisher, D. W., Y. W. Isachsen, and L. V. Rickard. 1970. Geologic map of New York-Lower Hudson Sheet, New York (scale 1:250,000). New York State Museum, New York, New York, USA.

Pallis, T., and W. Marzulli. 2006. Landslides in New Jersey (scale 1:100,000). DGS 06-3. New Jersey Geological Survey, Trenton, New Jersey, USA.

Pristas, R. P. 2004. Bedrock geology of New Jersey, New Jersey (scale 1:100,000). DGS 04-6. New Jersey Geological Survey, Trenton, New Jersey, USA.

Pristas, R. P. 2007. Surficial geology of New Jersey, New Jersey (scale 1:100,000). DGS 07-2. New Jersey Geological Survey, Trenton, New Jersey, USA.

Sevon, W. D., T. M. Berg, L. D. Schultz, and G. H. Crowl. 1989. Geology and mineral resources of Pike County, Pennsylvania (Plate 1, Bedrock Geology) (1:50,000 scale). County Report C 52. Pennsylvania Geological Survey, Harrisburg, Pennsylvania, USA.

Sevon, W. D., T. M. Berg, L. D. Schultz, and G. H. Crowl. 1989. Geology and mineral resources of Pike County, Pennsylvania (Plate 2, Surficial Geology) (1:50,000 scale). County Report C 52. Pennsylvania Geological Survey, Harrisburg, Pennsylvania, USA.

Witte, R. W., and J. B. Epstein. 2005. Surficial geologic map of the Culvers Gap quadrangle, Sussex County, New Jersey (scale 1:24,000). GMS 04-1. New Jersey Geological Survey, Trenton, New Jersey, USA.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Delaware Water Gap National Recreation Area using data model version 2.1.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see table 3)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.pdf) document that contains all ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps
- An ESRI map document file (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth. Not all data layers may be represented in the Google Earth data.

Table 3. Geology data layers in the Delaware Water Gap National Recreation Area GIS data

Data Layer	Code	On Geologic Map Graphic?	Google Earth Layer?
Cross Section Lines	sec	No	No
Fault and Fold Symbols	sym	Yes	No
Bedding Measurements (strike and dip)	atd	No	No
Cleavage Measurements (strike and dip)	atd	No	No
Joint Measurements (strike and dip)	atd	No	No
Geologic Attitude Observation Localities	atd	No	No
Mine Point Features	min	No	No
Glacial Feature Points (direction of ice movement)	gfp	No	No
Measured Unit Thickness	gml	No	No
Geologic Observation Localities	gol	No	No
Fossil Localities	gsl	No	No
Hazard Point Features	hzp	No	No
Point Geologic Units (Dmhf biostrome)	gpt	No	No
Bedrock Elevation Contours	cn1	No	No
Geologic Line Features	glf	No	No
Hazard Feature Lines (sinkholes)	hzl	No	Yes
Glacial Feature Lines	gfl	No	Yes
Faults	flt	Yes	Yes
Folds	fld	Yes	Yes
Linear Dikes	dke	No	Yes
Linear Geologic Units (Hamilton Group, Mahantango Fm.)	gln	No	No
Eolian Sand Sheet Boundaries	eafa	No	No
Eolian Sand Sheets	eaf	No	No
Bedrock Outcrop Boundaries	ocra	No	No
Bedrock Outcrops	ocr	No	No
Surficial (glacial) Contacts	sura	Yes	Yes
Surficial (glacial) Units	sur	Yes	Yes
Geologic (bedrock) Contacts	glga	Yes	Yes
Geologic (bedrock) Units	glg	Yes	Yes

Geologic Map Graphics

The Geologic Map Graphics display the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overviews, as indicated in table 3. Cartographic elements and basic geographic information have been added to overviews. Digital elevation data and geographic information, which are part of the overview graphics, are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out Map Unit Properties Table correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between geologic units and park stories are also summarized.

Use Constraints

Graphic and written information provided in GRI GIS data and this report are not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within list listed distance (table 4) of their true location. Please contact GRI with any questions.

Table 4. Horizontal error for map scales.

Map Scale	Horizontal Error	
	meters	feet
1:24,000	12	40
1:48,000	24	80
1:50,000	25	83
1:100,000	51	167
1:250,000	127	416

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

adit. A horizontal passage from the surface into a mine.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

amphibole. A common group of rock-forming silicate minerals. Hornblende is the most abundant type.

amphibolite. A metamorphic rock consisting mostly of the minerals amphibole and plagioclase with little or no quartz.

anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.

aquiclude. See "confining bed."

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

arc. See "volcanic arc" and "magmatic arc."

arenite. A general term for sedimentary rocks composed of sand-sized fragments with a pure or nearly pure chemical cement and little or no matrix material between the fragments.

argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.

argillite. A compact rock, derived from mudstone or shale, more highly cemented than either of those rocks. It does not easily split like of shale or have the cleavage of slate. It is regarded as a product of low-temperature metamorphism.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

augen. Describes large lenticular mineral grains or mineral aggregates that have the shape of an eye in cross-section. Found in metamorphic rocks such as schists and gneisses.

augite. A dark-green to black pyroxene mineral that contains large amounts of aluminum, iron, and magnesium. Found in igneous and high-temperature metamorphic rocks.

axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.

barrier island. A long, low, narrow island formed by a ridge of sand that parallels the coast.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

biotite. A widely distributed and important rock-forming mineral of the mica group. Forms thin, flat sheets.

boudinage. A structure common in strongly deformed sedimentary and metamorphic rocks, in which an originally continuous layer or bed has been stretched, thinned, and broken at regular intervals into bodies resembling "boudins" (sausages).

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

brittle. Describes a rock that fractures (breaks) before sustaining deformation.

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

cleavage (mineral). The tendency of a mineral to break preferentially in certain directions along planes of weaknesses in the crystal structure.

cleavage. The tendency of a rock to split along parallel, closely spaced planar surfaces. It is independent of bedding.

col. A low spot, or pass over a mountain ridge.

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

concretion. A hard, compact aggregate of mineral matter, subspherical to irregular in shape; formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock. Concretions are generally different in composition from the rocks in which they occur.

confining bed. A body of relatively impermeable or distinctly less permeable material stratigraphically adjacent to one or more aquifers. Replaced the term "aquiclude."

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental rifting. Process by which a region of crust undergoes extension (pulling apart), resulting in the formation of many related normal faults, and often associated with volcanic activity.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental shield. A continental block of Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust.

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

convergent boundary. A plate boundary where two tectonic plates are colliding.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

creep. The slow, imperceptible downslope movement of mineral, rock, and soil particles under gravity.

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

cutbank. A steep, bare slope formed by lateral erosion of a stream.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

drift. All rock material (clay, silt, sand, gravel, boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier. Includes unstratified material (till) and stratified deposits (outwash plains and fluvial deposits).

drumlin. A low, smoothly rounded, elongate oval hill, mound, or ridge of compact glacial till built under the margin of the ice and shaped by the flow of the glacier. The drumlin's long axis is parallel to the direction of ice movement.

ductile. Describes a rock that is able to sustain deformation (folding, bending, or shearing) before fracturing.

electrical resistivity survey. A measure of the difficulty with which electric current flows through unconsolidated sediment and rock.

electromagnetic survey (method). An electrical exploration method based on the measurement of alternating magnetic fields associated with currents artificially or naturally maintained in the subsurface.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

epicenter. The point on Earth's surface that is directly above the focus (location) of an earthquake.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

eustatic. Relates to simultaneous worldwide rise or fall of sea level.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

facies (metamorphic). The pressure and temperature conditions that result in a particular, distinctive suite of metamorphic minerals.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fan delta. An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

flysch. A marine sedimentary facies characterized by a thick sequence of poorly fossiliferous, thinly bedded, graded marls and sandy and calcareous shales and muds, rhythmically interbedded with conglomerates (rare), coarse sandstones, and graywackes. Typically deposited in deep ocean basins near convergent plate boundaries and rising mountains.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

garnet. A hard mineral that has a glassy luster, often with well defined crystal faces, and a variety of colors, dark red being characteristic. Commonly found in metamorphic rocks.

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

glacial erratic. Boulders transported by glaciers some distance from their point of origin.

gneiss. A foliated rock formed by regional metamorphism with alternating bands of dark and light minerals.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

granoblastic. Describes the texture of a metamorphic rock in which recrystallization formed crystals of nearly the same size in all directions.

granodiorite. A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

graywacke. A term commonly used in the field for a dark gray to dark green, very hard, dense sandstone of any composition but with a chlorite-rich matrix; these rocks have undergone deep burial.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

gully. A small channel produced by running water in earth or unconsolidated material (e.g., soil or a bare slope).

hanging valley. A tributary glacial valley whose mouth is high above the floor of the main valley, which was eroded by the main body of the glacier.

hanging wall. The mass of rock above a fault surface (also see "footwall").
hinge line. A line or boundary between a stable region and one undergoing upward or downward movement.
hornblende. The most common mineral of the amphibole group. Hornblende is commonly black and occurs in distinct crystals or in columnar, fibrous, or granular forms.
hornfels. A fine-grained rock composed of a mosaic of grains that are the same size in each dimension without preferred orientation. Typically formed by contact metamorphism, which occurs near the contact with an intrusion of molten material.
horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").
hydraulic conductivity. Measure of permeability coefficient.
hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.
hydrolysis. A decomposition reaction involving water, frequently involving silicate minerals.
igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.
incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.
intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.
island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.
isoclinal. Describes a fold with parallel limbs.
isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.
isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.
joint. A break in rock without relative movement of rocks on either side of the fracture surface.
kame delta. A flat-topped, steep-sided hill of well-sorted sand and gravel deposited by a meltwater stream flowing into a proglacial or other ice-marginal lake. The proximal margin of the delta was built in contact with glacier ice.
karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.
karst valley. A closed depression formed by the coalescence of several sinkholes.
lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.
lamination. Very thin, parallel layers.
landslide. Any process or landform resulting from rapid, gravity-driven mass movement.
lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.
lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.
levee. Raised ridge lining the banks of a stream. May be natural or artificial.
limb. Either side of a structural fold.
limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.
lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.
lithification. The conversion of sediment into solid rock.
lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.
lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.
lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.
lodgment till. The plastering beneath a glacier of successive layers of basal till commonly characterized by compact fissile structure and containing stones oriented with their long axes generally parallel to the direction of ice movement.
loess. Windblown silt-sized sediment, generally of glacial origin.
magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.
magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.
mantle. The zone of Earth's interior between the crust and core.
marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.
marker bed. A distinctive layer used to trace a geologic unit from one geographic location to another.
mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.
matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.
meander. Sinuous lateral curve or bend in a stream channel. An entrenched meander is incised, or carved downward into the surface of the valley in which a meander originally formed. The meander preserves its original pattern with little modification.
mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

meteoric water. Pertaining to water of recent atmospheric origin.

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

microcrystalline. A rock with a texture consisting of crystals only visible with a microscope.

mid-ocean ridge. The continuous, generally submarine and volcanically active mountain range that marks the divergent tectonic margin(s) in Earth's oceans.

migmatite. Literally, "mixed rock" with both igneous and metamorphic characteristics due to partial melting during metamorphism.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

nonconformity. An erosional surface preserved in strata in which crystalline igneous or metamorphic rocks underlie sedimentary rocks.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

oil field. A geographic region rich in petroleum resources and containing one or more wells that produce, or have produced, oil and/or gas.

oolite. A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.

orogeny. A mountain-building event.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

outwash. Glacial sediment transported and deposited by meltwater streams.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parent material. Geologic material from which soils form.

parent rock. Rock from which soil, sediments, or other rocks are derived.

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

perthite. A variety of feldspar consisting of parallel or subparallel intergrowths in which the potassium-rich phase (usually microcline) appears to be the host from which the sodium-rich phase (usually albite) separated at a critical temperature.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phyllite. A metamorphosed rock, intermediate in grade between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart a silky sheen to the surfaces ("schistosity").

plagioclase. An important rock-forming group of feldspar minerals.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

platform. Any level or nearly level surface, ranging in size from a terrace or bench to a plateau or peneplain.

platy. Refers to a sedimentary particle whose length is more than 3 times its thickness. Also refers to a sandstone or limestone that splits into thin layers having thicknesses in the range of 2 to 10 mm (0.08 to 0.4 in).

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

progradation. The seaward building of land area due to sedimentary deposition.

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

pyroxene. A common rock-forming mineral. It is characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

recharge. Infiltration processes that replenish groundwater.

red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.

reflection survey. Record of the time it takes for seismic waves generated from a controlled source to return to the surface. Used to interpret the depth to the subsurface feature that generated the reflections.

refraction survey. A type of seismic survey that measures the travel times of seismic waves that have travelled nearly parallel through a medium of high-velocity. Used to determine general soil types, the depth to strata boundaries, or depth to bedrock.

regolith. General term for the layer of rock debris, organic matter, and soil that commonly forms the land surface and overlies most bedrock.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

riprap. A layer of large, durable, broken rock fragments irregularly thrown together in an attempt to prevent erosion by waves or currents and thereby preserve the shape of a surface, slope, or underlying structure.

rip-up clast. A mud clast (usually of flat shape) that has been "ripped up" by currents from a semiconsolidated mud deposit, transported, and deposited elsewhere. Often associated with storms or other high-energy events.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

schistose. A rock displaying schistosity, or foliation.

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

serpentinite. A rock consisting almost wholly of serpentine-group minerals such as antigorite and chrysotile. Commonly derived from the alteration of peridotite.

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a sediments associated with a major sea level transgression-regression.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

sinkhole. A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.

slate. A compact, fine-grained metamorphic rock that can be split into slabs and thin plates. Most slate was formed from shale.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

specific conductance. The measure of discharge of a water well per unit of drawdown.

speleothem. Any secondary mineral deposit that forms in a cave.

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

striations. Parallel scratches or lines.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.

subaerial. Describes conditions and processes that exist or operate in the open air on or immediately adjacent to the land surface.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

syncline. A downward curving (concave-up) fold with layers that dip inward; the core of the syncline contains the stratigraphically younger rocks.

system (stratigraphy). The group of rocks formed during a period of geologic time.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or azimuth of elongation of a linear geologic feature.

turbidite. A sediment or rock deposited from a turbidity current (underwater flow of sediment) and characterized by graded bedding, moderate sorting, and well-developed primary structures in the sequence noted in the Bouma cycle.

type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.

type section. An exact location where a geologic formation is most typical; a locality to which all other occurrences of that formation may be compared.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

undercutting. The removal of material at the base of a steep slope or cliff or other exposed rock by the erosive action of falling or running water (such as a meandering stream), of sand-laden wind in the desert, or of waves along the coast.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

upwarp. Upward flexing of Earth's crust.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

zircon. A common accessory mineral in siliceous igneous rocks, crystalline limestone, schist, and gneiss, also in sedimentary rocks derived from and in beach and river placer deposits. When cut and polished, the colorless varieties provide exceptionally brilliant gemstones. Very durable mineral, often used for age-dating.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of May 2013.

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

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NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views program (geology-themed modules are available for geologic time, paleontology, glaciers, caves and karst, coastal geology, volcanoes, and a wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/Views/

NPS Resource Management Guidance and Documents

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS 2006 management policies (chapter 4; Natural resource management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual: Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

Geological Surveys and Societies

Pennsylvania Bureau of Topographic and Geologic Survey: http://www.dcnr.state.pa.us/topogeo/index.aspx

New Jersey Geological and Water Survey: http://www.state.nj.us/dep/njgs/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

U.S. Geological Survey Reference Tools

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")

U.S. Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Meeting Participants

The following people attended the GRI scoping meeting for Delaware Water Gap National Recreation Area, held on 3 October 2001, or the follow-up report writing conference call, held on 16 November 2011. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

2001 Scoping Meeting Participants

Name	Affiliation	Position
Bill Laitner	NPS, Delaware Water Gap NRA	Superintendent
Tim Connors	NPS, Geologic Resources Division	Geologist
Ron Pristas	NJ Geological Survey	Geologist
Mike Girard	NJ Geological Survey	Geologist
Don Monteverde	NJ Geological Survey	Geologist
Jack Epstein	U.S. Geological Survey	Geologist
John R. Wright	NPS, Delaware Water Gap NRA	
Jacki Katzmire	NPS, Delaware Water Gap NRA	

2011 Conference Call Participants

Name	Affiliation	Position
Allan Ambler	NPS, Delaware Water Gap NRA	Biologist
Brinnen Carter	NPS, Delaware Water Gap NRA	Cultural resource manager
Kara Deutsch	NPS, Delaware Water Gap NRA	Natural resources planning
Richard Evans	NPS, Delaware Water Gap NRA	Ecologist
Jason Kenworthy	NPS, Geologic Resources Division	Geologist, GRI reports coordinator
Matt Marshall	NPS, Eastern Rivers and Mountains Network	Program manager
Leslie Morlock	NPS, Delaware Water Gap NRA	GIS coordinator
Kathleen Saunt	NPS, Delaware Water Gap NRA	Education and outreach coordinator
Jeffrey Shreiner	NPS, Delaware Water Gap NRA	Biologist
Amanda Stein	NPS, Delaware Water Gap NRA	Biologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist, GRI report author

Appendix B: Geologic Resource Laws, Regulations, and Policies

The Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of September 2013. Contact GRD for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC. §§ 4301 – 4309 -** Requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a FOIA requester. **National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169-** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing . . . cave resources . . . in park units. **43 C.F.R Part 37** state that all NPS caves are "significant" and set forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.***, provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (February 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes I & M, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes Native American collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Mining Claims	**Mining in the Parks Act of 1976, 16 USC. § 1901 *et seq.*** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC. § 21 *et seq.*** Allows US citizens to locate mining claims on Federal lands. Imposes administrative & economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 C.F.R. § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 C.F.R. Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 C.F.R. Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC. § 1 *et seq.*** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: 16 USC. § 230a (Jean Lafitte NHP & Pres.) 16 USC. §450kk (Fort Union NM), 16 USC. § 459d-3 (Padre Island NS), 16 USC. § 459h-3 (Gulf Islands NS), 16 USC. § 460ee (Big South Fork NRRA), 16 USC. § 460cc-2(i) (Gateway NRA), 16 USC. § 460m (Ozark NSR), 16 USC.§698c (Big Thicket N Pres.), 16 USC. §698f (Big Cypress N Pres.)	**36 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to: - Demonstrate bona fide title to mineral rights; - Submit a plan of operations to NPS describing where, when, how they intend to conduct operations; - Prepare/submit a reclamation plan; and - Submit a bond to cover reclamation and potential liability. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators must comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil & Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC. § 181 *et seq.***, and the **Mineral Leasing Act for Acquired Lands, 30 USC. § 351 *et seq.*** do not authorize the BLM to lease federally owned minerals in NPS units. **Exceptions**: Glen Canyon NRA (16 USC. § 460dd et seq.), Lake Mead NRA (16 USC. § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC. § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. **Exceptions**: Native American Lands Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, (25 USC. § 396), and the Indian Leasing Act of 1938 (25 USC. §§ 396a, 398 and 399) and Indian Mineral Development Act of 1982 (25 USC.S. §§ 2101-2108), all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC. § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 C.F.R. § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 C.F.R. Parts 3100, 3400, and 3500** govern Federal mineral leasing. **Regulations re: Native American Lands within NPS Units:** 25 C.F.R. pt. 211 governs leasing of tribal lands for mineral development. 25 C.F.R. pt. 212 governs leasing of allotted lands for mineral development. 25 C.F.R. pt. 216 governs surface exploration, mining, and reclamation of lands during mineral development. 25 C.F.R. pt. 224 governs tribal energy resource agreements. 25 C.F.R. pt. 225 governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC.S. §§ 2101-2108). 30 C.F.R. §§ 1202.100-1202.101 governs royalties on oil produced from Indian leases. 30 C.F.R. §§ 1202.550-1202.558 governs royalties on gas production from Indian leases. 30 C.F.R. §§ 1206.50-1206.62 & §§ 1206.170-1206.176 governs product valuation for mineral resources produced from Indian oil and gas leases. 30 C.F.R. § 1206.450 governs the valuation coal from Indian Tribal and Allotted leases. 43 C.F.R. pt. 3160 governs onshore oil and gas operations, which are overseen by the Bureau of Land Management	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC. §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 *et. seq.*** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 C.F.R. Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 C.F.R. Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: - Only for park administrative uses. - After compliance with NEPA & other federal, state, and local laws, and a finding of non-impairment. - After finding the use is park's most reasonable alternative based on environment and economics. - Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. - Spoil areas must comply with Part 6 standards - NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human- caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611**are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to: - Prevent unnatural erosion, removal, and contamination. - Conduct soil surveys. - Minimize unavoidable excavation. - Develop/follow written prescriptions (instructions).

NPS 620/122518, October 2013

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

Natural Resource Stewardship and Science
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Fort Collins, CO 80525

www.nature.nps.gov

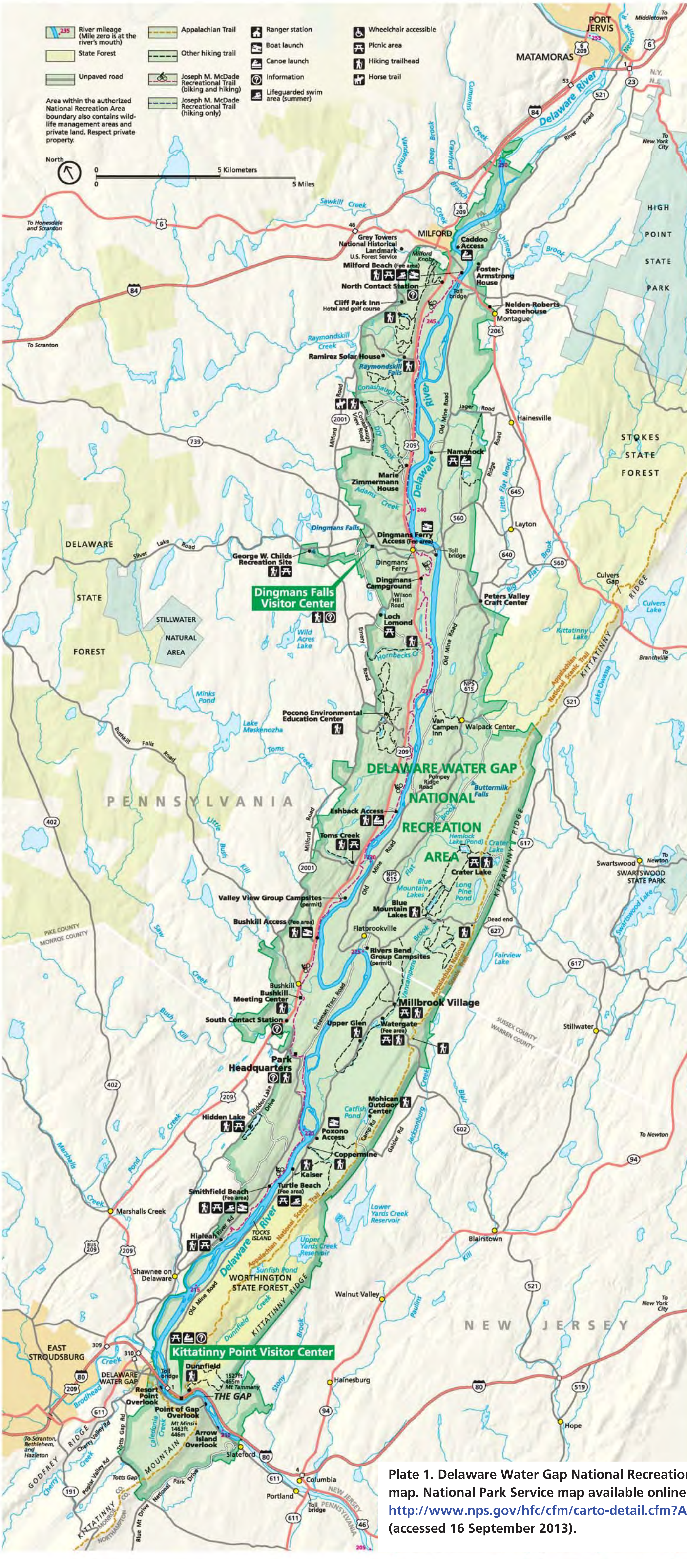


Plate 1. Delaware Water Gap National Recreation Area park map. National Park Service map available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=DEWA (accessed 16 September 2013).

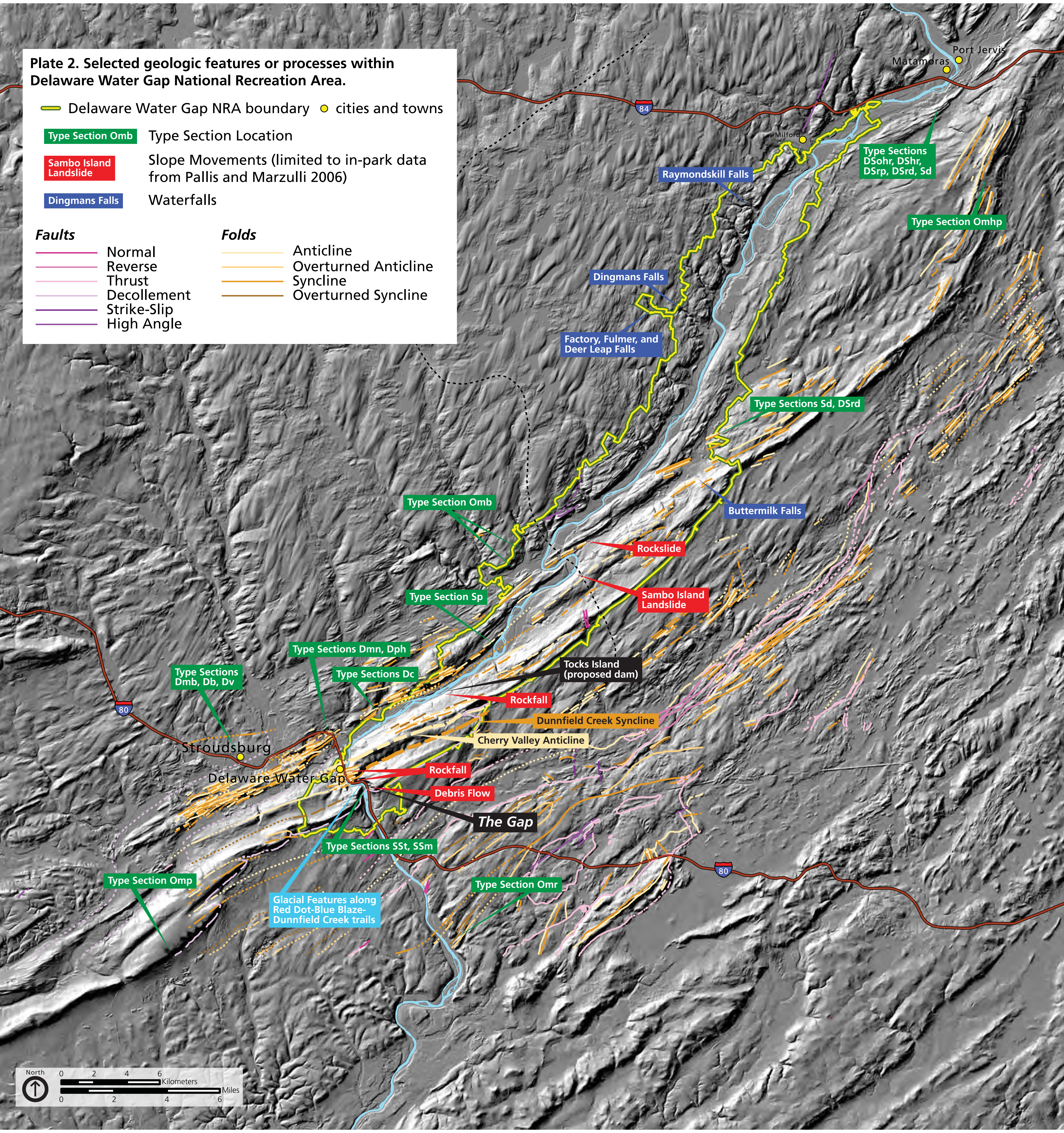


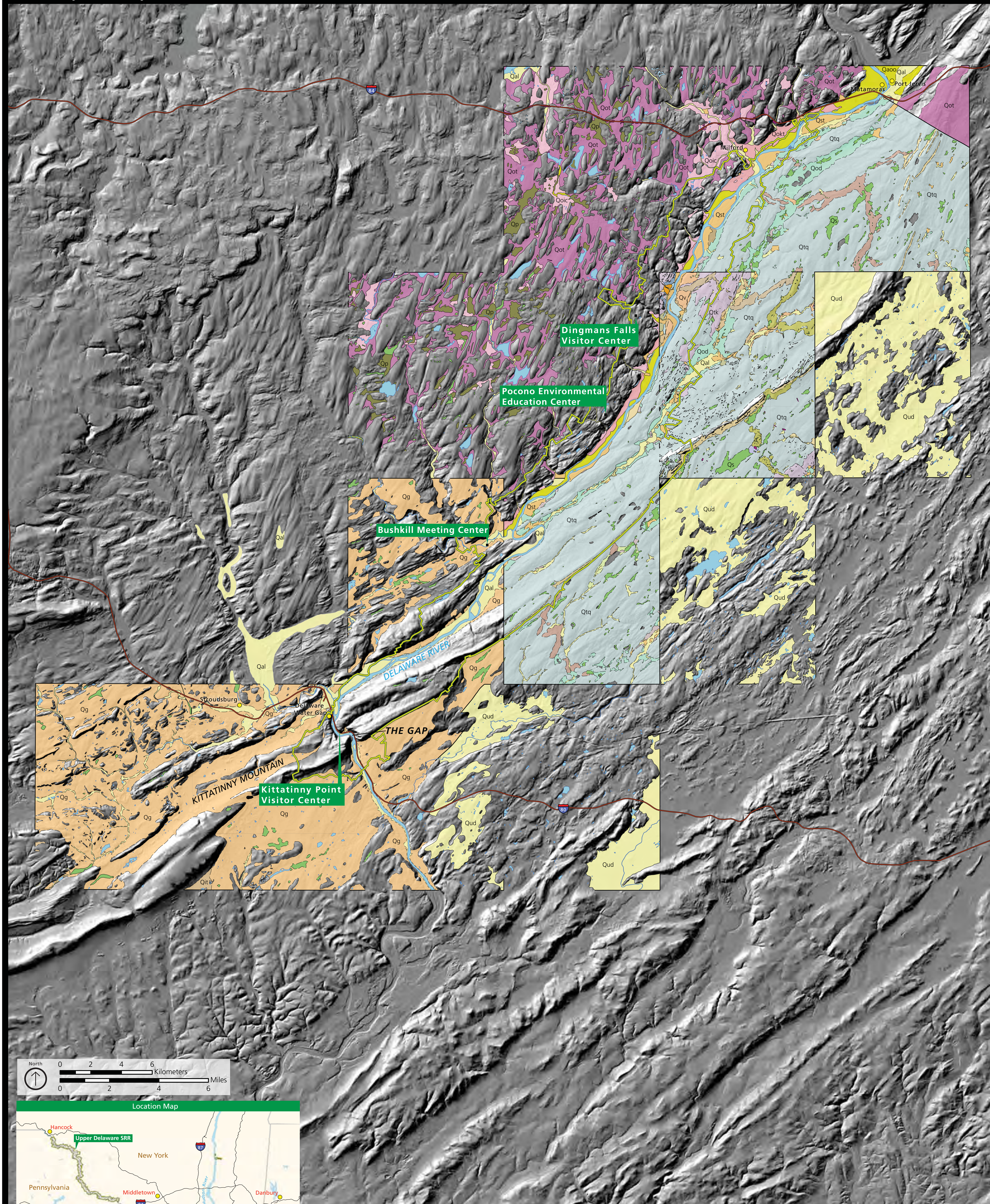
Plate 2. Selected geologic features or processes within Delaware Water Gap National Recreation Area.
Delaware Water Gap NRA boundary
cities and towns
Type Section Omb
Type Section Location
Sambo Island Landslide
Slope Movements (limited to in-park data from Pallis and Marzulli 2006)
Dingmans Falls
Waterfalls
Faults
Normal
Reverse
Thrust
Decollement
Strike-Slip
High Angle
Folds
Anticline
Overturned Anticline
Syncline
Overturned Syncline
Port Jervis
Matamoras
Milford
84
Type Sections DSohr, DShr, DSrp, DSrd, Sd
Raymondskill Falls
Type Section Omhp
Dingmans Falls
Factory, Fulmer, and Deer Leap Falls
Type Sections Sd, DSrd
Buttermilk Falls
Type Section Omb
Rockslide
Sambo Island Landslide
Type Section Sp
Type Sections Dmn, Dph
Type Sections Dmb, Db, Dv
Type Sections Dc
Tocks Island (proposed dam)
Rockfall
80
Dunnfield Creek Syncline
Cherry Valley Anticline
Stroudsburg
Delaware Water Gap
Rockfall
Debris Flow
The Gap
Type Sections SSt, SSm
Type Section Omp
Glacial Features along Red Dot-Blue Blaze-Dunnfield Creek trails
Type Section Omr
80
North
0 2 4 6 Kilometers
0 2 4 6 Miles

Surficial Geologic Map of Delaware Water Gap NRA

New Jersey and Pennsylvania

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



NPS Boundary

Infrastructure

- points of interest
- cities
- roads

Surficial Contacts

- known or certain
- approximate
- concealed
- inferred
- quadrangle boundary
- water or shoreline
- subaqueous (inferred)

Surficial Units

	water
Qafl	Artificial fill (Quaternary)
Qmd	Mine dump deposits (Quaternary)
Qp	Peat (Quaternary)
Qud	Undifferentiated surficial deposits (Quaternary)
Qs	Swamp and marsh deposits (Quaternary)
Qal	Alluvium (Quaternary)
Qaf	Alluvial fan deposits (Quaternary)
Qaoo	Alluvium and olean outwash, undifferentiated (Quaternary)
Qac	Alluvium and colluvium, undifferentiated (late Wisconsinan to Holocene)
Qba	Boulder accumulations (Quaternary)
Qsr	Shale-chip rubble (Quaternary)
Qoic	Olean ice, contact stratified sand and gravel (Quaternary)
Qokt	Olean kame terrace (Quaternary)
Qot	Olean till (Quaternary)
Qta	Talus deposits (late Pleistocene to Holocene)
Qst	Stream terrace deposits (late Pleistocene to Holocene)
Qst2	Stream terrace deposits, younger Minisink Valley terrace (late Wisconsinan to Holocene)
Qst3	Stream terrace deposits, older Minisink Valley terrace (late Wisconsinan to Holocene)
Qe	Eolian deposits (Pliocene to late Pleistocene)
Qed	Sand dunes (late Wisconsinan)
Qg	Glacial deposits, undifferentiated (Quaternary)
Qmt	Meltwater terrace deposits (late Wisconsinan)
Qtq	Till, derived from Kittatinny Mountain (late Wisconsinan)
Qtk	Till, derived from Kittatinny and Minisink Valley (late Wisconsinan)
Qk	Kame (Quaternary)
Qod	Glacial lake delta deposits from proglacial lakes (late Wisconsinan)
Qv	Valley, train deposits (late Wisconsinan)
Qf	Outwash fan, near Branchville (late Wisconsinan)
Qfdb	Outwash fan, Dry Brook (late Wisconsinan)
Qfa	Outwash fan, Adams Creek (late Wisconsinan)
Qwmrk	Recessional moraine (late Wisconsinan)
Qdfm	Dingmans Ferry recessional moraine (late Wisconsinan)
Qom	Ogdensburg, Culvers Gap recessional moraine (late Wisconsinan)
Qm	Recessional moraine (late Wisconsinan)
Qd	Glacial lake delta deposits, Lake Owassa (late Wisconsinan)
Qfd	Outwash fan, Dingmans Creek (late Wisconsinan)
Qwft	Glaciofluvial terrace deposits (late Wisconsinan)
Qwfv	Glaciofluvial plain deposits (late Wisconsinan)
Qwic	Ice, contact deposits (late Wisconsinan)
Qit	Older till (Quaternary)

This map was produced by Max Jackl (Colorado State University) in April, 2013. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data product include digital New York State Museum and New Jersey Geological Survey publications and paper U.S. Geological Survey and Pennsylvania Geological Survey publications (see Geologic Map Data Section in report for specific sources).

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 12 m (40 ft) (1:24,000 scale data), 24 m (80 ft) (1:48,000 scale data), 25 m (83 ft) (1:50,000 scale data), 50 m (166 ft) (1:100,000 scale data), or 127 m (416 ft) (1:250,000 scale data) of their true location.

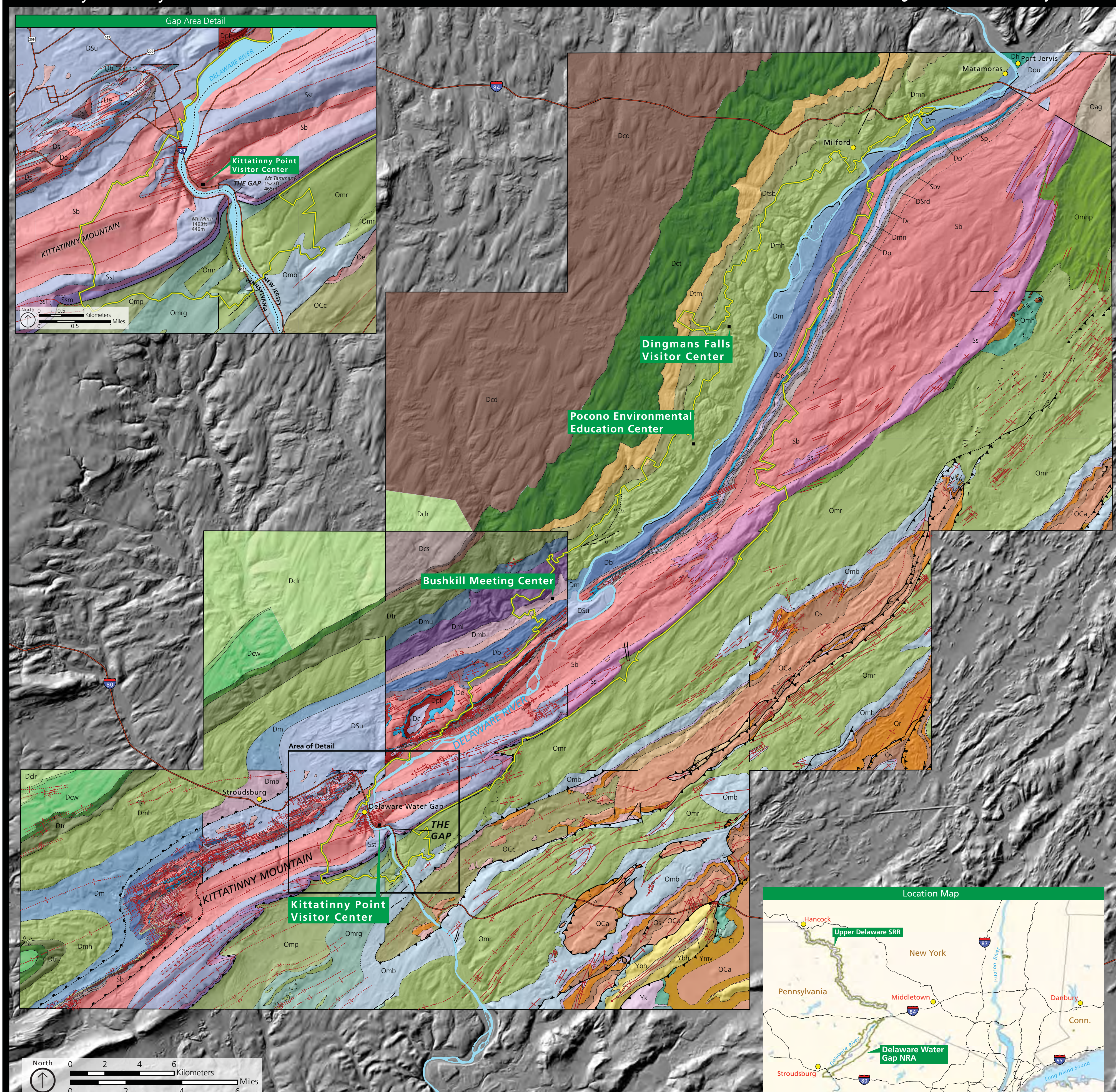
All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter "GRI" as the search text and select a park from the unit list.

Bedrock Geologic Map of Delaware Water Gap NRA

New Jersey and Pennsylvania

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory



North
0 2 4 6 Kilometers
0 2 4 6 Miles

This map was produced by Max Jackl (Colorado State University) in April, 2013. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

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NPS Boundary

Infrastructure
- points of interest
- cities
- roads

Folds
- known or certain, approximate and concealed
- queried
- anticline
- syncline
- overturned anticline
- overturned syncline
- plunge direction

Faults
- known or certain, approximate and concealed
- queried
- teeth are on upthrown block
- decollement fault
- up and down fault motion

Geologic Contacts
- known or certain, approximate and concealed
- queried
- gradational
- quadrangle boundary
- water or shoreline
- subaqueous (inferred)

Geologic Units

Catskill Formation
- Dclr Long Run Member (Upper Devonian)
- Dcbr Beaverdam Run Member (Upper Devonian)
- Dcw Walcksville Member (Upper Devonian)
- Dcs Shohola Member (Upper Devonian)
- Dca Analomink Red Shale Member (Upper Devonian)
- Dcd Delaware River Flags Member (Upper Devonian)
- Dct Towamensing Member (Upper Devonian)

Trimmers Rock Formation
- Dtr Undivided (Upper Devonian)
- Dtm Millrift Member (Upper Devonian)
- Dtsb Sloat Brook Member (Upper Devonian)

Hamilton Group
- Dmh Mahantango Formation (Middle Devonian)
- Dmu Mahantango Formation, Upper Member (Middle Devonian)
- Dmhc Mahantango Formation, Centerfield Member (Middle Devonian)
- Dml
- Dh Mahantangle Formation and Marcellus Shale, undivided (Middle Devonian)
- Dm Marcellus Shale (Middle Devonian)
- Dmb Marcellus Shale, Brodhead Creek Member (Middle Devonian)
- Dmsu Marcellus Shale, Stony Hollow and Union Springs Shale Members, undivided (Middle Devonian)
- Dou Onondaga Limestone, undivided (Lower to Middle Devonian)
- Db Onondaga Limestone, Buttermilk Falls Limestone (Lower to Middle Devonian)
- Dpt Palmerton Sandstone (Lower to Middle Devonian)
- Dse Schoharie Formation and Esopus Formation, undivided (Lower to Middle Devonian)
- Ds Schoharie Formation (Lower to Middle Devonian)
- De Esopus Formation (Lower Devonian)

Oriskany Group
- Do Oriskany Group, undivided (Lower Devonian)
- Dr Oriskany Group, Ridgley Sandstone (Lower Devonian)
- Drs Oriskany Group, Ridgley Sandstone and Shriver Chert, undivided (Lower Devonian)

Helderburg Group
- Dhg Helderburg Group (Lower Devonian)
- Dph Helderburg Group, Port Ewan Shale, Minisink Limestone, and New Scotland Formation, undivided (Lower Devonian)
- Dp Port Ewan Shale (Lower Devonian)
- Dmn Helderburg Group, Minisink Limestone and New Scotland Formation, undivided (Lower Devonian)
- Dc Helderburg Group, Coeymans Formation, undivided (Lower Devonian)
- DShr Lower part of Helderburg Group and Rondout Formation, undivided (upper Silurian to Lower Devonian)
- DSohr Shriver Chert of the Oriskany Group, Helderburg Group and Rondout Formation, undivided (upper Silurian to Lower Devonian)

- DSrp Rondout Formation (upper Silurian to Lower Devonian)
- DSrd Rondout Formation and Decker Formation, undivided (upper Silurian to Lower Devonian)
- DSu Undifferentiated Devonian and Silurian rocks (upper Silurian to Middle Devonian)
- Sd Decker Formation (upper Silurian)
- Sbv Bossardville Limestone (upper Silurian)
- Sp Poxono Island Formation (upper Silurian)
- Sbcu Bloomsburg Red Beds, disseminated chalcocite (upper Silurian)
- Sb Bloomsburg Red Beds (middle to upper Silurian)

Shawangunk Formation
- Ss Undivided (lower to middle Silurian)
- Sst Tammany Member (lower to middle Silurian)
- Ssl Lizard Creek Member (lower to middle Silurian)
- Ssm Minsi Member (lower to middle Silurian)

Beemerville Intrusive Suite
- Obs Nepheline syenite (Upper Ordovician)
- Obt Tinguaite (Upper Ordovician)
- Obp Phonolite (Upper Ordovician)
- Obb Bostonite (Upper Ordovician)
- Obm Malignite (Upper Ordovician)
- Obla Lamprophyre (Upper Ordovician)
- Obo Ouachitite Breccia (Upper Ordovician)

- Omh Hornfels (Middle to Upper Ordovician)

Martinsburg Formation
- Omp Pen Argyl Member (Middle to Upper Ordovician)
- Omhp High Point Member (Upper Ordovician)
- Omr Ramseyburg Member (Middle to Upper Ordovician)
- Omrg Ramseyburg Member, graywacke beds (Middle to Upper Ordovician)
- Omb Bushkill Member (Middle to Upper Ordovician)

- Oag Austin Glen Formation (Middle Ordovician)
- Oj acksonburg Limestone (Middle Ordovician)
- Ojl Jacksonburg Limestone, cement limestone facies (Middle Ordovician)
- Ow Sequence at Wantage (Middle Ordovician)

Beekmantown Group
- Obu Upper part (Ordovician)
- Obl Lower part (Ordovician)
- Oe Epler Formation (Lower Ordovician)
- Or Rickenbach Dolomite (Lower Ordovician)

- Os Stonehenge Formation (Lower Ordovician)
- OCa Allentown Dolomite (Upper Cambrian to Lower Ordovician)
- OCc Carbonate rocks (Cambrian to Ordovician)
- Cl Leithsville Formation (Lower to Middle Cambrian)
- Ch Hardyston Quartzite (Lower Cambrian)
- Ymv Venite (Middle Proterozoic)
- Yba Byram Intrusive Suite, microperthite alaskite (Middle Proterozoic)
- Ybh Byram Intrusive Suite, hornblende granite (Middle Proterozoic)
- Ymr Marble (Middle Proterozoic)
- Yq Quartz-plagioclase-epidote-biotite gneiss (Middle Proterozoic)
- Yk Potassic feldspar gneiss (Middle Proterozoic)
- Ylo Oligoclase-quartz gneiss (Middle Proterozoic)
- Ya Amphibolite (Middle Proterozoic)

Surficial Geologic Map Unit Properties Table: Delaware Water Gap National Recreation Area

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Artificial fill (Qafl); Mine dump deposits (Qmd)	**Qafl** consists of loose, unconsolidated mixtures of rock fragments, sand, silt, clay, concrete and manufactured materials put in place by humans. Such materials are usually associated with construction, road development, earthen dams, and railway beds. **Qafl** may be as much as 8 m (25 ft) thick. **Qmd** contains blocks of mine waste, including slate from the Martinsburg Formation, in piles more than 30 m (100 ft) high. Other deposits of **Qmd** contain blocks of siltstone, cherty (siliceous nodules) limestone, dolomite, and shale from mine operations.	**Slope movements**—**Qafl** is susceptible to erosion and slope movements if poorly consolidated. Steeply-sloped piles of **Qmd** may be susceptible to slope movements. **Abandoned mineral lands**—**Qmd** is associated with the long history of mineral and rock resource extraction in the area. Slate quarries and dumps are present on both sides of the Delaware River. **Qmd** is associated with active mines and roadways, and is used as aggregate. **Surface water and groundwater quality and quantity**—units have no surficial aquifer potential.	**Caves and karst**—In the past sinkholes and other karst features may have been filled by human activities. **Connections to park stories and resources**—units are associated with modern or historic human development and/or resource extraction.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qafl** primarily used to raise the land surface, construct earthen dams, and form a solid base for roads and railways. **Qmd** created by mining or quarrying activities.
	Peat (Qp)	**Qp** occurs in poorly drained, natural depressions where the water table is at or near the surface. Examples of such settings include swamps and marshes. **Qp** consists of decaying vegetation and deposits may be more than 3 m (10 ft) thick.	**Slope movements**—**Qs** may be interbedded with colluvium deposits (associated with slope processes). **Qp** and **Qs** are easy to excavate, with low erosion resistance. **River channel migration and flooding**—**Qud** is located along riparian zones of active streams and rivers. **Abandoned mineral lands—**sand and gravel pits may have targeted those resources in these units. Peat from **Qs** was mined near Oak Grove. **Corridor construction projects**—marshy and wetland habitats may be impacted from corridor construction projects. **Surface water and groundwater quality and quantity**—**Qp** and **Qs** have no surficial aquifer potential. Qud units have variable aquifer potential depending on the primary material (alluvium, glacial deposits, etc) at each locality. Because the water table it at or near the surface where **Qp** is mapped, those areas are unsuitable for foundations, septic systems, and sanitary-landfill sites due to the potential for contamination.	**Paleontological resources**—units may contain pollen. **Qs** contains partially decomposed remains of mosses, sedges, trees, and other plants. **Qp** is decayed vegetation. **Connections to park stories and resources**—Units are associated with marshy, wetland habitats and riparian zones. Areas of **Qs** are heavily vegetated. Historically, marshes and swamps were drained to support increased development.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Glacial deposits of **Qud** are from the most recent major ice-age glaciation (termed the "Wisconsinan") and pre-Wisconsinan glacial advances during the Pleistocene. **Qs** may be accumulating in kettles, shallow postglacial lakes, and hollows in ground moraine that formed after the Wisconsinan glacial advance.
	Undifferentiated surficial deposits (Qud)	**Qud** includes alluvium (deposits associated with streams), swamp deposits, and glacial deposits consisting of clay, silt, sand, gravel, and organic-rich muck.			
	Swamp and marsh deposits (Qs)	**Qs** is loose, unconsolidated clay, silt, and sand mixed with decomposing organic matter in moist, shallow, undrained areas. **Qs** may be as much as 12 m (40 ft) thick and may contain cobbles and boulders.			
	Alluvium (Qal)	**Qal** is deposited by streams along floodplains and channels. Itincludes unconsolidated, poorly layered, poorly to moderately sorted mixtures of (in order of increasing grain size) clay, silt, sand, gravel, cobbles, and occasional boulders.	**Slope movements**—Units have low resistance to erosion and are easily excavated. However they hold relatively low slopes. Slumping is possible. **River channel migration and flooding**—Because units are associated with modern river channels, areas mapped as Qal and Qaf have a high potential for flooding. **Surface water and groundwater quality and quantity**—**Qal** may yield large quantities of water, but may not be sufficiently thick to be a viable source for groundwater. Some groundwater contains excessive concentrations of iron and manganese. Well-sorted sands and gravels in **Qal** of Monroe County constitute one of the most productive aquifers in the county.	**Glacial features and processes**—some deposits of **Qaf** are associated with postglacial and outwash terraces and may be dissected by modern streams. **Connections to park stories and resources**—associated with valley-bottom and riparian habitats.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qal** and **Qaf** are currently accumulating in river and stream channels and along riparian zones. They record the evolution of the modern fluvial system after the retreat of glaciers.
	Alluvial fan deposits (Qaf)	**Qaf** is also associated with rivers, forming smooth, fan-shaped surfaces with low to steep slopes at tributary mouths where two streams come together. Lobes of **Qaf** may dip as much as 30° toward the trunk valley and may be as much as 12 m (40 ft) thick.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Alluvium and Olean outwash, undifferentiated (Qaoo)	**Qaoo** consists of mixed, unconsolidated alluvium and outwash. Material within **Qaoo** includes clay, silt, sand, gravel, and occasional boulders. Some planar surfaces in the outwash formed as bedding features during deposition. Alluvium, deposited by streams not of glacial origin, tends to be finer grained than outwash that was deposited by glacial meltwater streams. **Qaoo** may occur in lenses several meters thick, or may be up to 150 m (500 ft) thick in deep infilled valleys.	**Slope movements**—erosion resistance is low for this unit and it forms a moderate to poor foundation for heavy structures. Slumping is possible in many places. **Abandoned mineral lands—**sand and gravel pits may have targeted those resources for use as aggregate. **River channel migration and flooding**—Because it is associated with modern river channels, areas mapped as **Qaoo** have a high potential for flooding. **Surface water and groundwater quality and quantity**—High infiltration capacity and good groundwater quality. It is generally unsuitable for septic systems.	None documented.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Thick deposits of **Qaoo** exist at Matamoras. Sediment mapped as **Qaoo** was derived from Catskill Formation rocks.
	Alluvium and colluvium, undifferentiated (Qac)	**Qac** occurs in valley bottoms and adjacent slopes and consists of stratified (layered), poorly sorted sand, silt, and minor gravel. **Qac** may be as much as 5 m (15 ft) thick.	**Slope movements**—**Qac** is associated with active slope processes and may contain mass-flow deposits. Slumping is possible. Most development should be avoided on this unit due to the active nature of its formation. Erosion resistance is low. **River channel migration and flooding**—**Qac** along streams has a high potential for flooding.	**Connections to park stories and resources**—are associated with valley-bottom, slope, and riparian habitats.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qac** is currently accumulating in river and stream channels and along slopes.
	Boulder accumulations (Qba)	**Qba** contains unsorted mixtures of angular to rounded boulders. Most boulders are less than 1 m (3 ft) in diameter, but some diameters reach 2 m (6 ft) or more. Most boulders are sandstone.	**Slope movements**—**Qba** is associated with active slope processes and is so localized and irregular in surface expression that it is not a viable candidate for much development. Erosion resistance is moderately low.	**Glacial deposits and features**—**Qba** is associated with glacial and periglacial (colder than usual climates near glaciers) conditions that accelerated frost-wedging of large rocks into smaller boulders. **Connections to park stories and resources**—Exposures of **Qba** occur in open flats, below ledges, in small drainages, and around the margins of peat deposits.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Unit records accelerated weathering and mass-wasting processes associated with cold glacial and periglacial climates.
	Shale-chip rubble (Qsr)	**Qsr** contains unconsolidated, poorly to well-bedded, wedge-shaped deposits of platy fragments of claystone and siltstone. Individual platy fragments are 3 to 5 cm (1 to 2 in) long. Thickness of **Qsr** may reach up to 15 m (50 ft) at the bases of slopes. Beds of **Qsr** dip as much as 25° toward the valleys. Shale colluvium may be interlayered with aeolian sand and alluvium and locally grades to glacial and postglacial stream terraces flanking many valleys.	**Slope movements**—**Qsr** accumulates through active slope processes. Slopes of **Qsr** are likely unstable and susceptible to continued slumping and sliding, particularly when rubble is disturbed. Erosion resistance is moderately low. **Abandoned mineral lands**— **Qsr** could be a mining target for aggregate.	**Glacial deposits and features**—unit records slope processes associated with postglacial conditions. **Paleontological resources**—Sparingly fossiliferous; areas of **Qsr** could be of interest to fossil collectors.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Unit records accelerated weathering and slope processes associated with cold glacial and periglacial climates. **Qsr** occurs in thick aprons at the bases of cliffs on the west side of Minisink Valley.
	Olean ice-contact stratified sand and gravel (Qoic)	**Qoic** contains loose, stratified sand and gravel with occasional large boulders. **Qoic** was deposited by streams and flowing water near stagnant glacial ice. Thickness of **Qoic** deposits ranges from several meters to more than 60 m (200 ft).	**Slope movements**—erosion resistance is moderately low for this unit, and it is susceptible to slumping. Slumps and slides within **Qoic** caused road closures along Highway 209 at mile marker 15. **Dmh** also flanks the road along this stretch.	**Glacial deposits and features**—**Qoic** formed at the leading or retreating edge of glacial ice. **Connections to park stories and resources**—**Qoic** is associated with hummocky (irregular) surface topography and undrained depressions.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Units were deposited by fluvial (river) processes in close proximity to stagnant glacial ice. The material in **Qokt** reflects local bedrock compositions.
	Olean kame terrace (Qokt)	**Qokt** contains loose, stratified sand and gravel, and commonly contains large boulders. The composition of beds and lenses of this unit may change abruptly. It ranges from several meters to more than 60 m (200 ft) thick.	**Slope movements**—erosion resistance is moderately low for this unit, and it is associated with sloping surfaces that could be prone to slumping.	**Glacial deposits and features**—**Qokt** includes valley-bottom and valley-side kames, some upland kames, and kame terraces. **Connections to park stories and resources**—**Qokt** is associated with hummocky (irregular) surface topography and undrained depressions, which may host wetlands.	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Olean till (Qot)		**Qot** includes random mixtures of unsorted, nonstratified (layered) clay, silt, sand, pebbles, cobbles, and boulders. Thickness of this unit ranges from less than 1 m (3 ft) to more than 50 m (164 ft). In outcrop exposures, the till may appear reddish brown, brown, and gray, often dependent on the immediately adjacent bedrock.	**Slope movements**—unvegetated slopes are susceptible to mass wasting. Clay-rich layers, as well as till atop glacially polished bedrock are susceptible to landslides. Debris flows and slumps are also possible. Erosion resistance is moderately low. **River channel migration and flooding**—flooding may be an issue along stream valleys. **Surface water and groundwater quality and quantity**—permeability associated with this unit is highly variable and largely unpredictable.	**Glacial deposits and features**—**Qot** contains lodgment till (deposited from the base of glacial ice) and ablation till (deposited by sudden melting of glacial ice).	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qot** was deposited beneath melting glacial ice as a sudden dump of mixed material that had been entrained within the moving glacier.
QUATERNARY	Talus deposits (Qta)		**Qta** contains unsorted (random sizes), loose, nonstratified (unlayered) angular boulders. Boulders can reach 4 m (15 ft) in length. Deposits of **Qta** as much as 6 m (20 ft) thick form aprons over rock and till at the bases of bedrock cliffs.	**Slope movements**—erosion resistance is moderately low. Unit is associated with active slope processes, such as blockfall and slumping. Infrastructure should be avoided at the bases of cliffs.	**Connections to park stories and resources**—unit contains quartzite and quartz-pebble conglomerate fragments. Possible source of replacement building stones.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qta** was deposited by rockfall after the retreat of the late Wisconsinan glacier (late Pleistocene) and continues to form in the Holocene. Unit records accelerated weathering and mass-wasting processes associated with cold glacial and periglacial climates. These processes continue at a subdued rate today. Unit is especially prevalent on the steep hillslopes of Kittatinny Mountain.
QUATERNARY	Stream terrace deposits	Stream terrace deposits (Qst) Younger Minisink Valley terrace (Qst2) Older Minisink Valley terrace (Qst3)	Units contain stratified (layered), well- to moderately sorted sand and silt. Beds of stream terrace deposits are massive (lacking bedding structures) to laminated and may be as much as 6 m (20 ft) thick. **Qst** forms terraces with surfaces up to 12 m (40 ft) above the modern floodplain. Exposures tend to be yellowish brown. Where more than one terrace level exists, such as in Minisink Valley, the younger terrace is called **Qst2** and the older, higher terrace is **Qst3**. **Qst2** lies 6 to 11 m (20 to 35 ft) above the mean annual elevation of the Delaware River and generally consists of 6 m (20 ft) of fine sand and silt above 6 m (10 ft) of pebble gravel and sand. **Qst3** lies 12 to 15 m (40 to 50 ft) above the river and consists of as much as 3 m (10 ft) of fine- and medium-grained sand.	**Slope movements**—erosion resistance is low. Units may be susceptible to erosion and slope processes when disturbed on slopes. **River channel migration and flooding**—terrace deposits along modern streams and rivers may be inundated during floods.	None documented.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Stream terrace deposits mark former locations of the river above the modern valley. As evidenced by their positions atop glacial outwash and early postglacial fluvial sand and gravel, these units formed after the late Pleistocene glacial deposition ended. These abandoned floodplains record the change in the fluvial regime from a braided glacial meltwater-fed stream to its present incised, low-sinuous meandering course.
QUATERNARY	Eolian deposits (Qe)		**Qe** locally forms winnowed sand sheets and small dunes. In outcrop exposures, the sand and silt of **Qe** are very pale brown to yellowish brown and as much as 5 m (15 ft) thick.	**Slope movements**—erosion resistance is low. **Surface water and groundwater quality and quantity**—units are fairly localized and highly permeable. Wastewater treatment development should probably be avoided in **Qe**.	**Glacial deposits and features**—deposited by wind which transported sediment from unvegetated areas following glacial retreat.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qe** was deposited on unvegetated post-glacial surfaces during the late Pleistocene, early to middle Pleistocene, and Pliocene (on uplands). **Qed** formed just after glacial retreat during the late Pleistocene.
QUATERNARY	Sand dunes (Qed)		**Qed** is fine to very fine sand that occurs in low mounds and ridges. The sand was transported by wind and overlies glacial outwash deposits in Minisink Valley. Deposits of **Qed** may reach 3 m (10 ft) in thickness and appear yellowish brown to brown in outcrop exposures.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Glacial deposits, undifferentiated (Qg)	**Qg** is a map unit that may include till (see **Qot**), ground moraine, and stratified (layered) glacial drift deposits. Unit can reach up to 30 m (100 ft) in thickness.	**Slope movements**—erosion resistance is moderately low. Till atop glacially polished bedrock is susceptible to landslides. **Abandoned mineral lands**—quarried for sand and gravel. **Paleontological Resource Management**—a field-based park survey may uncover Pleistocene fossils within the park. **Surface water and groundwater quality and quantity**—permeability associated with this unit is highly variable and largely unpredictable.	**Paleontological resources**—Pleistocene units within the park potentially contain remains of mastodon, freshwater mollusks, elk-moose, turtles, turkeys, deer, peccary, horse, bison, woodchuck, chipmunk, squirrel, mouse, wood rat, vole, beaver, myotis, bat, mole, raccoon, weasel, skunk, gray fox, wolf, and lynx, among other Pleistocene flora and fauna. **Connections to park stories and resources**—The thickest deposits of **Qg** (more than 60 m [200 ft]) occur under Delaware River near Shawnee Island.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qg** records processes of deposition by glaciers during the most recent glacial advance (Wisconsinan) of the Pleistocene.
	Meltwater terrace deposits (Qmt)	**Qmt** contains stratified, relatively well-sorted sand, cobbles, pebbles, and gravels with minor amounts of silt. This unit was deposited by glacial meltwater streams as flanking terraces within valley-train (see **Qv**), glacial-lake delta deposits, and other meltwater terrace deposits. **Qmt** may be as much as 6 m (20 ft) thick.	**Slope movements**—erosion resistance is moderately low.	**Glacial deposits and features**—includes boulder strath terraces cut into glacial till deposits along meltwater stream courses in upland areas.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qmt** reflects abundant meltwater streams that formed as the last glaciers retreated from the area during the late Pleistocene. Terraces are traceable for long distances downstream and vary between distal and proximal (to glacial ice) deposits.
	Till: Derived from Kittaninny Mountain (Qtq); Derived from Kittaninny and Minisink valleys (Qtk)	Units consist of scattered patches of noncompact to slightly cohesive, boulder "upper till" overlying a mantle of compact "lower till" that was deposited atop bedrock and some older (pre-Wisconsinan glacial period) surficial deposits. **Qtq** includes clasts of unweathered quartz-pebble conglomerate, quartzite, red sandstone, and red shale from Kittatinny Mountain. It appears yellowish brown, light olive brown, reddish brown, and brown in outcrop exposures that may reach 45 m (150 ft) in thickness. **Qtk** appears indistinctly layered and may be yellow brown or light yellowish brown in outcrop. Clasts in **Qtk** include unweathered slate, siltstone, sandstone, dolomite, limestone, chert, minor quartzite, and quartz-pebble conglomerate derived from bedrock outcrops in Kittaniny and Minisink valleys.	**Slope movements**—unvegetated slopes are susceptible to mass wasting. Clay-rich layers may be particularly unstable on slopes and prone to debris flows or slumping. Landslides are documented within glacial tills in the park, particularly where such units overlie glacially polished bedrock. Erosion resistance is moderately low. **Surface water and groundwater quality and quantity**—permeability associated with this unit is highly variable and largely unpredictable.	**Glacial deposits and features**—units are unsorted, reflecting the variety of materials entrained in glacial ice.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—Glacial till was deposited quickly and directly from glacial ice as it melted.
	Kame (Qk)	**Qk** contains layered, well- to poorly sorted sand, silt, pebbles, gravel, and occasional boulders in small collapsed hills and ridges. **Qk** is interlayered with and overlies glacial till deposits. It may be as much as 15 m (50 ft) thick. This lumped unit may contain kames, eskers, kame terraces, and kame deltas. Some portions of this unit may be rather solid with calcareous cement.	**Slope movements**—erosion resistance is low to moderate in this unit (cemented layers). Unit may be unstable on slopes and prone to rockfall where boulders weather out of sloped exposures. **Surface water and groundwater quality and quantity**—**Qk** has highly variable sorting, texture, and permeability, which make the prediction of its water-yield characteristics difficult.	**Glacial deposits and features**—**Qk** includes sediments that filled ice holes and crevasses within glacial ice.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qk** records the morphology and evolution of the glacier during the late Pleistocene (Wisconsinan) event.
	Glacial-lake delta deposits from proglacial lakes (Qod)	**Qod** includes stratified silt, sand, and gravel deposited by glacial meltwater streams into proglacial lakes that formed beyond and at the edge of a stagnant glacier margin. Thickness of **Qod** may reach as much as 45 m (150 ft) and the beds are yellowish brown, reddish brown, and light gray in exposures. Layers of **Qod** tend to occur in crossbeds that dip (are tilted) 20° to 35° toward the center of the lake basin. Further into the basin, the deposits become finer grained and are not tilted as steeply.	**Slope movements**—erosion resistance is moderately low.	**Glacial deposits and features**—surfaces of **Qod** deposits are very kettled (pocked with small, round depressions).	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qod** records the margins of a series of proglacial lakes, including lakes in Paulins Kill and Wallpack valleys, and Lake Owassa in the Kittatinny Valley, that formed as glaciers melted and retreated from the area.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Valley-train deposits (Qv)	**Qv** consists of stratified (layered), well- to moderately sorted sand, boulder-cobble to pebble gravel, and minor silt. **Qv** was deposited by meltwater streams originating at the glacier and extending more than 8 km (5 mi) beyond the glacier margin. **Qv** may be as much as 30 m (100 ft) thick.	**Slope movements**—erosion resistance is moderately low. **Surface water and groundwater quality and quantity**—units may form permeable, unconfined surface aquifers.	**Glacial deposits and features**—**Qv** contains bedding, crossbeds, troughs, and terraces, that reflect a fluvial origin. Channels and bars meandered across the landscape as the meltwater stream system developed..	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qv** represents an extensive meltwater stream system that developed at the margins of retreating glaciers during the late Pleistocene. **Qv** was deposited atop glacial lake deposits (see **Qod** and **Qd**) as glacial lakes drained and their basins filled with stream deposits. In places, thin eolian sand deposits (see **Qe**) overlie **Qv**, indicating windy, unvegetated conditions that existed after glacial retreat.
	Outwash fan: Near Branchville (Qf) Dry Brook (Qfdb) Adams Creek (Qfa)	**Qf**, **Qfdb**, and **Qfa** are all stratified, well- to moderately sorted sand, cobble-pebble gravel, and minor silt deposits. Bedding within these units is tilted (dips) toward the larger, trunk valley by as much as 10°. Deposits may be as much as 18 m (60 ft) thick and grade into valley-train deposits (see **Qv**) from individual drainages at Branchville, Dry Brook, and Adams Creek.			**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—All three units formed as deposits at the mouths of individual streams where they joined the major drainage of the Minisink Valley during the last glacial retreat of the late Pleistocene.
	Recessional moraine: Recessional moraine (Qwmrk) Dingmans Ferry (Qdfm) Ogdensburg-Culvers Gap (Qom) Recessional moraine (Qm)	**Qwmrk**, **Qdfm**, **Qom**, and **Qm** contain mixed sediments as much as 24 m (80 ft) thick that were deposited directly from glacial ice along recessional (retreating) ice margins. Some areas contain till (see **Qtq**). Sediments include unstratified to poorly stratified sand, gravel, and silt. Recessional moraines locally overlie till deposits in uplands and outwash deposits in river valleys. **Qdfm** and **Qom** have nearly identical compositions where they occur at Dingmans Ferry and Ogdensburg-Culvers Gap, respectively.	**Slope movements**—erosion resistance is moderately low. Ridges may be mantled by boulders that may be prone to rockfall.	**Glacial deposits and features**—segmented ridges in these units mark former lobate (tongue-shaped) glacier margins. Surface topographies of these units may be irregular (hummocky) and form ridges and knolls.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qdfm** was deposited at the active margin of the Kittatinny and Minisink Valley ice lobes.
	Glacial-lake delta deposits-Lake Owassa (Qd)	**Qd** includes stratified silt, sand, and gravel deposited by glacial meltwater streams into proglacial lakes that formed beyond and at the edge of a stagnant glacier margin. Thickness of **Qd** may reach as much as 30 m (100 ft) and the beds are yellowish brown, reddish brown, and light gray in exposures. Layers of **Qd** tend to occur in crossbeds that dip (are tilted) 20° to 35° toward the center of the lake basin. Further into the basin, the deposits become finer grained and are not tilted as steeply.	**Slope movements**—erosion resistance is moderately low.	**Glacial deposits and features**—the surfaces of **Qd** deposits are very kettled (pocked with small, round depressions).	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qd** (much like **Qod**) was deposited in glacial Lake Owassa, which formed in the Kittatinny Valley in successively younger deltas that advanced (prograded) basinward as deposition progressed.
	Outwash fan-Dingmans Creek (Qfd)	**Qfd** is stratified, well- to moderately sorted sand, cobble-pebble gravel, and minor silt deposits in fan-shaped lobes. Bedding within these units is tilted (dips) toward the larger, trunk valley by as much as 10°. Deposits may be as much as 18 m (60 ft) thick and grade into valley-train deposits (see **Qv**) from individual drainages at Dingmans Creek.	**Slope movements**—erosion resistance is moderately low. **Surface water and groundwater quality and quantity**—these units are all relatively well drained and may function as unconfined surficial aquifers.	**Glacial deposits and features**—units were deposited by glacial meltwater.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qfd** formed as deposits at the mouth of an individual stream where it joined the major drainage of the Minisink Valley during the last glacial retreat of the late Pleistocene.
	Glaciofluvial terrace deposits (Qwft)	**Qwft** contains sand, pebble-to-cobble gravel, and minor silt in yellowish-brown to reddish-brown exposures as much as 12 m (40 ft) thick. These terraces formed along the courses of glacial meltwater streams.			**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qwft** and **Qwfv** record the presence of glacial streams that formed during the melting of the late Pleistocene glaciers.
	Glaciofluvial plain deposits (Qwfv)	**Qwfv** formed by meandering glacial streams as a planar surface. **Qwfv** contains sand, pebble-to-cobble gravel, and minor silt in yellowish-brown to reddish-brown exposures as much as 24 m (80 ft) thick.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY	Ice-contact deposits (Qwic)	**Qwic** contains sand, pebble-to-cobble gravel, occasional boulders, and minor silt deposits. In exposures as much as 45 m (150 ft) thick, this unit appears yellowish brown to reddish brown.	**Slope movements**—erosion resistance is moderately low. **Surface water and groundwater quality and quantity**—these units are all relatively well drained and may function as unconfined surficial aquifers.	**Glacial deposits and features**—**Qwic** occurs as knolls and ridges that are higher than adjacent glacial-lake levels or glaciofluvial plains (see **Qwfv**).	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qwic** formed in ice-walled basins during the late Pleistocene glaciation.
QUATERNARY	Older till (Qit)	**Qit** occurs as grayish to dark-yellowish-orange and brown, deeply weathered, mixed deposits of silt and clay with occasional cobbles. Unit may be as much as 6 m (20 ft) thick.	**Slope movements**—till atop glacially polished bedrock is susceptible to landslides. Debris flows and slumps are also possible. **Surface water and groundwater quality and quantity**—clay-rich units such as **Qit** may form relatively impermeable layers that can underlie wetlands. Permeability associated with this unit is highly variable and largely unpredictable.	**Glacial deposits and features**—till formed as mixed deposits when ice melted quickly and dumped all entrained material at once.	**Gap formation, ice age glaciation, and Appalachian Mountain erosion**—**Qit** represents deposits from a glaciation (Illinoian?) that occurred earlier than the last glacial maximum (Wisconsinan) in the late Pleistocene.

Bedrock Geologic Map Unit Properties Table: Delaware Water Gap National Recreation Area

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN	Catskill Formation	Long Run Member (Dclr)	**Dclr** is 914 m (3,000 ft) of alternating beds of gray sandstone, and red siltstone and shale. Grain size becomes finer toward the tops of some beds, also known as a fining-upward sequence or Bouma cycle. Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Surface water and groundwater quality and quantity**—as an aquifer, **Dclr** can yield 150 L/min (40 gal/min); emerging groundwater is low in solutes, soft, and potentially corrosive.	**Paleontological resources**—**Dclr** contains rare spiriferid brachiopods, roots, and burrows. **Sedimentary features**—**Dclr** contains possible turbidites (submarine landslides). Planar bedding, crossbeds, red beds, mudcracks, channels, and load casts are also present. **Dclr** contains dark, yellowish-orange, ferroan (iron-rich) dolomite nodules.	**Appalachian mountain building and the assembly of Pangaea**—Catskill Formation rocks were deposited in a delta that migrated as the Acadian highlands rose to the southeast. The Catskill Formation is the youngest Paleozoic unit on the bedrock map. Younger Paleozoic rocks were eroded away from the Middle Delaware River valley region and adjacent Pocono Plateau. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Beaverdam Run Member (Dcbr)	**Dcbr** contains 91 m (300 ft) of greenish-gray sandstone with lesser amounts of siltstone and shale. Unit weathers to dark yellowish orange to brown. Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Surface water and groundwater quality and quantity**—as an aquifer, **Dcbr** can yield 170 L/min (45 gal/min).	**Paleontological resources**—**Dcbr** contains burrows, *Tentaculites*, crinoids, brachiopods, and plant fragments. **Sedimentary features**—planar bedding, crossbeds, channels, and load casts.	
		Walcksville Member (Dcw)	**Dcw** is 488 m (1,600 ft) of alternating greenish-gray sandstones and red shales. A notable, 1.2-m- (4-ft-) thick, grayish-reddish-purple shale chip conglomerate occurs in this unit. Fining-upward sequences occur in most beds. Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Surface water and groundwater quality and quantity**—as an aquifer, **Dcw** can yield 132 L/min (35 gal/min).	**Paleontological resources**—**Dcw** contains bioturbated beds. **Sedimentary features**—planar bedding, crossbeds, ripple laminations, and mudcracks.	
		Shohola Member (Dcs)	**Dcs** consists of interbedded 2- to 8-m- (5- to 25-ft-) thick greenish-gray and grayish red very fine to medium-grained sandstone and sandy shale with lesser amounts of gray sandstone and shale. Bedding in **Dcs** is thin to very thick. Unit is more than 610 m (2,000 ft) thick. Moderately high erosion resistance. Lower erosion resistance for shale layers.	None documented.	**Sedimentary features**—**Dcs** contains conglomerates and load casts near the bases of the sandstone beds. **Connections to park stories and resources**—greenish-gray and gray sandstone beds have been quarried for flagstone.	
		Analomink Red Shale Member (Dca)	**Dca** is about 30 m (100 ft) of medium grayish-red, silty, finely laminated shale with thin beds of brownish-gray sandy siltstone and very fine-grained sandstone. Moderate erosion resistance.	**Slope movements**—Thick shale units may form zones of weakness in the rock column, making undercut exposures prone to movement	None documented.	
		Delaware River Flags Member (Dcd)	**Dcd** contains cyclic sequences of gray, planar-bedded and cross-bedded, fine- to medium-grained sandstone with some thin red siltstone and claystone, as well as thin coarse-grained conglomerate beds. Individual beds within **Dcd** range from a few centimeters to more than 1 m (4 ft) thick. Maximum thickness of **Dcd** is 853 m (2,800 ft). Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Surface water and groundwater quality and quantity**—as an aquifer, **Dcd** can yield 379 L/min (100 gal/min), which is adequate for domestic wells.	**Connections to park stories and resources**—**Dcd** sandstones can split evenly into smooth flagstones. Sandstones are low-rank graywackes.	
		Towamensing Member (Dct)	**Dct** includes medium-gray sandstone interlayered with greenish-gray siltstone and shale. Some coarser-grained conglomerate layers are present locally. Locally, the thickness of **Dct** can reach 495 m (1,625 ft). Dct weathers to light gray to olive gray and pale brown to grayish orange. Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Surface water and groundwater quality and quantity**—as an aquifer, **Dct** can yield 114 L/min (30 gal/min). Emerging groundwater is soft.	**Sedimentary features**—crossbeds. **Connections to park stories and resources**—sandstones are “flaggy.”	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN	Trimmers Rock Formation	Trimmers Rock Formation, undivided (Dtr)	**Dtr** consists of gray to olive-gray, thin- to medium-bedded sandstone, interlayered with siltstone and silty shale. Fining-upward cycles (Bouma cycles) are common in this unit. **Dtr** is about 323 m (1,060 ft) thick. Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Slope movements**—**Dtr** tends to form a loose, colluvial shale-chip gravel. **Dtr** is more resistant and supports a steeper slope than does **Dmh** (below). **Surface water and groundwater quality and quantity**—as an aquifer, **Dtr** can yield 341 L/min (90 gal/min). Emerging groundwater is soft, low in solutes, and potentially corrosive.	**Paleontological resources**—**Dtr** fossil remains include diverse plants, corals, bryozoans, brachiopods, bivalves, gastropods, "worms," trilobites, arthropods, crinoids, and fish. **Sedimentary features**—planar laminations, crossbeds, load and groove casts. **Connections to park stories and resources**—some sandstones in the upper beds could be quarried for flagstones.	**Appalachian mountain building and the assembly of Pangaea**—mountains uplifted by the Acadian orogeny affected sedimentary system. Dtr, Dtm, and Dtsb record the transition between marine conditions and the advancing Catskill deltaic system. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Millrift Member (Dtm)	**Dtm** contains dark- to medium-gray siltstone, shale, and sandstone in thin- to medium-bedded exposures. Some sandstone beds are massive and thick bedded. The maximum thickness of this member is approximately 305 m (1,000 ft). Moderately high erosion resistance. Lower erosion resistance for shale layers.	**Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—as an aquifer, **Dtm** and **Dtsb** can yield 227 L/min (60 gal/min). Emerging groundwater can contain excessive manganese locally.		
		Sloat Brook Member (Dtsb)	**Dtsb** contains more dark- to medium-gray siltstone and silt shale than does **Dtm**, which has more sandstone. The maximum thickness of this member is approximately 290 m (950 ft). Moderate erosion resistance.			
	Hamilton Group-Mahantango Formation	Mahantango Formation, undivided (Dmh)	**Dmh** is predominantly medium- to dark-gray, laminated to finely bedded siltstone, claystone, clay shale, and silty shale. Although regionally variable, **Dmh** is approximately 610 m (2,000 ft) thick. It weathers to grayish orange to dark yellowish orange and brown. Units have moderate erosion resistance; lower erosion resistance for claystone and shale-rich beds.	**Slope movements**—**Dmh** and **Dmhn** tend to weather into thick, shale-chip gravel that mantles slopes. **Dmh** cannot support steep slopes relative to other, sandstone-rich units (see **Dtr**). **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Seismic hazards**—slumps and slides within **Dmh** caused were triggered in part by a 2011 earthquake and the saturation of material in severe storm events. **Qoic** also flanks the road along this stretch. **Surface water and groundwater quality and quantity**—as an aquifer, **Dmh** can yield 265 L/min (70 gal/min). Emerging groundwater is soft to moderately hard, basic, low in solutes, and potentially corrosive.	**Paleontological resources**—**Dmh** contains bioturbated beds and biostromes. Fossils include brachiopods, crinoids, bryozoans, gastropods, pelecypods, trilobites, cephalopods, and solitary and colonial corals. Sea star *Hudsonaster wardi* was first described from Mahantango Formation rocks near Milford. **Dmhc** is a biostrome containing brachiopods, crinoids, bryozoans, gastropods, pelecypods, trilobites, cephalopods, and solitary (horn) and colonial (horn) corals. Unit is also known as the "Centerfield Reef" due to the abundance of fossils. Popular fossil collecting areas exist near Saylorsburg. **Sedimentary features**—the lower contact with **Dmb** (below) is gradational, with a marked difference in hardness. **Dml** is harder than **Dmb**.	**Appalachian mountain building and the assembly of Pangaea**—Hamilton Group rocks and fossils record shallower water conditions than those responsible for the Marcellus. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Upper Member (Dmu)	**Dmu** is medium-dark-gray, fairly coarse-grained, thin-bedded siltstone and silty shale. Unit is approximately 213 m (700 ft) thick.			
		Nis Hollow Member (Dmhn)	**Dmhn** contains medium-light- to medium-dark-gray, laminated to medium-bedded, blocky siliceous (contains abundant silica) siltstone and sandstone. In weathered outcrop exposures, **Dmhn** appears brown to dark yellowish brown and is about 5 m (15 ft) thick.			
		Centerfield Member (Dmhc)	**Dmhc**, a conspicuous zone about 274 m (900 ft) above the base of **Dmh**, is a 5- to 8-m- (15- to 25-ft-) thick biostrome (layered accumulation of fossils) consisting of medium-dark- to dark-gray calcareous siltstone and laminated to poorly bedded silty shale. Unit weathers to olive gray, grayish orange, and dark yellowish brown.			
		Lower Member (Dml)	**Dml** is medium-dark-gray, fairly coarse-grained, thin-bedded siltstone and silty shale. Unit is approximately 335 m (1,100 ft) thick.			
		Biostrome (Dmhf)	**Dmhf** consists of medium-light-gray siltstone biostrome (layered accumulation of fossils) beds that occur at varying stratigraphic horizons within **Dmh**. Weathered exposures of **Dmhf** are grayish orange, dark yellowish orange, and brown.			
		Mahantango Formation and Marcellus Shale, undivided (Dh)	**Dh** consists of shale and siltstone. The Hamilton Group is 790 to 850 m (2,600 to 2,800 ft) thick. Locally, **Dh** may include sandstone and conglomerate.			

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN	Hamilton Group-Marcellus Shale	Marcellus Shale (Dm)	**Dm** is dark-gray to grayish-black clay shale and silty clay shale. Some minor argillaceous (considerable clay content) siltstone beds occur locally. Unit is carbonaceous (contains carbon). **Dm** is approximately 290 m (950 ft) thick. Weathered exposures of **Dm** appear light to medium gray, light brown to yellowish brown, and dark yellowish orange to grayish orange. Erosion resistance is moderate.	**Slope movements**—**Dm** commonly weathers to produce thick, unconsolidated deposits that are prone to movement. The basal shales are locally oversteepened (in areas such as along U.S. Hwy 209) due to glacial erosion during the last ice age and are constantly spalling off, forming shale-chip rubble (**Qsr**) at cliff bases. **Marcellus Shale gas extraction**—Marcellus Shale is a regionally significant target for natural gas extraction. Viable deposits do not occur within the park, but proximity to active exploration poses resource management concerns. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—as an aquifer, **Dm** can yield 416 L/min (110 gal/min). Emerging groundwater is soft to moderately hard, basic, low in solutes, and potentially corrosive. Drilling for Marcellus Shale gas creates a potential water quantity and/or quality threat	**Paleontological resources**—marine fossils are present in **Dm**. Marcellus Shale contains fossil remains of plant material, conulariids, bryozoans, brachiopods, bivalves, "worms," cephalopods, trilobites, and arthropods. **Sedimentary features**—quartz-chlorite (chert) nodules occur parallel to bedding.	**Appalachian mountain building and the assembly of Pangaea**—Black, pyritic shales of **Dh**, **Dm**, **Dmb**, and **Dmsu** accumulated in an anoxic basin, which facilitated the burial of organic-rich sediments. That organic material became the natural gas and petroleum products now extracted throughout the northeast. Volcanic ash layers signal a return of tectonic activity and the beginning of the Acadian orogeny. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Brodhead Creek Member (Dmb)	**Dmb** is dark-gray, laminated to poorly bedded silty shale. Unit is approximately 244 to 274 m (800 to 900 ft) thick. The lower contact of **Dmb** is gradational with **Dmsu** (below). Erosion resistance is moderate.		**Paleontological resources**—**Dmb** is sparingly fossiliferous. **Type sections**—**Dmb** described from exposures near Stroudsburg. **Sedimentary features**—**Dmb** contains gray, shaly limestone concretions up to 0.3 m (1 ft) long.	
		Stony Hollow and Union Springs shale members, undivided (Dmsu)	**Dmsu** contains interlayered dark-gray, limy (limestone-rich) silty to sandy shale, silty shale, and limy shale. Unit is approximately 60 m (200 ft) thick. Continuous limestone beds pinch and swell within this unit. Erosion resistance is moderate.		**Paleontological resources**—**Dmsu** contains poorly preserved brachiopods and is considered sparingly fossiliferous.	
	Onondaga Limestone	Onondaga Limestone, undivided (Dou)	**Dou** members include shale and limestone of the Schoharie Formation (see **Dse**), Carlisle Center Siltstone, Buttermilk Falls Limestone (**Db**), and Espous Shale (see **Dse**). Moderate erosion resistance.	**Slope movements**—**Db** weathers to deep deposits of white, gray, orange, brown, and red clay. These clay deposits may be prone to movement. Pits and collapsed mine workings outline exposures of **Db**. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—carbonate rocks of **Db** buffer acidity in streams flowing over them.	**Paleontological resources**—lower portions of **Db** have large (up to 2.5 cm [1 in] in diameter) crinoid columns. **Db** contains ostracode and brachiopod debris. **Type sections**—**Db** described from exposures near Stroudsburg. **Sedimentary features**—chert nodules exist within **Db**. **Cave and karst**—**Dou** and **Db** host a variety of karst features. **Connections to park stories and resources**—chert nodules may have provided tool material for American Indians. **Db** has been utilized for road material.	**Appalachian mountain building and the assembly of Pangaea**—Onondaga Limestone was deposited during a period of marine shallowing (regression). Volcanic ash layers signal a return of tectonic activity and the beginning of the Acadian orogeny. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Buttermilk Falls Limestone (Db)	**Db** is clayey to silty, thin- to medium-bedded limestone. Upper portions of the unit are medium- to dark-gray, fossiliferous, clayey limestone. Middle portions of the unit are medium-gray, fossiliferous, silty, limy claystone with some limestone lenses. The lower portions of the unit contain medium- to dark-gray, fossiliferous, very limy siltstone and claystone. **Db** is about 80 m (270 ft) thick. Moderate erosion resistance.			
	Palmerton Sandstone (Dpt)		**Dpt** consists of medium-dark- to very-light-gray, medium- to very coarse-grained sandstone and conglomeratic (coarser) sandstone. A few beds of siltstone and finer-grained sandstone occur in the lower portions of the unit. Weathered outcrops of **Dpt** appear pale yellowish orange to dark yellowish orange and grayish orange. Unit is locally 20 m (66 ft) thick. Sandstone and conglomerate have moderately high erosion resistance.	**Slope movements**—**Dpt** may be vulnerable to rockfall if undercut and exposed on slopes.	**Paleontological resources**—**Dpt** contains favositid corals, crinoid columnals, and brachiopod molds. **Sedimentary features**—**Dpt** may contain brown ironstone concretions. Rounded quartz pebbles in **Dpt** may be up to 2 cm (0.75 in) long.	**Appalachian mountain building and the assembly of Pangaea**—massive sandstones and conglomerates of this unit reflect a shift toward nearshore, higher-energy depositional environments during this period of the Devonian. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
	Schoharie Formation and Esopus Formation, undivided (Dse)		Mapped where **Ds** and **De** cannot be distinguished, **Dse** is poorly exposed and locally deeply weathered. In the upper portions, it contains evenly bedded, fossiliferous, cherty siltstone to fine-grained sandstone that appears gray in fresh exposures. Weathered exposures are gray, orange, and brown. Lower portions o.f **Dse** are dark-gray, laminated to fine-bedded silty shale and shaley siltstone. Generally weathers to darker tones than the upper portion. Total thickness of this unit is approximately 46 m (150 ft). **Dse** is exposed along Pennsylvania State Route 33.	**Slope movements**—**Dse** is deeply weathered in this area and may be prone to slumping and slope movements in areas exposed on slopes.	**Paleontological resources**—**Dse** is fossiliferous and contains abundant *Taonurus* and burrows. **Connections to park stories and resources**—occasional chert may have provided tool and trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—**Dse**, **Ds**, and **De** record a return to deeper water depositional environments following a period of sea level drop and subsequent erosion. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN	Schoharie Formation (Ds)		**Ds** consists of medium-gray to grayish-black, medium- to thick-bedded calcareous (contains some limestone) siltstone and silty limestone. Beds range from a few centimeters to 2 m (6 ft) thick. **Ds** is approximately 30 m (100 ft) thick and weathers to light gray. It has less-developed cleavage (propensity to break apart on planar partings) than **De** (below). **Ds** is exposed in the Eureka Stone Co. quarry at the southwest end of Godfrey Ridge. **Ds** is more resistant than **De** to erosion.	**Slope movements**—calcareous cements may dissolve, leaving portions of this unit friable and prone to movement. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park.	**Paleontological resources**—**Ds** has burrowed layers (*Taonurus*) and brachiopods are common. The Schoharie Formation contains fossil remains of corals, brachiopods, gastropods, cephalopods, and trilobites. **Connections to park stories and resources**—occasional dark-gray chert may have provided tool and trade material for American Indians. **Ds** could be used for crushed stone and has been used for road material.	**Appalachian mountain building and the assembly of Pangaea**—**Dse**, **Ds**, and **De** record a return to deeper water depositional environments following a period of sea level drop and subsequent erosion. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
	Esopus Formation (De)		**De** contains medium- to dark-gray, shaley, laminated siltstone and lesser silty shale and minor calcareous (contains limestone) siltstone. **De** weathers to a lighter shade of gray. **De** is approximately 55 m (180 ft) thick. **De** is less resistant than **Ds** to erosion. Outcrops of **De** exist 1 km (0.6 mi) north of Bossardsville.	**Slope movements**—calcareous cements may dissolve, leaving portions of this unit friable and prone to Slope movements. Clayey layers of this unit may be prone to slumping if exposed on slopes. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park.	**Paleontological resources**—Brachiopods are uncommon, but the unit is extensively burrowed (*Taonurus* and *Skolithos*).	
	Oriskany Group	Oriskany Group, undivided (Do)	**Do** contains approximately 34 m (110 ft) of interbedded light- to dark-gray, thin to thick layers of conglomeratic, limy, coarse-grained quartz sandstone and silty, quartzose limestone beds. The sandstone component decreases lower in the unit. **Do** weathers to brownish orange and orangish gray. sandstones within **Do** are moderately resistant to erosion and form ledges up to 5 to 6 m (15 to 20 ft) thick.	**Slope movements**—Ledges may be prone to rockfall. Calcareous cements may dissolve, leaving portions of this unit friable and prone to Slope movements. Erosion resistance is moderately high. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—carbonate rocks of **Do** buffer acidity in streams flowing over them.	**Paleontological resources**—**Do** contains abundant spiriferid brachiopods and partly silicified (cemented by silica-rich compound) coquina. **Sedimentary features**—quartz pebbles within **Do** may be up to 1 cm (0.5 in) long. **Caves and karst**—limestone and calcareous cements within these units are soluble and may host karst features such as pits, caves, and sinking streams. **Connections to park stories and resources**—sandstone ledges within **Do** may provide nesting habitat. As determined from archaeological sites within the park, occasional chert beds and lenses provided tool and trade material for American Indians. **Do** has been utilized for road material.	**Appalachian mountain building and the assembly of Pangaea**—Oriskany Group rocks were deposited near sea level in supratidal and intertidal flats, barrier bars, and subtidal zones. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
		Ridgely Sandstone (Dr)	**Dr** contains medium- to coarse-grained, limonitic and hematitic (iron-rich), conglomeratic sandstone. Weathered outcrop exposures of **Dr** are gray to yellowish orange. Dr is less than 30 m (100 ft) thick.		**Paleontological resources**—**Dr** has spiriferid brachiopod molds. **Sedimentary features**—**Dr** contains pebbles up to 2 cm (0.75 in) long.	
		Ridgely Sandstone and Shriver Chert, undivided (Drs)	**Drs** includes **Dr** (above) and underlying Shriver Chert, which consists of interbedded, dark-gray chert and limestone in roughly equal amounts with minor medium- to light-gray, calcareous, medium- to very coarse-grained sandstone and conglomerate beds. The chert unit is 16 to 25 m (54 to 82 ft) thick.		**Paleontological resources**—chert layers contain abundant spiriferid brachiopods. **Connections to park stories and resources**—dark-gray chert (present as nodules, lenses, and irregular beds) may have provided tool and trade material for American Indians. Beds of chert may be more than 3 m (10 ft) thick.	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN	Helderberg Group	Helderberg Group, undivided (Dhg) Port Ewen Shale, Minisink Limestone, and New Scotland Formation, undivided (Dph) Port Ewen Shale (Dp) Minisink Limestone and New Scotland Formation, undivided (Dmn) Coeymans Formation, undivided (Dc)	**Dhg** includes Alsen, Becraft, New Scotland (**Dmn**), Kalkberg, Coeymans (**Dc**), and Manlius limestones; and Port Ewen Shale (**Dph**, **Dp**), and Rondout Dolostone (**DSohr**, below). **Dph** consists of **Dp**, which is 27 m (90 ft) of fossiliferous, medium- to dark gray, irregularly bedded, limy siltstone and shale overlying 18 m (60 ft) of gray irregularly laminated (finer bedding) limy shale and siltstone. The Minisink Limestone (**Dph** and **Dmn**) is 4 m (14 ft) thick and consists of dark-gray, fine-grained, clayey limestone. The New Scotland Formation (**Dph** and **Dmn**) contains 23 m (75 ft) of dark-gray, fossiliferous silty, limy shale with lenses of clayey, fine-grained limestone. **Dc** is approximately 34 m (110 ft) of medium- to dark-gray, fossiliferous limestone and light-gray, coarse-grained sandstone with very coarse-grained quartz pebble conglomerate. **Dp** is exposed at the east end of Godfrey Ridge. Erosion resistance is moderate; it is higher for sandstone and conglomerate.	**Slope movements**—calcareous cements may dissolve, leaving portions of this unit friable and prone to movement. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—carbonate rocks of **Dmn** buffer acidity in streams flowing over them.	**Paleontological resources**—**Dph** is fossiliferous. **Dp** is burrowed and contains brachiopods, corals, ostracodes, trilobites, and crinoids. In an area north of Tocks Island, **Dc** includes a reef facies unit of light- to pinkish-gray, bioclastic (composed of fragments made by organisms) limestone. **Dc** also contains trace fossils. Rounded outcrop of Coeymans reef with stromatoperoids and other fossils along River Road is suitable for interpretation **Type sections**—Minisink Limestone (Dph or Dmn) described from exposures near Minisink Hills. Flatbrookville and Maskenozha members of New Scotland Formation (not mapped separately) described from exposures along “Fllatbrookville—Wallpack Center Road.” Depue Limestone and Shawnee Island members of Coeymans Formation (not mapped separately) described from exposures near Shawnee on Delaware. Peters Valley Member of Coeymans Formation (not mapped separately) described from southwest side of Wallpack Ridge. Stormville Member of Coeymans Formation (not mapped separately) described from exposures on Godfrey Ridge. **Cave and karst**—limestone and calcareous cements within these units are soluble and may host karst features such as pits, caves, and sinking streams. **Connections to park stories and resources**—as determined from archaeological sites within the park, nodules and nodular dark-gray chert beds and lenses provided tool and trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—Trace fossils within **Dc** record alternating high-energy to moderately low-energy shallow marine environments during this period of the Devonian. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
DEVONIAN-SILURIAN	Lower part of the Helderberg Group and Rondout Formation, undivided (DShr)		**DShr** is poorly exposed limestone; argillaceous (contains an appreciable amount of clay) limestone; calcareous sandstone, conglomerate, and shale; and dolomite. Unit is approximately 61 m (200 ft) thick. Erosion resistance is moderate; it is higher for sandstone and conglomerate.	**Slope movements**—calcareous cements may dissolve, leaving portions of this unit friable and prone to movements.	See corresponding descriptions (**DSrp**, **DSohr**, **DSrd**, **Dmn**, and **Dc**).	See corresponding descriptions.
DEVONIAN-SILURIAN	Shriver Chert of the Oriskany Group, Helderberg Group and Rondout Formation, undivided (DSohr)		Unit **DSohr** includes the Shriver Chert (**Drs**), Port Ewen Shale (**Dph** and **Dp**), Minisink Limestone (**Dph** and **Dmn**), New Scotland Formation (**Dph** and **Dmn**), Coeymans Formation (**Dc**), and dolomite, shale, and limestone of the Rondout Formation (**DShr**, **DSrp**, and **DSrd**).	See corresponding descriptions.	See corresponding descriptions.	See corresponding descriptions.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
DEVONIAN SILURIAN	Rondout Formation (DSrp)	**DSrp** consists of dolostone, limestone, Binnewater Sandstone, High Falls Shale, Warwarsing Limestone, Decker Limestone, Bossardville Limestone (**Sbv**), and shale and dolostone of the Poxono Island Formation (**Sp**). Part of **DSu**. Unit ranges from 0 to 120 m (0 to 400 ft) thick.	**Slope movements**—Calcareous cements may dissolve, leaving portions of this unit friable and prone to movements. In areas where sandstone is undercut, the units may be prone to rockfall (e.g., Hibachi Rock). **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—carbonate rocks of **DSrd** buffer acidity in streams flowing over them.	See corresponding descriptions (**Sbv**, **Sp**, **DSrd**, and **DSu**).	See corresponding descriptions.
	Rondout and Decker formations, undivided (DSrd)	**DSrd** contains 9 m (30 ft) of light to dark gray calcareous shale and argillaceous limestone (contains a considerable amount of clay) with dark- to medium-gray dolomite and biostromal limestone. These layers overlie 26 m (85 ft) of calcareous quartz-pebble conglomerate, sandstone, siltstone, and argillaceous limestone. Erosion resistance is moderate; it is higher for sandstone and conglomerate.		**Paleontological resources**—**DSrd** contains leperditiid ostracodes and biostromal limestone. **Type sections**—Duttonville and Mashipacong members of Rondout Formation described from exposures near Duttonville. Clove Brook and Wallpack Center members of Decker Formation described from exposures near Dutonville and Wallpack Center, respectively. **Sedimentary features**—mudcracks, crossbeds, and planar bedding. **Cave and karst**—limestone, calcareous cement, and, to a lesser extent, dolomite within these units are soluble and may host karst features such as pits, caves, and sinking streams. **Connections to park stories and resources**—limestone beds have been quarried and the limestone burned to produce agricultural lime.	**Appalachian mountain building and the assembly of Pangaea**—These units represent hundreds of millions of years of mixed marine, nearshore, deepwater, and terrestrial deposition on the eastern coast of ancient North America. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
	Undifferentiated Devonian and Silurian rocks (DSu)	**DSu** is a sequence of carbonates (limestone and dolomite), shales, and siltstones, with minor calcareous sandstone and conglomerate. All of these rock types exist in a structurally complex configuration. Erosion resistance is moderate; it is higher for sandstone and conglomerate.	**Slope movements**—Calcareous cements may dissolve, leaving portions of this unit friable and prone to Slope movements. In areas where sandstone is undercut, the units may be prone to rockfall. **Surface water and groundwater quality and quantity**—as an aquifer, **DSu** can yield 606 L/min (160 gal/min). Carbonate rocks can yield much more, possibly because of increased permeability due to dissolution conduits. Emerging groundwater from noncarbonates is moderately hard and low in solutes. Emerging groundwater from carbonate units is high in solutes and hard to very hard.	See corresponding descriptions of Devonian and Silurian units.	**Appalachian mountain building and the assembly of Pangaea**—**DSu** represents hundreds of millions of years of mixed marine, nearshore, deepwater, and terrestrial deposition on the eastern coast of ancient North America. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
SILURIAN	Decker Formation (Sd)	**Sd** consists of fine- to medium-bedded, arenaceous, argillaceous (contains considerable clay), pyritic, partly dolomitic limestone interlayered with minor amounts of conglomerate, shale, siltstone, and dolomite. Limestone is very fine to medium grained, with shades of gray, green, and purple in fresh exposures. Weathered exposures are gray, yellow, and orange. The sandstones are mostly gray and weather to gray, yellow, and orange. The shale and siltstone have green and gray shades that weather to yellowish gray and orange. Dolomite is gray and green and weathers to pale yellowish orange. **Sd** is approximately 21 to 30 m (70 to 100 ft) thick. Erosion resistance is moderate; it is higher for sandstone and conglomerate.	**Slope movements**—Calcareous cements and limestones may dissolve, leaving portions of this unit friable and prone to Slope movements. In areas where sandstone is undercut, the unit may be prone to rockfall.	**Paleontological resources**—**Sd** contains brachiopods, corals, and ostracodes, as well as trace fossils and trails. **Type sections**—Clove Brook and Wallpack Center members of Decker Formation described from exposures near Dutonville and Wallpack Center, respectively. **Sedimentary features**—mudcracks. Conglomeratic layers contain quartz pebbles up to 1.3 cm (0.5 in) long.	**Appalachian mountain building and the assembly of Pangaea**—Units record the continued marine depositional setting during the Silurian and into the Devonian. Deformed during the Alleghany Orogeny, during which Pangaea was assembled. The paleontological record of the Decker Formation records a shallow marine, moderate- to low-energy environment punctuated by higher-energy storm-like conditions.

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
SILURIAN	Bossardville Limestone (Sbv)		**Sbv** is predominantly fine-grained limestone, and argillaceous (contains considerable clay) and pyritic limestone. Locally, thin layers of light-olive-gray shale exist. Fresh exposures of **Sbv** are gray and weather to grayish orange. Unit is approximately 30 m (100 ft) thick. Erosion resistance is moderately high.	**Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—carbonate rocks of **Sbv** buffer acidity in streams flowing over them.	**Paleontological resources**—**Sbv** contains possible algal laminations and leoerditiid ostracode fossil-rich layers. Other fossils in this unit include crinoids, brachiopods, and rugose corals. **Sedimentary features**—laminations, ripples, and mudcracks. **Cave and karst**—limestone within this unit is soluble and may host karst features such as pits, caves, and sinking streams. **Connections to park stories and resources**—**Sbv** has been quarried for concrete aggregate, road material, and cement limestone. Limestone from this unit was burnt to produce agricultural lime. Quarries of **Sbv** exist in Bossardsville.	**Appalachian mountain building and the assembly of Pangaea**—Units record the continued marine depositional setting during the Silurian and into the Devonian. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
SILURIAN	Poxono Island Formation (Sp)		**Sp** consists of green, gray, and pink, laminated to medium-bedded, very fine-grained dolomite interbedded with argillaceous (contains considerable clay) limestone with similar characteristics. Unit weathers to yellowish orange. Some reddish, sandy shale is present in lower portions of the unit. Thickness of **Sp** is approximately 213 m (700 ft). Erosion resistance is moderately high.	**Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park.	**Paleontological resources**—**Sp** contains ostracodes. **Type sections**—**Sp** described from exposures along Delaware River opposite Poxono Island. **Sedimentary features**—mudcracks and 15 cm (0.5 ft) of dessication breccia (forms when mudcracks are disturbed by sudden flow and piled up, then buried). **Cave and karst**—carbonate rocks within this unit are soluble and may host karst features such as pits, caves, and sinking streams.	**Appalachian mountain building and the assembly of Pangaea**—Unit represents a return to predominantly marine conditions following the terrestrial setting of the Bloomsburg Red Beds. Deformed during the Alleghany Orogeny, during which Pangaea was assembled.
SILURIAN	Bloomsburg Red Beds	Bloomsburg Red Beds, disseminated chalcocite (Sbcu)	**Sbcu** contains disseminated chalcocite as an isolated portion of **Sb**.	**Slope movements**—blocks of sandstone and conglomerate susceptible to rockfall where thick, erosion resistant beds are undercut on steep slopes. In some areas, such as Sambo Island, units act as "polished" slip surfaces for soil slumps (may contain unconsolidated glacial till **Qit**, **Qot**, **Qtk**, or **Qtq**). Known soil slips, rockfalls, and debris flows in the Bloomsburg Red Beds exist within the park. Faults along bedding planes within the formation increase the potential for slope movements of overlying rock formations where excavation (e.g., for roads) exposes these zones of weakness. **Sb** and **Sbcu** identified as particularly susceptible to slope movement. Fractures and joints created rockfall hazards. **Abandoned mineral lands**—gates have been installed to prevent human access, but allow bat access to the Pahaquarry copper mine. **Surface water and groundwater quality and quantity**—faults along bedding within the Bloomsburg Red Beds are commonly zones of weathering and groundwater flow.	**Delaware Water Gap**—Prominent unit within the Gap. **Paleontological resources**—contains the first occurrence in New Jersey of an ancestral horseshoe crab and *Skolithos* burrows (indicating intermittent brackish-water setting). **Sb** contains fish scales in several places. **Folds and Faults**—**Sb** is exposed within the Dunnfield Creek syncline, visible within the Gap. **Sedimentary features**—"red beds" formed when sediments or rocks containing iron were exposed to oxygen, indicating terrestrial deposition. **Sb** also contains scattered ferroan (iron-rich) dolomite concretions. Additional sedimentary features include crossbeds, planar bedding, mudcracks, cut-and-fill structures, and channels. Mudcracks and angular fragments similarly suggest a continental or terrestrial depositional setting during this period of the Silurian. **Connections to park stories and resources**—**Sb** has been quarried for road material and fill. Pahaquarry Copper Mine targeted **Sbcu**. Conglomeratic layers contain clasts of angular quartz and red jasper up to 1 cm (0.5 in) long. Bedding plane faults and fractures in Bloomsburg Red Beds rendered the proposed location of the Tocks Island Dam unsuitable.	**Appalachian mountain building and the assembly of Pangaea**—meandering streams deposited **Sb** in lower energy settings than those of **Ss**. Mudcracks reveal periods of dessication where water flow ceased completely. Folds formed during the Alleghany Orogeny, during which Pangaea was assembled.
SILURIAN	Bloomsburg Red Beds	Bloomsburg Red Beds (Sb)	**Sb** is dominated by red, green, and gray sandstone, siltstone, and shale, with minor amounts of conglomeratic sandstone. Overall thickness of the unit is about 457 m (1,500 ft). Massive beds within the unit may be more than 3 m (10 ft) thick. Fining-upward sequences are common. The lower contact of **Sb**, at the base of the first red bed encountered moving from the base upsection, is remarkably sharp and irregular. It cuts across bedding to rise more than 152 m (700 ft) within a horizontal distance of less than 2 km (1 mi) in the Delaware Water Gap.			

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age		Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
SILURIAN	Shawangunk Formation	Shawangunk Formation, undivided (Ss)	**Ss** contains gray to olive-gray, unevenly to moderately well bedded quartzite and conglomeratic quartzite, with minor amounts of siltstone and shale. Unit is 335 to 387 m (1,100 to 1,270 ft) thick. **Ss** has high erosion resistance.	**Slope movements**—Slope failures include documented rockfalls within the park. **Ss, Ssl, Ssm** identified as particularly susceptible to slope movement. Fractures and joints create rockfall potential. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park. **Surface water and groundwater quality and quantity**—as an aquifer, **Ss** has low yields (up to 19 L/min [5 gal/min]). Emerging groundwater is low in solutes, soft, and potentially corrosive.	**Delaware Water Gap**—Prominent units within the Gap. **Sst** is the resistant unit exposed atop Kittatinny Mountain and within the Gap. **Ssl** and **Ssm** visible in the Gap. **Paleontological resources**—three species of the enigmatic jellyfish-like genus *Rutgersella* were originally described from discoveries near the Gap. **Ssl** is burrowed with trails, and contains rare ball-and-pillow structures. **Ssl** contains rare fossils of eurypterids, *Dipleurozoa*, and *Lingula*. These resources may be prone to theft where exposed near visitor use areas. **Ssm** contains trace fossils including *Skolithos verticalis* and *Arthrophycus*. **Type sections**—**Sst** and **Ssm** described from exposures along I-80 within the Gap. **Ssl** described from exposures near Lehigh Gap. **Folds and faults**—in some places, a detachment or decollement occurs along the lower contact of **Ss**. This type of surface represents movement during mountain building. **Sst** forms the ridge of the Cherry Creek anticline. Tilted layers of **Ssl** and **Ssm** are visible in the Gap. **Sedimentary features**—**Ss** contains shale pebbles up to 5 cm (2 in) long. Quartzite in **Ss** is limonitic (iron rich), pyritic (iron sulfide), and feldspathic (contains feldspar). **Sst** contains some ferroan dolomite and calcite concretions. Quartz and argillite pebbles up to 5 cm (2 in) long occur in **Sst**. Features also include planar bedding, channels, mudcracks, flaser bedding, and crossbeds. **Ssl** contains rare collophane (carbonate fluorapatite) nodules and quartz pebbles. **Ssl** is limonitic, pyritic, and graphitic (see **Ss**). **Taconic Unconformity**—Silurian Shawangunk Formation sediments were deposited atop an erosional surface on the Ordovician Martinsburg Formation. **Cave and karst**—Cold Air Cave formed by an assemblage of boulders from the Shawangunk Formation. **Connections to park stories and resources**—ridges and cliffs of the Shawangunk Formation are part of the Kittatinny-Shawangunk National Raptor Migration Corridor, which also provides breeding and nesting habitat for many bird species. **Sst** and **Ssm** may be used as building stone.	**Appalachian mountain building and the assembly of Pangaea**—Lower contacts of **Ss** and **Ssl** are unconformable, indicating a period of erosion or nondeposition termed the Taconic Unconformity. Shawangunk Formation rocks were deposited as coarse-grained terrestrial, high-energy fluvial sediments, marking erosion of the Taconic highlands. Folds formed during the Alleghany Orogeny, during which Pangaea was assembled.
		Tammany Member (Sst)	**Sst** contains 168 to 457 m (550 to 1,500 ft) of gray, fine- to coarse-grained, thin- to thick-bedded conglomeratic quartzite and scant, interlayered, dark-gray argillite (a compact claystone that has been partially changed by heat and/or pressure, but not enough to become slate).			
		Lizard Creek Member (Ssl)	**Ssl** consists of gray to olive, fine- to coarse-grained, thin- to thick-bedded argillite (a compact claystone that has been partially changed by heat and/or pressure, but not enough to become slate) and quartzite. Some siltstone and shale beds occur locally. Weathered exposures of this unit appear grayish to dark yellowish orange. Unit is 83 to 183 m (273 to 600 ft) thick.			
		Minsi Member (Ssm)	**Ssm** is gray to olive, fine- to coarse-grained, thin- to thick-bedded quartizte interbedded with dark-gray argillite (a compact claystone that has been partially changed by heat and/or pressure, but not enough to become slate). Weathered exposures of **Ssm** appear light brown to dark yellowish orange and gray. Unit is 76 m to 92 m (250 to 303 ft) thick.			

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
SILURIAN-ORDOVICIAN	Beemerville Intrusive Suite	Undifferentiated dikes (SObl)	**SObl** includes discrete, crosscutting (cuts across fabrics of surrounding country rock) igneous intrusions of lamprophyre, tinguaite, phonolite, bostonite, and malignite. Moderately high erosion resistance.	**Slope movements**—Units may weather to produce slippery clay-rich material that is prone to slumping on slopes; however, these units are highly localized and probably do not occur in abundance in any single area. Where unweathered, units may pose rockfall hazards when more resistant than the surrounding country rock.	None documented.	**Appalachian mountain building and the assembly of Pangaea**—The Beemerville Intrusive Suite (or Complex) represents rocks emplaced in subsurface plutons following the Taconic Orogeny. They intruded rocks of the Martinsburg Formation. **Obs** of the Beemerville Intrusive Suite produced an age of 424 ± 20 million years ago by the Rb-Sr method and 437 ± 22 million years by the K-Ar method. **Obt** occurs as thin dikes (intrusions that cut the fabric of the surrounding rock) in **Obs** and in sills (intrusions that parallel the fabric of the surrounding rock) and dikes in the Martinsburg Formation **Obp** occurs as thin dikes in **Obt** and in sills and dikes within the Martinsburg Formation and Beekmantown Group. **Obb** occurs as dikes and sills within the Martinsburg Formation. **Obm** occurs as sills in the Martinsburg Formation. **Obla** occurs as dikes in the Martinsburg Formation, Beekmantown Group, and Allentown Dolomite. **Obo** (biotite grains from Rutan Hill) produced an age of 436 ± 41 million years by the Rb-Sr technique and 437 ± 22 million years by the K-Ar technique.
		Nepheline syenite (Obs)	**Obs** is medium- to dark-gray, medium- to coarse-grained syenite. In general, the unit is undeformed, but it exhibits flow foliation (banding created by parallel alignment of alternating dark and light minerals). **Obs** contains the following minerals: nepheline, orthoclase, socialite, aegirine, and biotite with minor amounts of magnetite, apatite, titanite, fluorite, zircon, and pyrite. Moderately high erosion resistance. **Obs** occurs in two stocks and a small plug (types of igneous intrusion) in the Rutan Hill area.			
		Tinguaite (Obt)	**Obt** consists of medium- to dark-gray and greenish-gray, fine-grained igneous rock. **Obt** contains the following minerals as phenocrysts (relatively large crystals): nepheline, orthoclase, aegirine, and biotite. These minerals also occur in the finer-grained surrounding groundmass, along with minor amounts of magnetite, apatite, titanite, and zircon. Moderately high erosion resistance.			
		Phonolite (Obp)	**Obp** consists of medium-dark-gray, very fine-grained rock. Much of **Obp** has been altered or weathered (sericitized [replacing original minerals with sercitic muscovite] and chloritized [replacing original minerals with chlorite] by hot, hydrothermal fluids), albitized (process by which calcium-rich plagioclase is replaced by sodium-rich albite) and/or carbonatized (replacement of original minerals by carbonate minerals). **Obp** contains nepheline and orthoclase.			
		Bostonite (Obb)	**Obb** medium- to dark-gray, very fine-grained rock with conspicuously large crystals of altered orthoclase. orthoclase phenocrysts occur in a finer-grained groundmass (matrix) of orthoclase, microperthite, and/or plagioclase, and minor amounts of aegirine, biotite, magnetite, apatite, and zircon.			
		Malignite (Obm)	**Obm** contains dark-gray, medium- to coarse-grained rock. Bluish-white orthoclase, white nepheline, and abundant biotite make up the larger crystals (phenocrysts) in a fine-grained matrix. the matrix of **Obm** contains orthoclase, nepheline, biotite, aegerine, melanite, magnetite, apatite, and titanite.			
		Lamprophyre (Obla)	**Obla** contains dark-gray to grayish-black, very fine-grained and altered mafic (low in silica content) rock. original mineralogy of **Obla** is difficult to discern given the high degree of alteration.			
		Ouachitite breccia (Obo)	**Obo** is dark-gray to black breccia (a chaotic mix of angular fragments in a finer-grained matrix). larger fragments in **Obo** include potassic (contains potassium) synite, lamprophyre, and carbonatite, as well as exotic (not part of local melts) pieces of Middle Proterozoic rocks, carbonate rocks of the Lehigh Valley sequence, and slaty Martinsburg Formation (see **Omp**, **Omhp**, **Omr**, **Omrg**, and **Omb**). The groundmass of **Obo** contains extremely fine-grained calcite, magnetite, biotite, chlorite, albite, and apatite and somewhat larger crystals of biotite, pyroxene, orthoclase, magnetite, apatite, and nepheline.			

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
ORDOVICIAN	Hornfels (Omh)	**Omh** is a dark-gray to black, extremely fine-grained rock. Very high erosion resistance.	None documented.	None documented.	**Appalachian mountain building and the assembly of Pangaea**—**Omh** is an example of contact metamorphism due to the intense heat associated with emplacement of **Obs** within the Martinsburg Formation. Other bodies of hornfels exist around the large intrusive sills of the Beemerville Intrusive Suite, but were not mapped due to lack of adequate exposure.
	Martinsburg Formation: Pen Argyl Member (Omp)	**Omp** contains dark-gray to nearly black, thick- to thin-bedded claystone slate. Claystone is cyclically interlayered with quartzose slate and carbonaceous (contains carbon) slate. Fining-upward sequences are common. Unit is more than 1,524 m (5,000 ft) thick.	**Slope movements**—claystones and shales in these units may form zones of weakness prone to failure when the unit occurs on a slope. Weathered slates and shales are clay rich and may be prone to slumping. More-resistant greywackes pose a rockfall hazard when undercut on slopes. No significant landslide involves this unit within the park. **Omrg** identified as particularly susceptible to slope movement. **Paleontological resource management**—a park-specific paleontological resource survey could provide detailed site-specific recommendations for inventory, monitoring, interpretation, and protection of fossils within the park.	**Delaware Water Gap**—**Omr** is exposed at the base of the Gap. **Paleontological resources**—**Omr** contains scant graptolites. **Omhp** contains graptolites. assigned to the *Climacograptus spiniferus* zone; assigning an Edenian (Caradocian) age within the Ordovician (about 455 million years ago). In general, the Martinsburg Formation contains fossil remains of conulariids, bryozoans, brachiopods, bivalves, nautiloids, gastropods, trilobites, "worms," and crinoids. **Type sections**—**Omp** described from exposures near Pen Argyl. **Omhp** described from exposures in High Point State Park. **Omr** described from exposures near Ramseyburg. **Omb** described from exposures along Bushkill and Little Bushkill creeks. **Folds and faults**—tilted layers of **Omr** are visible at the eastern edge of the Gap. **Sedimentary features**—**Omp** contains sole marks and possible turbidites (submarine landslides). **Omhp** includes scoured shale remnants, rip-up clasts, graded bases, parallel laminated tops, and load casts. Greywacke is generally a dark-gray, compact, coarse-grained sandstone that consists of poorly sorted, angular to subangular grains of quartz and feldspar, with a variety of dark rock and mineral fragments embedded in a compact clay-rich matrix. **Omr** and **Omb** contains possible turbidites (submarine landslides). **Taconic Unconformity**—Silurian Shawangunk Formation sediments were deposited atop an erosional surface on the Ordovician Martinsburg Formation. **Connections to park stories and resources**—**Omp** and **Omb** were extensively quarried for slate and used as lightweight aggregate and fill. Active quarries still exist in these units (not inside the park). The Martinsburg Formation erodes into rolling hills. **Omr** and **Omrg** were targets in slate quarries.	**Appalachian mountain building and the assembly of Pangaea**—Martinsburg Formation sediments were deposited in a rapidly subsiding basin as the Iapetus Ocean closed. The source area for Martinsburg sediments was Appalachia to the southeast. As the basin deepened, deep-sea sediments and sediments from underwater mass-wasting events (turbidites) accumulated. The top of the Martinsburg Formation was exposed and heavily eroded during a period of nondeposition, prior to deposition of the Shawangunk Formation. That period corresponded to the close of the Taconic Orogeny.
	Martinsburg Formation: High Point Member (Omhp)	**Omhp** is dark-gray greywacke with intervals or interbeds of dark shale. Unit weathers to light gray and pale yellowish brown. Silica cements dominate, but carbonate cements exist locally. Unit is approximately 114 m (375 ft) thick locally.			
	Martinsburg Formation: Ramseyburg Member (Omr)	**Omr** consists of dark-gray slate with alternating beds of gray, thick- to thick-bedded greywacke and greywacke siltstone (20% to 30% of the unit). Unit is approximately 930 m (2,800 ft) thick. Fining-upward (Bouma) sequences are common, but are often truncated in this unit.			
	Martinsburg Formation: Ramseyburg Member-graywacke beds (Omrg)	**Omrg** contains prominent greywacke-bearing layers with slate.			
	Martinsburg Formation: Bushkill Member (Omb)^	**Omb** is dark- to medium-gray, thin-bedded to laminated claystone slate and occasional quartzose and greywacke siltstone and carbonaceous (contains carbon) slate. **Omb** also contains minor dolomite lenses. Fining-upward (Bouma) sequences are common. **Omb** grades downward into **Oj** by increasing carbonate content. Unit is up to 1,220 m (4,000 ft) thick locally. greywacke within **Omb** contains beds with muscovite, chlorite, albite, and quartz. See description of **Omhp**. Mapped areas of **Omb** are restricted to the extreme southeastern corner of the park.			
	Austin Glen Formation (Oag)	**Oag** contains graywacke and shale. **Oag** is part of the Lorraine, Trenton, and Black River groups and is up to 490 m (1,600 ft) thick. Erosion resistance is moderate.	**Slope movements**—shale in this unit may form zones of weakness prone to failure when the unit occurs on a slope.	None documented.	**Appalachian mountain building and the assembly of Pangaea**—by the time Oag is deposited, clastic sedimationtation is predominant. Deformed during the Taconic and Alleghany orogenies. **Oag** is the last unit deposited prior to deposition of the Martinsburg Formation.

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age	Map Unit (Symbol)		Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
ORDOVICIAN	Jacksonburg Limestone	Jacksonburg Limestone (Oj)	**Oj** consists of gray, medium- to coarse-grained, well-bedded limestone. At the base of **Oj** is a dolomite pebble to cobble conglomerate. Limestone becomes more shaly toward the top of the unit. **Oj** is approximately 38 to 61 m (125 to 200 ft) thick. erosion resistance is moderately high.	None documented.	**Paleontological resources**—**Oj** and **Ojl** contain conodonts of the North American Midcontinent Province Conodont Fauna 8–9; indicating Rocklandian and Kirkfieldian time (Llandeilian age) within the middle Ordovician (about 460 million years ago) **Cave and karst**—carbonate rocks within these units are soluble and may host karst features such as pits, caves, and sinking streams. Jacksonburg Limestone landscapes have lakes and sinkholes. **Connections to park stories and resources**—**Oj** may weather to produce calcium-rich soils.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. **Oja** and **Ojl** were among the last (youngest) units deposited as part of the massive carbonate bank of the Iapetus Ocean. Deformed during the Taconic and Alleghany orogenies. **Oj** occurs in tectonic units above the Sarepta thrust fault.
		Jacksonburg Limestone-cement limestone facies (Ojl)	**Ojl** is gray, medium- to coarse-grained, well-bedded calcarenite (arenite is a consolidated sedimentary rock composed of sand-sized fragments with a pure or nearly pure chemical cement) and fine to medium crystalline limestone. **Ojl** is approximately 20 to 30 m (66 to 98 ft) thick. erosion resistance is moderately high.			
	Sequence at Wantage (Ow)		**Ow** consists of interbedded gray to dark-gray limestone, dolomite, conglomerate, siltstone, and shale. All rock types are thin- to medium-bedded with limestone generally grading downsection into silty argillite (a compact claystone that has been partially changed by heat and/or pressure, but not enough to become slate). Weathered exposures are yellowish brown to olive gray. Unit ranges in thickness from 0 to 492 m (0 to 150 ft). Erosion resistance is moderately high; it is higher for conglomerates.	**Slope movements**—Calcareous cements may dissolve, leaving portions of this unit friable and prone to Slope movements. In areas where conglomerate is undercut, the units may be prone to rockfall.	**Sedimentary features**—crossbeds. **Cave and karst**—limestone, calcareous cement, and, to a lesser extent, dolomite within this unit are soluble and may host karst features such as pits, caves, and sinking streams. **Connections to park stories and resources**—chert in **Ow** may have provided tool and/or trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. Deformed during the Taconic and Alleghany orogenies.
	Beekmantown Group	Upper part (Obu)	**Obu** consists of dolomite and minor limestone. erosion resistance is moderately high.	**Slope movements**—In areas where quartzite is undercut, the units may be prone to rockfall.	**Paleontological resources**—**Oe** and **Or** contain conodonts of the *Rossodus manitouensis* zone of the North American Midcontinent Province Conodont Fauna; which date it to Ibexian (Tremadocian) age within the early Ordovician, or about 470 to 485 million years ago. **Cave and karst**—carbonate rocks (dolomite) within this unit are soluble and may host karst features such as pits, caves, and sinking streams. Solution collapse breccia may also be present; it forms when overlying material collapses into dissolved pits within limestone or evaporate deposits (salts) prior to the consolidation of sediments. **Connections to park stories and resources**—nodular and bedded chert in **Oe** may have provided tool and/or trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. Deformed during the Taconic and Alleghany orogenies.
		Lower part (Obl)	**Obl** contains dolomite and minor limestone. Erosion resistance is moderately high			
		Epler Formation (Oe)	**Oe** consists of interbedded, very fine-grained to nearly cryptocrystalline, gray limestone and darker dolomite. **Oe** ranges from 200 to 270 m (650 to 885 ft) thick. **Oe** also contains orthoquartzite. Erosion resistance is moderately high; it is very high for orthoquartzite. **Oe** is exposed in the Paulins Kill window.			
		Rickenbach Dolomite (Or)	**Or** includes gray, fine- to coarse-grained dololutite, dolarenite (arenite is a consolidated sedimentary rock composed of sand-sized fragments with a pure or nearly pure chemical cement), and dolorudite (rudite is a consolidated sedimentary rock composed of grains larger than sand with a pure or nearly pure chemical cement). Lower portions of the unit are thick bedded, with bedding becoming thinner and more laminated upsection. Unit ranges from 135 to 220 m (443 to 722 ft) thick. Erosion resistance is moderately high. **Or** grades downward into **Os**.			

Gray-shaded units are not mapped within Delaware Water Gap National Recreation Area.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
ORDOVICIAN	Stonehenge Formation (Os)	**Os** consists of gray, fine- to medium-grained limestone with moderate amounts of interbedded, laminated dolomite and dark-gray chert. Unit ranges from 84 to 198 m (275 to 650 ft) thick. In portions of **Os** that have undergone extensive deformation, boudins (sausage-shaped forms) of dolomite appear to "float" in the limestone. **Os** occurs only in tectonic units above the Sarepta thrust fault.Erosion resistance is moderately high.	None documented.	**Paleontological resources**—dolomite and limestone in **Os** are commonly mottled and burrowed. Fossils include conodont fauna of zone A to the *Rossodus manitouensis* zone of the North American Midcontinent Province Conodont Fauna; the fossil remains in this unit date it precisely to Ibexian (Tremadocian) age within the early Ordovician, or about 470 to 485 million years ago. **Cave and karst**—carbonate rocks and, to a lesser extent, dolomite within this unit are soluble and may host karst features such as pits, caves, and sinking streams. Solution collapse breccia may also be present; it forms when overlying material collapses into dissolved pits within limestone or evaporate deposits (salts) prior to the consolidation of sediments. **Connections to park stories and resources**—nodular chert in **Os** may have provided tool and/or trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. **Os** grades downward into the Allentown Dolomite (**OCa**), marking more or less continuous deposition at this time. Deformed during the Taconic and Alleghany orogenies.
ORDOVICIAN-CAMBRIAN	Allentown Dolomite (OCa)	**OCa** contains gray, very fine- to medium-grained dolomite. **OCa** weathers to an alternating light- and dark-gray banded appearance. Unit also contains scattered beds and lenses of quartzite. Unit is approximately 575 m (1,900 ft) thick in northern New Jersey. Thrust faulting truncates **OCa**, making the determination of its total thickness difficult. Erosion resistance is moderately high; it is very high for quartzite.	**Slope movements**—In areas where quartzite is undercut, the units may be prone to rockfall.	**Paleontological resources**—**OCa** contains oolite layers and algal stromatolites (fossil algae). Shelly fauna exist near the top and bottom of the unit elsewhere in New Jersey and place **OCa** in the Trempealeauan and Dresbachian ages of the Ordovician and Cambrian, respectively (about 490 to 500 million years ago). **Sedimentary features**—ripple marks and mudcracks. **Cave and karst**—dolomite within this unit is somewhat soluble and may host karst features such as pits. **Connections to park stories and resources**—nodular chert in **OCa** may have provided tool and/or trade material for American Indians.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. Deformed during the Taconic and Alleghany orogenies.
ORDOVICIAN-CAMBRIAN	Carbonate rocks (OCc)	Carbonate rocks can include limestones and dolomites. This unit occurs as bedrock on the surficial geologic map of the area. More specific descriptions occur throughout this table. Erosion resistance is moderately high.	None documented.	**Cave and karst**—carbonate rocks (dolomite) within this unit are soluble and may host karst features such as pits, caves, and sinking streams.	**Appalachian mountain building and the assembly of Pangaea**—carbonate deposition in the Iapetus Ocean continued from the Cambrian through much of the Ordovician. Deformed during the Taconic and Alleghany orogenies.
CAMBRIAN	Leithsville Formation (Cl)	**Cl** is thick-bedded, medium-gray, finely crystalline dolomite cyclically interlayered with platy and shaly dolomite. In some places, the unit contains light-gray to tan phyllite with beds and stringers (small, irregular bodies) of quartz and dolomite sandstone. Locally, unit is about 350 m (1,148 ft) thick. Erosion resistance is moderately high.	None documented.	**Paleontological resources**—**Cl** contains archaeocyathids. **Cave and karst**—carbonate rocks (dolomite) within this unit are soluble and may host karst features such as pits, caves, and sinking streams.	**Appalachian mountain building and the assembly of Pangaea**—originally deposited in the Iapetus Ocean. Deformed during the Taconic and Alleghany orogenies. **Cl** likely contains a major intraformational disconformity (period of nondeposition or erosion) marking the Middle–Lower Cambrian boundary.
CAMBRIAN	Hardyston Quartzite (Ch)	**Ch** is 30 m (100 ft) of gray quartzite, quartz-pebble conglomerate, arkosic sandstone, silty shale, and jasper. Weathered outcrops appear brown. Jasper is yellowish brown and iron stained. High erosion resistance.	**Slope movements**—quartzites are prone to rockfall when undercut by less-resistant units on slopes.	None documented.	**Appalachian mountain building and the assembly of Pangaea**—originally deposited as beach and tidal-flat sands along the Iapetus Ocean. Deformed during the Taconic and Alleghany orogenies.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
MIDDLE PROTEROZOIC	Venite (Ymv)	**Ymv** is a composite unit of amphibolite containing abundant veins, lenses, and irregular bodies of albite-oligoclase granite. **Ymv** minerals include amphibole, albite and oligoclase (plagioclase), and quartz. May be an amphibolite-rich phase of the Losee Metamorphic Suite. Erosion resistance is moderately high.	None documented.	None documented.	**Ancient mountain building and Iapetus Ocean formation**—Metamorphic rocks were deformed and altered during the Grenville Orogeny, which culminated in the assembly of the supercontinent Rodinia. **Yba** and **Ybh** were emplaced during metamorphism of the Grenville Orogeny. Deformation may have also occurred during the Taconic and Alleghany orogenies.
	Byram Intrusive Suite: Microperthite alaskite (Yba)	**Yba** contains medium- to coarse-grained, pink and gray, foliated (banding defined by parallel orientations of alternating light and dark minerals) alaskite. **Yba** contains microperthite, quartz, and oligoclase. Erosion resistance is moderately high.	None documented.		
	Byram Intrusive Suite: Hornblende granite (Ybh)	**Ybh** is medium- to coarse-grained, gray and pink granite. Some portions of **Ybh** are foliated (banding defined by parallel orientations of alternating light and dark minerals). **Ybh** commonly contains interlayers and bands of **Ya**. **Ybh** contains microperthite, quartz, oligoclase, and hornblende. **Ybh** has layers that reached temperatures sufficient to partially melt them into migmatites (particularly interlayers of **Ya**). Erosion resistance is moderately high.			
	Marble (Ymr)	**Ymr** contains dolomite and calcite marble. The unit is highly weathered to serpentinite, tremolite, and talc. contains marble, serpentinite, tremolite, and talc.	**Slope movements**—calcareous (marble) materials within **Ymr** and **Yq** are soluble. Weathered layers of this unit may render it unstable on slopes. Talc is an extremely soft mineral. In areas where unweathered **Yq** is undercut, the potential exists for rockfall.		
	Quartz-plagioclase-epidote-biotite gneiss (Yg)	**Yq** appears light gray and coarse grained in massive to layered exposures. This predominantly calc-silicate rock is associated with marble (metamorphosed carbonates; see **Ymr**). **Yq** minerals include quartz, plagioclase feldspar, epidote, and biotite. Erosion resistance is moderately high.			
	Potassic feldspar gneiss (Yk)	**Yk** consists of fine- to medium-grained, gray and pink gneiss with lesser amounts of granofels. Foliation, or banding defined by parallel orientations of alternating light and dark minerals, is poorly to fairly developed in this unit. Some interlayers of feldspathic quartzite occur locally. **Yk** minerals include quartz, potassic (contains potassium) feldspar, biotite, magnetite, and, less commonly, garnet and/or sillimanite. Mineral assemblages of this unit reflect the amount of heat and/or pressure present during metamorphism. Erosion resistance is moderately high; it is very high for quartzite.	None documented.		
	Oligoclase-quartz gneiss (Ylo)	**Ylo** is medium-grained, light-greenish-gray, poorly foliated (bands defined by parallel orientations of alternating light and dark minerals), granoblastic gneiss and, less commonly, granofels. Some interlayers of amphibolite (see **Ya**) occur in this unit. **Ylo** minerals include oligoclase, quartz, biotite, magnetite, and chloritized (weathered and altered) augite. **Ylo** is likely a metamorphosed (changed by pressure and heat) quartz keratophyre. Erosion resistance is moderately high.			
	Amphibolite (Ya)	**Ya** is fine- to medium-grained, gray to nearly black amphibolite. **Ya** minerals include hornblende and andesine. Some areas also contain augite, hypersthene, or biotite. **Ya** is mostly a metasedimentary rock interlayered with marble (see **Ymr**) and other calcareous and quartzo-feldspathic (rich in quartz and feldspar) metasedimentary rocks. Erosion resistance is moderately high.	**Slope movements**—calcareous (marble) interlayers within **Ya** are soluble. In areas where unweathered **Ya** is undercut, the potential exists for rockfall.		