National Park Service
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Natural Resource Stewardship and Science

Shenandoah National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/767

ON THE COVER
The sun rises over the Blue Ridge Mountains in Shenandoah National Park.
National Park Service photograph.

THIS PAGE
Cliffs of Catoctin Formation greenstone at Little Stony Man, Shenandoah National Park.
Photograph by Trista L. Thornberry-Ehrlich (Colorado State University).

Shenandoah National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/767

Trista L. Thornberry-Ehrlich
Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Shenandoah National Park (Virginia) on 23–25 March 2005 and a follow-up conference call on 11 December 2012, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

This Geologic Resources Inventory report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information and the NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes within Shenandoah National Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. Geologic Map Graphics (in pocket) illustrate these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Shenandoah National Park preserves some of the most iconic and famous Blue Ridge landscapes. The park was authorized in 1926, established in 1935, and is a destination for more than 1.2 million visitors annually. The rocks and structures exposed in the Blue Ridge record a long geologic history that includes a billion-year-old mountain-building event, the opening and closing of an ancient ocean basin, Appalachian-Mountain building, and the opening of the Atlantic Ocean. For hundreds of millions of years since the Appalachian Mountains peaked at elevations comparable to the modern Himalayas, Earth surface processes have worn the mountains down, flanking them with unconsolidated surficial deposits and contributing to the formation of the Atlantic Coastal Plain along the eastern margin of North America. The now-muted peaks of these ancient mountains are beautifully on display within Shenandoah National Park.

Southworth et al. (2009) is the source map for the digital geologic map data for Shenandoah National Park. The mapped units can be divided into two main categories: bedrock and surficial. The bedrock is further divisible into four types: (1) Mesoproterozoic metamorphic and igneous rocks that are approximately 1.2 billion to 1.0 billion years old; (2) Neoproterozoic metamorphic and igneous rocks that are approximately 800 million to 570 million years old; (3) Paleozoic metamorphosed and non-metamorphosed sedimentary rocks that are approximately 540 million to 420 million years old; and (4) isolated intrusions of Jurassic age igneous rocks that are approximately 200 million to 150 million years old. Surficial, unconsolidated units from the Neogene and Quaternary periods are divisible based on the types of sediments composing them and the processes responsible for their formation: (1) fluvial deposits; and (2) deposits formed by slope processes and/or frost weathering.

The Mesoproterozoic and Neoproterozoic rocks represent the evolution of the North American continent through the assembly of fragments of oceanic and continental crust. They form the foundation atop which all other rocks in the Appalachians were deposited. They are predominant along the eastern edge of the park and the high peaks and ridges. The Paleozoic sedimentary package of rocks accumulated over millions of years as shallow seas periodically inundated the eastern part of North America. These rocks crop out along the western side of the park and into the Great Valley, locally referred to as the Shenandoah Valley. This entire stack of rocks was deformed and pushed westward during three major orogenies, mountain-building events, during the Paleozoic. The younger Mesozoic igneous rocks are present as dikes and formed as Earth's crust stretched during the opening of the Atlantic Ocean. The youngest, unconsolidated surficial deposits reflect the processes of weathering and erosion active since the end of the Paleozoic orogenic events.

Geologic features and processes include the following:

- Ancient Bedrock. The rocks that form the foundation of Shenandoah National Park contain myriad features of interest to geologists and visitors alike. The Catoctin Formation (geologic map units Zcm, Zcr, Zcs, and Zcp) contains ancient volcanic features that record a history of continental rifting. Sedimentary features within Neoproterozoic (Zmr and Zsr) and Paleozoic rocks preserve a record of the conditions of their deposition such as ripple marks in nearshore settings or mudcracks on mudflats. The Mesoproterozoic rocks ("Y" units) of the core of the Blue Ridge Mountains are among the oldest in the eastern United States.
- Type Sections, Reference Locations, and Radiometric Ages. The bedrock of the park provides excellent exposures for scientific study. Many locations provide

points of reference for comparisons to other rocks within the Blue Ridge. Radiometric ages obtained for the ancient bedrock of the park is helping to decipher some of North America's earliest geologic events.

- Blue Ridge-South Mountain Anticlinorium and Regional Structures. The Blue Ridge-South Mountain anticlinorium (regionally-extensive, arch-shaped fold) is a prominent geologic structure created during the final uplift of the Appalachian Mountains. Myriad folds and faults deform or cross the rocks throughout the park. Geologic structures are responsible for many landforms within the park.
- Bedrock Outcrop Habitats. Bedrock outcrops of different composition and morphology, as well as boulderfields and surficial deposits create different habitats. Some of these natural communities are globally rare or endemic to the park.
- Surficial Deposits. The deposition and weathering of surficial deposits creates landforms that document the most recent part of the ongoing geologic history at the park. Surficial deposits are grouped primarily by their depositional process and resulting geomorphology. The surficial deposits mapped within the park resulted from flowing water (Qa, Nt, Np, and Nf); slope failure (Qdf and Nd); and frost-wedging (Qb and Qc).
- Periglacial Features. The colder climates of the Pleistocene ice ages left lasting effects on the landscape of the park, although glaciers never reached central Virginia. Frost-weathering cycles fractured rocks and formed boulder-covered slopes, side-slope stone (or talus) "streams", and step features that act as sources of sediment for debris flows. Frost wedging continues today at a subdued rate.
- Paleontological Resources. Fossils, primarily traces of worm burrows, are known from Cambrian rocks within the park. Ordovician rocks are bioturbated and host some fossil algae layers. The Quaternary and Neogene deposits in the park (Qb, Qc, Nt, Np, and Nd) may also contain fossils.
- Cave and Karst Features. Carbonate rocks such as limestone and dolomite (Ct, Cwa, Ce, OCc, and Ob) are prone to dissolution and the formation of karst features such as caves, sinkholes, dissolution pits, and underground conduits.
- Connections with Park Stories. The geologic resources of the park played prominent roles in the area's human history. American Indians quarried stones regionally. Homesteaders established farms in a challenging landscape. Soldiers from the American Revolution and Civil War recognized strategic hollows and gaps within the Blue Ridge. The failure of a copper mine lead to the establishment of Skyland Lodge, which afforded early 20th century visitors access to the cooler temperatures, sparkling spring waters, and spectacular views from the top of the Blue Ridge Mountains. Geologists (and also President and First Lady) Herbert and Lou Henry Hoover chose the headwaters of the Rapidan River to build their rustic retreat, Rapidan Camp. Depression-era Civilian Conservation Corps teams built much of the park's stunning infrastructure, commonly sourcing local bedrock.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- Slope Movements. One of the primary geologic resource-management concerns at the park is to delineate areas at risk for slope movements. The steep slopes that characterize the park's landscape create potential for debris flows, landslides, slumping, rockfall and slope creep along trails, roads, and Skyline Drive. Debris-flow deposits (Qdf), quartzite block-field deposits (Qb), colluvium (Qc), and debris-fan deposits (Nd) attest to past and ongoing mass wasting events. Changing climate will likely increase the frequency and severity of seasonal storms. Storms can trigger mass wasting events such as the debris flows in 1995 in Madison, Green, and Albemarle counties.
- Bedrock Outcrop Management. The cliffs, barrens, and other outcrops within the park are a treasure for climbers, hikers, and rank among the most popular attractions. However, overuse degrades the associated habitats. Park staff members are preparing a Rock Outcrop Management Plan to balance visitor access with natural resource preservation.
- Surface Water and Sediment Loading. Many streams and rivers drain the steep slopes of the Blue Ridge Mountains in the park and are lined with the youngest geologic unit at the park—alluvium (Qa). Management issues associated with these active settings include seasonal runoff, flooding, and sediment loading, as well as surface water acidification by acid precipitation and bedrock buffering or lack thereof.
- Groundwater Quantity and Quality. Seeps and springs are common in the park. The park surrounds the headwaters of more than 200 streams and rivers. The hydrogeologic system of the park is fracture-driven and groundwater coming from springs and wells is relatively young. The system is vulnerable to contamination and a hydrogeologic model could be used to predict contamination potential and distribution.
- Disturbed Lands. Upon its establishment, Shenandoah National Park inherited a landscape altered by years of homestead and settlement activities as well as manganese, copper, and iron mining. All of these have links to geologic features and processes at the park.
- Earthquakes. Earthquakes are uncommon in Central Virginia. The most recent earthquake felt by visitors and park staff was in August 2011—a magnitude 5.8 earthquake that shook much of the eastern United States. Although major damage is perhaps not likely within the park due to earthquakes, they may trigger slope movements.
- Cave and Karst Hazards. Caves and karst features such as sinkholes can cause safety hazards. Dangerous gasses can concentrate to unsafe levels in some caves. People can fall into sinkholes and cavities. Karst features can greatly impact local hydrogeologic systems.

Acknowledgements

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section acknowledges contributors to this report.

Additional thanks to Callan Bentley (Northern Virginia Community College) who provided many photographs used in Geologic Features and Processes section. Georgia Hybels (NPS Geologic Resources Division) provided GIS assistance for some of the graphics in the report. Dan Hurlbert (Shenandoah National Park) provided information regarding abandoned roads in the park.

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Credits

Author

Trista L. Thornberry-Ehrlich (Colorado State University)

Review

Arthur Merschat (US Geological Survey)
Matt Heller, Anne Witte, and Wendy Kelly (Virginia Division of Geology and Mineral Resources)
Jim Schaberl, Wendy Cass, and Sally Hurlbert (Shenandoah National Park)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Jason Kenworthy (NPS Geologic Resources Division)

Source Map

Scott Southworth, John Aleinikoff, Christopher Bailey, William Burton, E.A. Crider, Paul Hackley, Joseph Smoot, and Richard Tollo (US Geological Survey)

GRI Digital Geologic Data Production

Jim Chappell, Philip Reiker, and Stephanie O’Meara (Colorado State University)

GRI Geologic Map Graphics Design

Max Jackl (Colorado State University)

GRI Geologic Map Graphics Review

Georgia Hybels, Rebecca Port, and Jason Kenworthy (NPS Geologic Resources Division)

Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting and history of Shenandoah National Park.

Geologic Resources Inventory Program

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

Park Setting

Shenandoah National Park encompasses more than 79,000 ha (197,000 ac) of mountainous western Virginia (plate 1 and fig. 1). Nearly 32,000 ha (80,000 ac) is designated wilderness area. The park, which incorporated more than 1,000 privately-owned tracts, was authorized on May 22, 1926, but was not fully established until December 26, 1935. After many generations of settlement and agricultural use, the

Figure 1. View from Big Run Overlook. The Blue Ridge Mountains are primary features in Shenandoah National Park. The park is a destination for more than a million visitors annually, particularly during the colorful fall season. National Park Service photograph. Available online: http://www.nps.gov/shen/photosmultimedia/index.htm (accessed 5 February 2014).

Civilian Conservation Corps (CCC, part of the Depression-era New Deal programs) reclaimed, replanted, and restored a more natural landscape to conserve for future generations. More than a million people visit the park every year. The park protects and preserves an abundance of natural resources, much of which is visible from the169-km-long (105-mi-long) Skyline Drive winding along the crest of the Blue Ridge Mountains and the 162 km (101 mi) of the Appalachian Trail (plate 1). The crest of the park is the drainage divide of the Blue Ridge: water drains northwest to the South Fork of the Shenandoah River; water drains southeast to the James and Rappahannock rivers.

Geologic Setting

Geologists have long studied the characteristic rocks and landscape of the central Appalachians (Rickard and Roberts 1937). Landscape development reflects the geologic history of the area and main groups of rock units. A geologic history involving (1) construction of the early North American continent as recorded in Mesoproterozoic and Neoproterozoic metamorphic and igneous rocks, (2) repeated orogenies resulting in the Appalachian Mountains evident from metamorphosed sedimentary Paleozoic rocks, (3) the breakup of the late Paleozoic supercontinent responsible for Jurassic-age igneous dikes, and (4) relentless weathering and erosion, as revealed by Neogene and Quaternary unconsolidated deposits, shaping the landscape that inspired the creation of Shenandoah National Park (figs. 4 and 5).

Shenandoah National Park is primarily in the western part of the Blue Ridge province (fig. 2). The mountainous belt of the Blue Ridge stretches from Pennsylvania to Georgia. Weathering and eroding streams have caused the narrowing of the northern section of the Blue Ridge into a thin band of steep ridges, climbing to heights of 1,234 m (4,050 ft) at Hawksbill, the highest point in the park. In general, the Blue Ridge province comprises rugged mountains with steep slopes. Erosion-resistant Mesoproterozoic gneisses and granites, Neoproterozoic greenstones and metasedimentary rocks, and Lower Cambrian quartzites form the heights of the Blue Ridge in Virginia (fig. 4) (Nickelsen 1956; Southworth et al. 2009). For example, gneisses and granites underlie peaks such as Old Rag Mountain (geologic map unit Yor) at 996 m (3,268 ft) above sea level (fig. 3). Metabasalts of the Catoctin Formation (Zcp, Zcs, Zcr, and Zcm) underlie the highest areas such as Stony Man at 1,223 m (4,011 ft). The quartzites (Ccw, Cch, and Cca) support linear ridges some 400 to 800 m (1,300 to 2,600 ft) in elevation (Southworth et al. 2009).

The highlands in the park are part of the Blue Ridge-South Mountain anticlinorium—a regional, "arch-shaped" fold structure (fig. 6). During the late Paleozoic Alleghany Orogeny, about 300 million years ago, the rocks underlying the park buckled and were transported westward atop younger rocks. The resulting anticlinorium is a large, overturned fold, tilted toward the west (Gooch 1958; Evans 1988; Southworth et al. 2009).

At one time, the Appalachian Mountains rivaled today's Himalayas in height and ruggedness. Hundreds of millions of years of weathering and erosion removed thousands of meters of rock. The modern Appalachians in the Blue Ridge are only the roots of the ancient mountain chain. The eroded sediment was transported to adjacent low-lying areas to become sandstones in the Cumberland and Allegheny Plateau to the west and to build up the Atlantic Coastal Plain stretching far to the east of Shenandoah National Park.

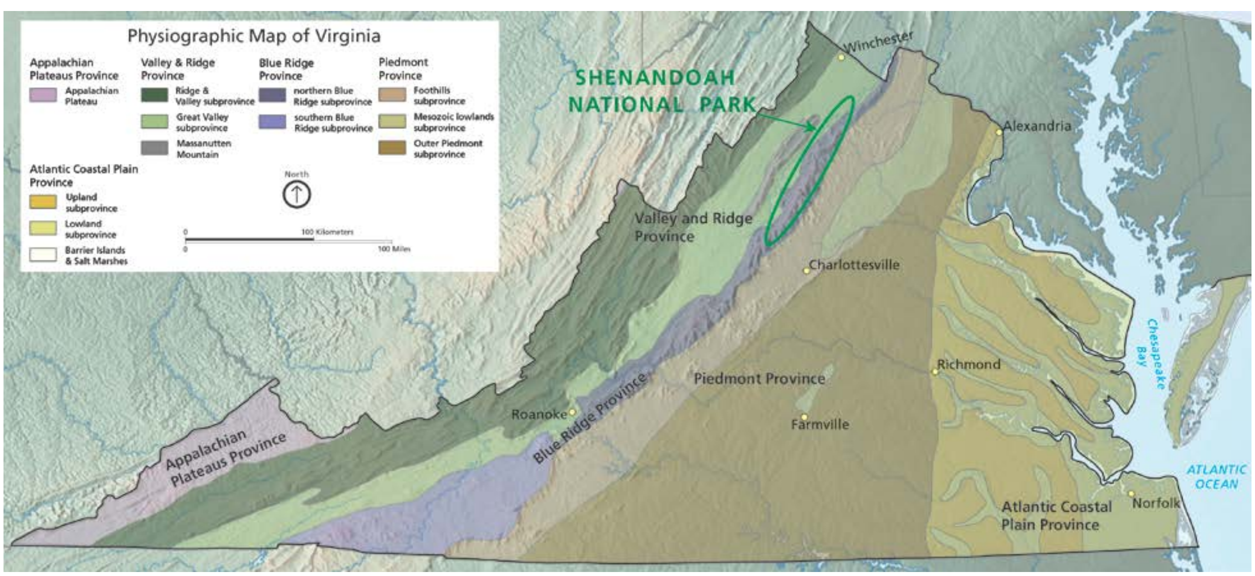


Figure 2. Physiographic provinces and subprovinces of Virginia. Note the location of Shenandoah National Park (green oval) along the crest of the Blue Ridge. Graphic is adapted from Bailey (1999) by Trista L. Thornberry-Ehrlich (Colorado State University). Basemap by Tom Patterson (National Park Service), available online: http://www.shadedrelief.com/physical/index.html (accessed 14 November 2013).

The westernmost portions of the park are part of the Great Valley section of the Valley and Ridge province. Long, parallel ridges separated by valleys characterize the landscape of the province. Weathering and erosion result in erosion-resistant sandstone and chert ridges that are adjacent to valleys underlain by more easily eroded shale and carbonate formations. The Great Valley, part of an extensive series of valleys that stretch from Quebec to Alabama, marks the boundary between the Blue Ridge and Valley and Ridge provinces in northern Virginia. The Shenandoah and Page valleys are the local sections of the Great Valley. Massanutten Mountain is a distinctive ridge in the Great Valley west of Shenandoah National Park. Ordovician and Silurian sandstones and shales underlie Massanutten Mountain (Om and Sm). Cambrian and Ordovician carbonate rocks (e.g., Ct, Cwa, Ce, OCc, Os, Ob, Oeln, and Om) underlie the valleys (Southworth et al. 2009).

Erosion and weathering continue to shape the landscape in the park today. These processes are evident in the variety of unconsolidated, geologically young, surficial units. In the highlands, debris flows and frost wedging contribute to the formation of debris fans (Nd and Qdf) and colluvium deposits (Qb and Qc). The lower reaches of the park have broad alluvial fans (Nf), alluvial plains (Np), and fluvial terraces (Nt) flanking rivers depositing alluvium (Qa) (Southworth et al. 2009).

Figure 3. The peak of Old Rag Mountain. Bedrock outcrops on this peak are among the premier attractions within Shenandoah National Park. View is from Skyline Drive. National Park Service photograph.

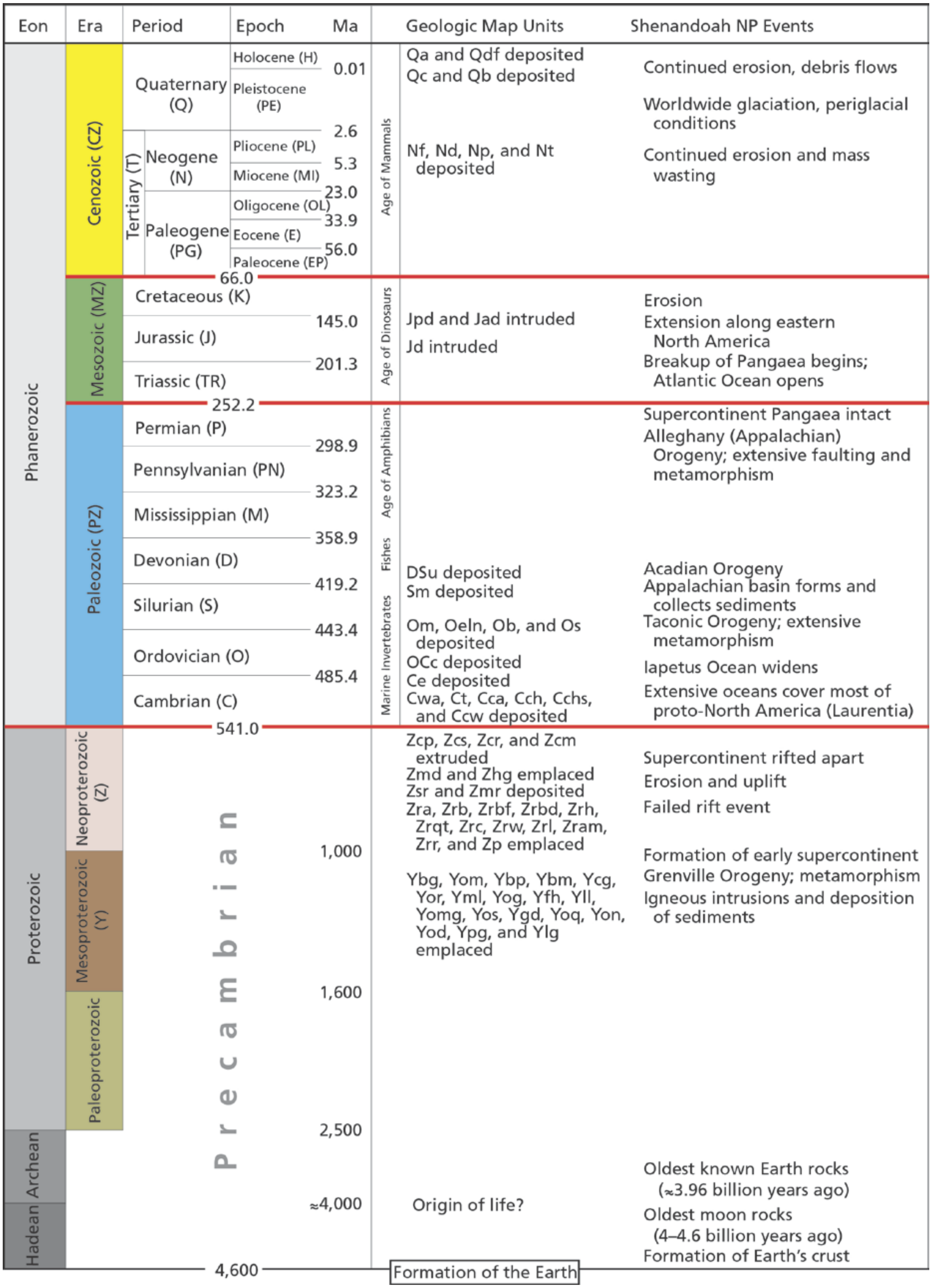
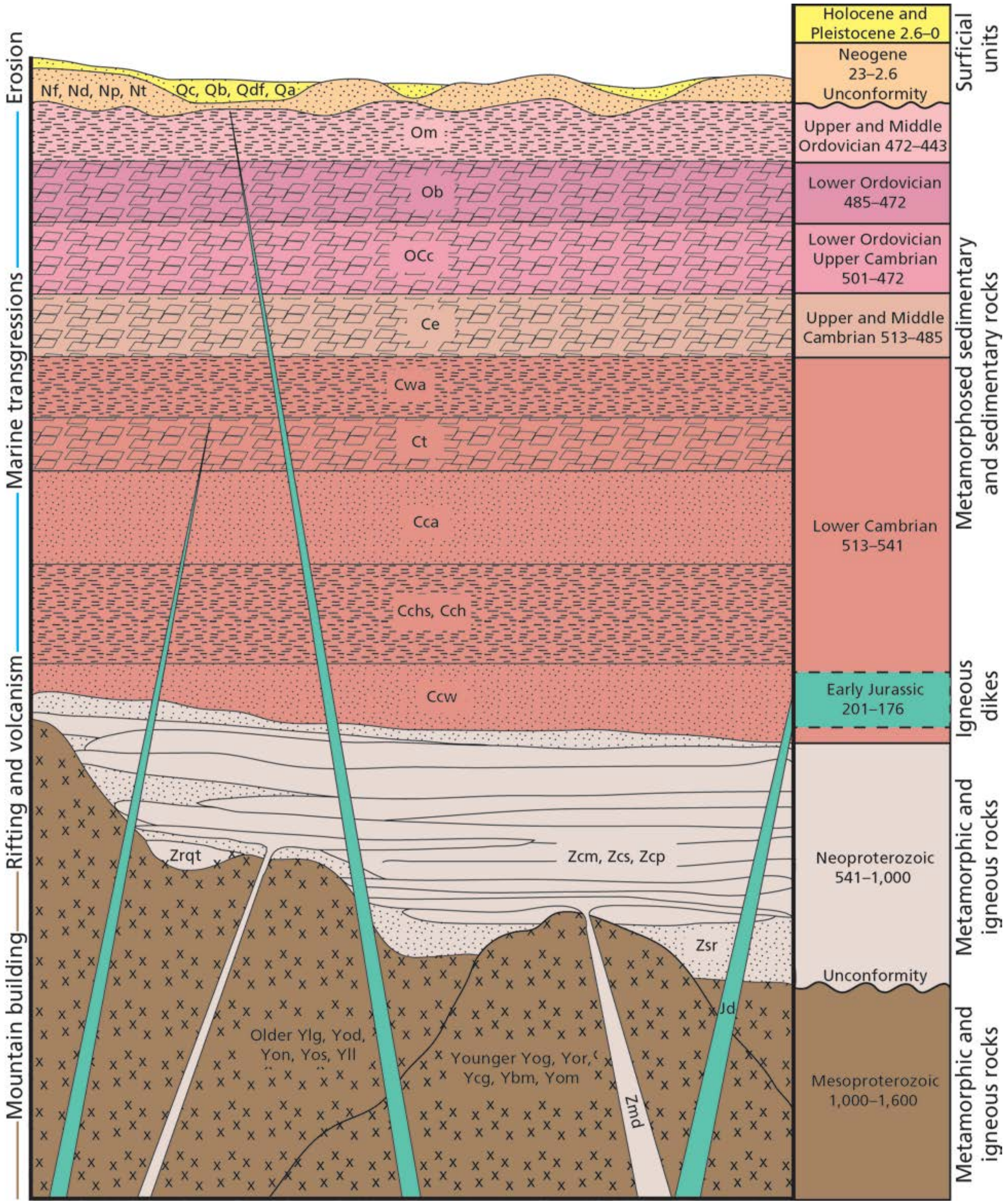


Figure 4. Geologic time scale. Geologic events affecting Shenandoah National Park are included with an emphasis on units appearing within the park ("Geologic Map Units"; see also fig. 5). The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. Red lines indicate major boundaries between eras; boundary ages are millions of years before present (Ma). 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).



** The numbers represent millions of years before present and indicate the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.*

Figure 5. Generalized cross section (not to scale) of Shenandoah National Park. Unit symbols are listed in the Map Unit Properties Table (in pocket). Time ranges given are those listed by Southworth et al. (2009). These may differ from the more recent dates used by the International Commission on Stratigraphy as shown on figure 4. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Only the units which appear within park boundaries are included. See the Map Unit Properties Table for more detail. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after a drawing in Gathright (1976).

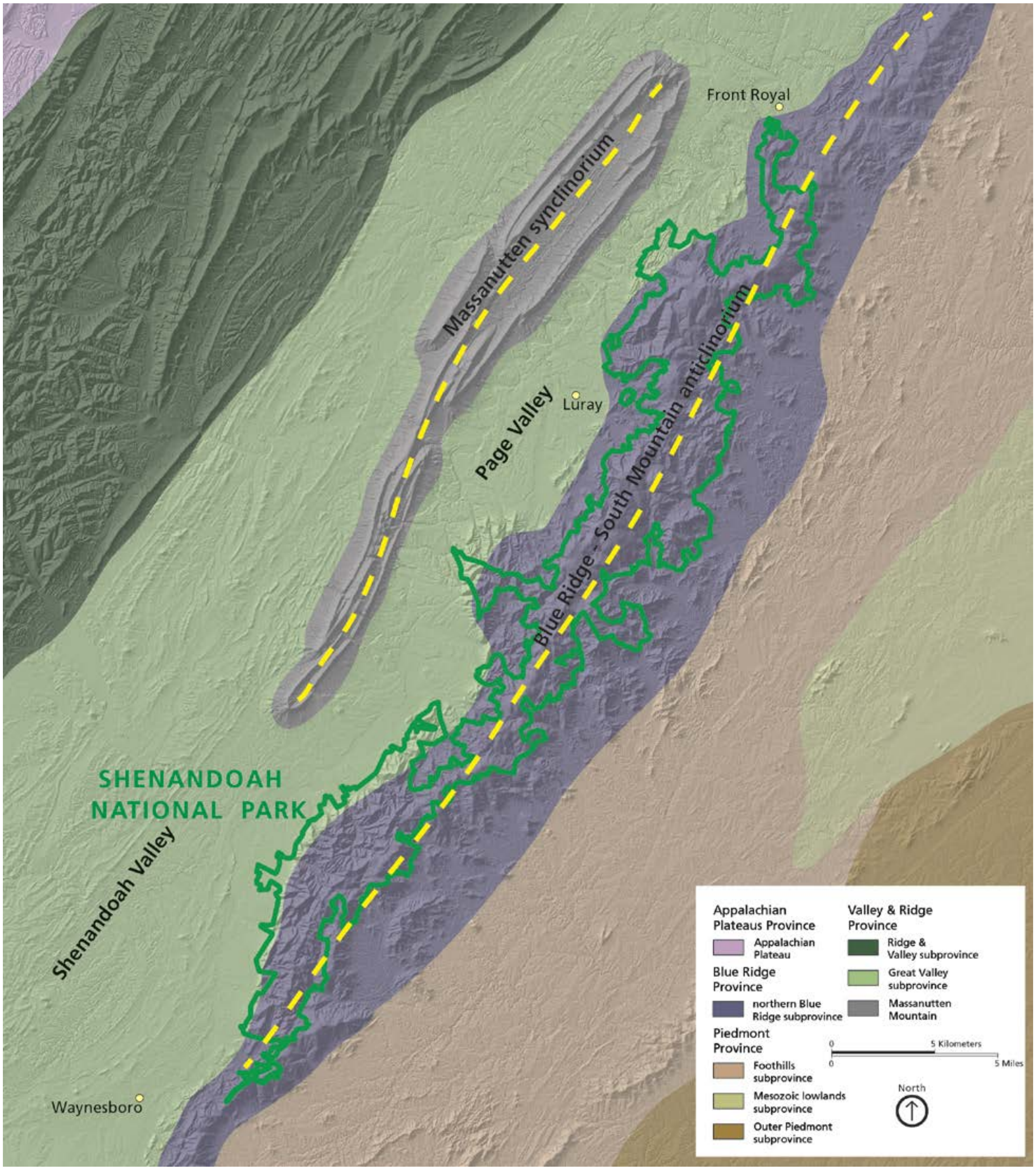


Figure 6. Physiographic map of western Virginia. Note the parallel relationship of structures such as the Blue Ridge-South Mountain anticlinorium, Massanutten synclinorium, and valleys and ridges of the Valley and Ridge province. There is a close relationship between landform and physiographic province boundaries. Major fold axes are yellow dashed lines. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Bailey (1999).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes noteworthy geologic features and processes in Shenandoah National Park.

The following geologic features and processes were discussed during the scoping meeting (22-23 March 2005; Thornberry-Ehrlich 2005), and a follow-up conference call (11 December 2012):

- Ancient bedrock
- Type sections, reference locations, and radiometric ages
- Blue Ridge-South Mountain anticlinorium and regional structures
- Bedrock outcrop habitats
- Surficial deposits
- Periglacial features
- Paleontological resources
- Cave and karst features
- Connections with park stories

Ancient Bedrock

Bedrock exposures, "outcrops", cover 1,600 ha (39,000 ac), representing 2% of the total park area but they are among the most popular natural features in the park (Fleming et al. 2007). Outcrops and cliffs of granitic gneiss, greenstone, and metasedimentary rocks are responsible for many of the scenic vistas, waterfalls, and recreational opportunities, including rock climbing. The "Map Unit Properties Table" describes each unit and identifies places where they are particularly well-exposed.

Mesoproterozoic Metamorphic and Igneous Rocks: Core of the Blue Ridge

The Blue Ridge Mountains of Virginia are the roots of an ancient mountain chain constructed intermittently over hundreds of millions of years during several major mountain-building events—orogenies (see "Geologic History" section). These are the oldest rocks in Shenandoah National Park at more than 1 billion years old. When they formed, they were many thousands of meters below the lofty peaks of the ancient mountain range. The rocks now exposed at the heights of the Blue Ridge in Shenandoah National Park (about 1,000 m [3,300 ft] above sea level) are buried nearly 3,700 m (12,000 ft) below the surface in the Great Valley west of the park. Because of this, Shenandoah National Park offers opportunities to examine the core of an ancient mountain fold-and-thrust belt—providing a view into Earth's ancient crust.

The Mesoproterozoic rocks ("Y" geologic map units), previously referred to as the Old Rag Granite and the Pedlar Formation (Gathright 1976; Southworth et al. 2009), exposed within Shenandoah National Park are among the oldest, most complex, structurally and lithologically (visible physical characteristics), in eastern North America (Southworth et al. 2009, 2010). They are difficult to distinguish from one another in outcrop and require chemical, isotopic, and petrologic (using a microscope) analyses to tell them apart. Collectively, these ancient rocks in the park are the result of a large "melting pot" of magma (molten rock) that crystallized episodically, was then metamorphosed and deformed, and further melted and recrystallized over tens of millions of years as the Appalachian Mountains formed (Southworth et al. 2009).

During the Grenville Orogeny, the Mesoproterozoic rocks were metamorphosed under extremely high temperature (700°C–800°C [~1,300°F–1,500°F]) and pressure (12 kilobars [~170,000 lbs/in^2]). One result of this metamorphism was the alignment of minerals, which rendered a striped (foliated) appearance. Such foliated rocks are termed "gneiss" (fig. 7).

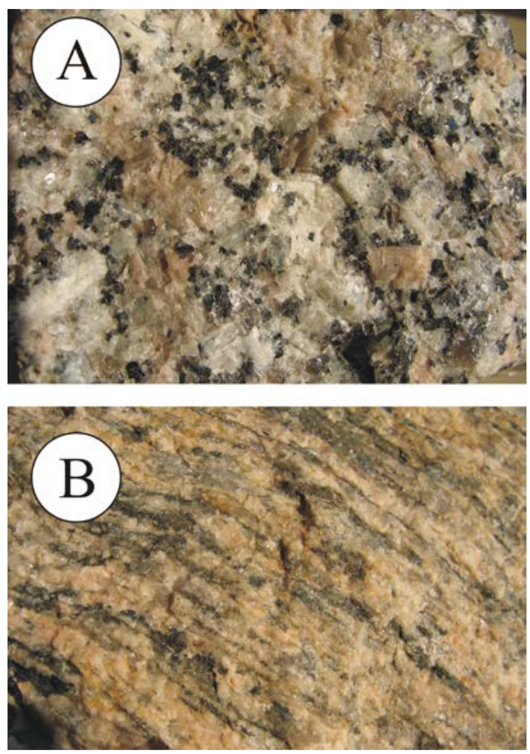


Figure 7. Granite and granite gneiss. Undeformed granites (A) in the basement complex are younger than the deformed granite gneisses (B). See also table 1. The striped appearance of the gneiss is termed "foliation" and occurs when granites (or other rocks) are compressed and their minerals align. Photograph by Callan Bentley (Northern Virginia Community College), available online: http://www.nvcc.edu/home/cbentley/shenandoah/index.htm (accessed 6 February 2014). Used with permission.

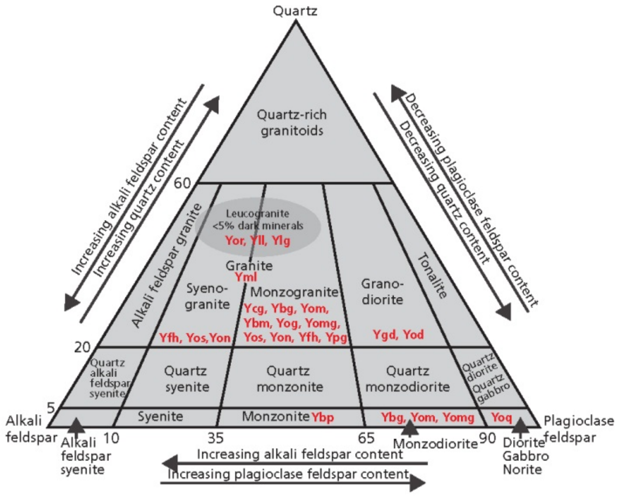


Figure 8. Classification diagram for intrusive igneous rocks. Red text refers to geologic map unit symbols whose compositions broadly fall within that field. Numbers refer to the percentage of the mineral constituent (quartz, alkali feldspar, or plagioclase feldspar) in the overall composition of the rock. Numbers 5, 20, and 60 refer to the overall quartz component, whereas numbers 10, 35, 65, and 90 refer to the contribution of plagioclase to the overall composition. The corners represent compositions very rich in the corresponding mineral and poor in the two other minerals, but not necessarily other possible component minerals. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) following standard IUGS (International Union of Geological Sciences) nomenclature.

The Mesoproterozoic rocks are classified by geologists based on the percentage of major minerals (quartz, alkali feldspar, and plagioclase) as metamorphosed granites, monzogranites, monzodiorites, monzonites, leucogranites, syenogranites, granodiorites, and diorites (fig. 8). In essence though, their compositions are broadly similar to granite and they can be collectively referred to as “granitoids.” Foliated rocks may also have the qualifier “gneissic.” See the “Map Unit Properties Table” for more details. The aforementioned “Pedlar formation” nomenclature now refers to a broad suite of granitic and gneissic rocks and is no longer a single unit (Southworth et al. 2009).

The oldest rocks in the park are strongly foliated leucogranitic gneisses (Ylg). Tollo et al. (2006) and Southworth et al. (2009) divide the Mesoproterozoic rocks into three broad temporal groups (table 1).

Table 1. Mesoproterozoic rock groups

#	Geologic map symbol	Description	Age*
1	Ylg, Ypg, Yod, Yon, Yoq, Ygd, Yos, Yomg, Yll, Yfh	Strongly foliated gneisses and metagranitoids	1,183 to 1,144
2	Yog	Variably foliated metagranitoids	1,143 to 1,111
3	Yml, Yor, Ycg, Ybm, Ybp, Yom, Ybg	Massive metagranitoids	1,078 to 1,028

***** ages are in millions of years***

Note that the amount of foliation decreases in younger rocks. The relation of the timing of the intrusion of the igneous plutons, to the timing of metamorphic events, and the development of foliation and deformation textures within the Mesoproterozoic rocks remains to be resolved (Southworth et al. 2009, 2010).

Neoproterozoic Metamorphosed Volcanic Rocks

The Neoproterozoic Catoctin Formation (geologic map units Zcp, Zcs, Zcr, and Zcm) is a prominent regional collection of metamorphosed basalts and associated rocks. The Catoctin Formation is exposed the eastern limb of the Blue Ridge-South Mountain anticlinorium from southern Pennsylvania 350 km (217 mi) south to near the James River in Virginia. The Catoctin Formation contains the metamorphosed sequence of at least 16 flood basalt flows (greenstone), intrusive dikes, and pyroclastic ashes and tuffs that erupted more than 550 million years ago. The rocks are mostly green, gray, and purple, aphanitic (extremely fine-grained), massive or schistose, and up to 300 m (1,000 ft) thick in the park (Furcron 1934; Reed 1969; Gathright 1976; Butler 2005; Southworth et al. 2009).

Relict volcanic features such as vesicles and amygdules, feeder dikes, pillow basalts, volcanic breccias, flow banding, and columnar joints provide clues to the eruptive history of the Catoctin Formation. When magma (molten rock) rises toward the surface, the lower pressure releases gasses and fluids similar to opening a carbonated beverage, forming bubbles or vesicles in the lava that can be preserved in the resultant rocks. Where these cavities fill with secondary minerals, amygdules are formed. Vesicles and amygdules occur within many of the vesicular flows, volcanic tuffs, pumice, and volcanic ash beds of the unit Zcp. Filled vesicles are visible along Overall Run, at Signal Knob Overlook, along the Dark Hollow Trail, Bearfence Mountain parking area, near Byrds Nest No. 4, and on the west side of Knob Mountain southeast of Rileyville (Badger 1999; Southworth et al. 2009).

As the molten lava emerged from feeder dikes (visible at Little Devils Stairs Overlook, the Summit Trail at Old Rag Mountain, and the north entrance to Marys Rock Tunnel) and spread over the landscape, it filled in valleys and covered hills (fig. 9) (Badger 1999; Southworth et al. 2009; Sally Hurlbert, Shenandoah National Park, park ranger, written communication, 8 November 2013). Where lava injected into local water-filled basins, submarine pillow structures are preserved at Dark Hollow Falls, east of Big Meadows, and the Appalachian Trail, near the Little Stony Man Parking Area (Lukert and Mitra 1986; Southworth et al. 2009; Sally Hurlbert, written communication, 8 November 2013). Clasts of underlying material (sands and gneisses) were entrained in the flows and are visible west of Hogwallow Flat, at Grindstone Mountain, on Bearfence Mountain, on the north side of Hawksbill, and in Weaver Hollow (Southworth et al. 2009). As the lava flowed over them, underlying rocks were altered (metamorphosed) through their contact with the extremely hot lava (Dilliard et al. 1999; Southworth et al. 2009). This fast, local contact

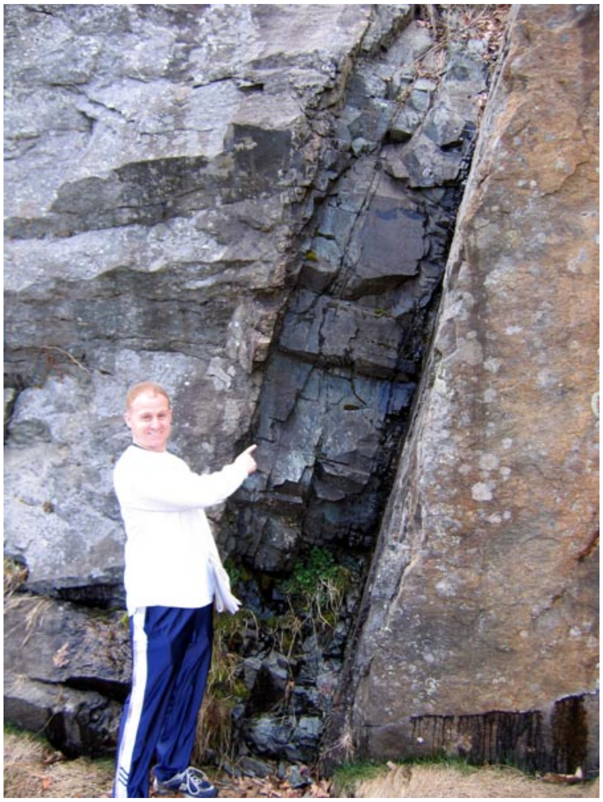


Figure 9. Feeder dike. This feeder dike is of Catoctin Formation basalt cutting across older basement rocks. Feeder dikes supplied magma that erupted onto the surface as basalt through fissures during the rifting of supercontinent Rodinia. Photograph by Callan Bentley (Northern Virginia Community College), available online: http://www.nvcc.edu/home/cbentley/shenandoah/index.htm (accessed 6 February 2014). Used with permission.

metamorphism formed unakite, a rock composed of pink potassium feldspar, quartz, and yellowish green epidote minerals.

Catoctin volcanism was predominantly silica-poor basalt flows that erupted effusively (non-explosively) from fissures. However, in the northeastern portion of the map area, metarhyolite flows and tuff (Zcr) record an episode of explosive volcanism involving silica-rich magma (Southworth et al. 2009). Volcanic breccias, containing fragments of dark red shales or siltstones within a metabasalt matrix, are visible at Little Stony Man (Badger 1999). These shale or siltstone grains within the breccias may have formed as rip-up clasts and were incorporated into the lava as it passed over lagoon or lake sediments. Another theory is wind-blown or water-transported silt-sized sediments were deposited into cracks and crevices of the fragmented surface of a previously solidified lava flow (Badger 1999; Sally Hurlbert, written communication, 8 November 2013). The Catoctin Formation is not the only volcanic unit in Shenandoah National Park. Outcrops of felsite (geologic map unit Zrbf) locally displays flow banding (Southworth et al. 2009) formed during eruption and lava flow.

Over millions of years, successive lava flows created a thick pile of basalt, the thickest section of which is more than 700 m (2,300 ft) (Reed 1969; Southworth et al.

Figure 10. Columnar basalt. As basalt cools it contracts, forming distinctive hexagonal columns. These examples are from the Catoctin Formation atop Compton Peak. Geology class for scale. Photograph by Callan Bentley (Northern Virginia Community College). Used with permission.

2009). As the lava cooled and contracted in the thicker flows, columnar joints formed in a process similar to mudcracks forming in drying mud. These joints yield a characteristic hexagonal shape to columns of basalt (fig. 10). This is visible in outcrops at Big Meadows, Compton Peak, Little Stony Man, Limberlost Trail, and at Indian Run Overlook (Badger 1999; Bentley 2008; Sally Hurlbert, written communication, 8 November 2013).

After the volcanic rocks erupted, they became part of the geologic foundation, which was deformed, metamorphosed, and later weathered. Some features were secondarily altered. For example, some vesicles can reach up to 10 cm (4 in) in diameter and exhibit foliation over metamorphosed amygdules suggesting that following eruption, the vesicles were filled with a secondary mineral to form amygdules (fig. 11). These were metamorphosed again, resulting in the development of foliation (layers of similarly-aligned minerals) (Trimbur et al. 1996).

Over millennia, feeder dikes and adjacent country rock were uplifted and weathered. Because the rocks have a

Figure 11. Amygdaloidal basalt. Amygdules, the oval-shaped masses in the photo, form when vesicles ("bubbles") in basalt are filled in with minerals. This Catoctin Formation rock is located along the Limberlost Trail. Photograph by Callan Bentley (Northern Virginia Community College), available online: http://www.nvcc.edu/home/cbentley/shenandoah/index.htm (accessed 6 February 2014). Used with permission.

Figure 12. Weathered feeder dikes. Basalt is less resistant to erosion than the surrounding Old Rag Granite (geologic map unit Yor). As it weathers away, "slots" form such as these on the Summit Trail on Old Rag Mountain. Columnar basalt weathering can produce "stairs" in these slots. Dikes are approximately 1 m (3 ft) wide. Photograph by Callan Bentley (Northern Virginia Community College), available online: http://www.nvcc.edu/home/cbentley/shenandoah/index.htm (accessed 6 February 2014). Used with permission.

different composition than the surrounding "country rock", differential weathering created "stairways" of diabase feeder dikes (Zmd) cutting through more resistant granites (e.g., Yor), such as those hikers enjoy along the summit trail to Old Rag Mountain (fig. 12; Hackley 2000; Bentley 2008).

Paleozoic Sedimentary Rocks and Metamorphism

Sedimentary features and structures in rocks record their original depositional environment. Even in rocks that have undergone metamorphism, sedimentary features may persist. The early Paleozoic sedimentary rocks from within the park and adjacent areas formed in myriad depositional settings, from deep marine to shallow marine to nearshore and deltaic settings. They were then metamorphosed during the Paleozoic orogenies so the rock names often have the prefix "meta."

In the metasedimentary Mechum River Formation (geologic map unit Zmr) graded and scoured beds record submarine landslides (turbidites) that occurred more than 540 million years ago. The Martinsburg Formation (Om) also contains turbidite deposits and load casts (Southworth et al. 2009). Load casts are bulbous-shaped, downward projections of one sedimentary material into another. These tend to form by soft-sediment deformation (occurring while the sediments are unconsolidated) as rapid sediment loading causes unequal settling and compaction of the underlying deposits.

In contrast to the deep marine environments, flowing-water sedimentary structures such as wavy laminations, cross-bedding, and coarsening-upward sequences occur within the Chilhowee Group rocks (Ccw, Cch, and Cca) (Southworth et al. 2009). Coarsening-upward sequences record a shift towards higher energy depositional environments through time such as a prograding delta or a point bar system in a stream (fig. 13). Wavy laminations are thinly bedded layers formed through deposition in flowing water conditions. Cross-beds are inclined beds that form in flowing water. Geologists use cross-beds to determine flow directions in sedimentary rocks—flow is perpendicular to the angled plane of the cross-bed. Chilhowee Group rocks with evident sedimentary structures are visible along the Thornton River Trail, at the Doyles River Overlook, at Blackrock Summit, at Sawmill Ridge Overlook and at Jeremys Run Overlook (Badger 1999).

Figure 13. Weverton Formation conglomerate. Conglomerate is deposited in relatively high energy stream and river environments. The Weverton Formation (geologic map unit Ccw) is one formation of sedimentary rocks that comprise the Chilhowee Group. Photograph by Callan Bentley (Northern Virginia Community College), available online: http://www.nvcc.edu/home/cbentley/shenandoah/index.htm (accessed 6 February 2014). Used with permission.

Some sedimentary features reveal occasional subaerial exposure. The Waynesboro Formation (Cwa) contains mudcracks, ripplemarks, and cross-beds. Mudcracks preserved in the sedimentary record form by the shrinkage of mud and clay generally in the course of drying in subaerial conditions. Ripplemarks are similar to cross-beds, but tend to be smaller in scale and if symmetrical in profile, it may reveal regular oscillation type flows, such as waves washing up and down a shoreline. The Antietam Formation (Cca), Waynesboro Formation (Cwa), and Conococheague Limestone (OCc) also contain bioturbated beds. Bioturbation occurs as organisms rework the sediments in their movements and forages after they are deposited. This is discussed further in the "Paleontological Resources" section.

Collapse breccia and "paleokarst" features within the Beekmantown Group (Ob) represent ancient karst processes such as cavern formation, sinkhole collapse, and carbonate dissolution prior to mountain building and subsequent re-exposure (Southworth et al. 2009).

Jurassic Intrusive Rocks

At the beginning of the Mesozoic Era, the Earth's crust pulled apart along what is now the East Coast of North America, opening a basin that would become the Atlantic Ocean Widespread normal faulting created, rift basins and fueled the emplacement and/or eruption of molten material. Three types of igneous rocks—all Jurassic in age—diabase dikes (geologic map unit Jd), peridotite dikes (Jpd), and alkalic dikes (Jad) record this activity. The dikes formed as magma injected along fractures within the Blue Ridge rocks. Jurassic diabase dikes (Jd) now form massive, black boulders with a rusty stain. They are common in the southernmost part of the park (Southworth et al. 2009).

Type Sections, Reference Locations, and Radiometric Ages

Geologists group rocks with similar age and composition together into "formations." Formations are typically named after a geographic feature where those rocks are commonly found (e.g., Old Rag Granite or Antietam Formation). The formation is the fundamental division of rocks on geologic maps. Formations can be compiled into groups (e.g., Chilhowee Group) or further divided into members (e.g., informal members of Catoctin Formation). Most stratified (sedimentary or interlayered sedimentary and volcanic) formations have an established "type section" defined by geologists where the formation is particularly well exposed. Other outcrops of those rocks can be compared to the type section. The spectacular bedrock outcrops within or in proximity to Shenandoah National Park serve as type sections (e.g., the Swift Run Formation [geologic map unit Zsr] along US Highway 33 at Swift Run Gap). Reference or type locations are given for many of the igneous units on the source map by Southworth et al. (2009). These are all listed on the "Map Unit Properties Table". Further information about geologic units and type sections is available via the US Geological Survey's geologic names lexicon: http://ngmdb.usgs.gov/Geolex/.

The ages of many rocks within the park have been determined via radiometric dating techniques. The GRI GIS data includes 38 locations and ages determined for 24 of the Mesoproterozoic and Neoproterozoic rocks. This dating and petrologic analysis has revealed a remarkably complex geologic history, particularly in the Precambrian granites and gneisses within the park, which range in age from about 700 million years ago to nearly 1.2 billion years ago (Southworth et al. 2009, 2010). Available dates are listed in the "Map Unit Properties Table".

Blue Ridge-South Mountain Anticlinorium and Regional Structures

The Blue Ridge terminates in southern Pennsylvania in a large, arch-shaped, regional fold (an "anticlinorium"), called the Blue Ridge-South Mountain anticlinorium (Logan and Dyer 1996). Shenandoah National Park is located on the western limb of the anticlinorium. Catoctin Mountain Park, in Maryland, is on the northern end some 275 km (170mi) northeast of the park (see Thornberry-Ehrlich 2009 for the Catoctin Mountain Park GRI report). The anticlinorium is tilted past vertical, or "overturned", to the northwest (fig. 14). The west limb dips steeply southeast, the crest is broad and flat and the east limb dips approximately 50°southeast. Within the park, the rocks are nearly horizontal because of their position near the crest of the structure (Southworth et al. 2009). Page Valley, Massanutten Mountain, and the Great Valley are west of the anticlinorium. Massanutten Mountain is one part of a synclinorium (large, trough-shaped regional fold) with ridges upheld by resistant sandstones (geologic map unit Sm). The entire synclinorium is 225 km (135 mi) long and 20 km (12 mi) wide and parallels much of the Blue Ridge-South Mountain anticlinorium (Southworth 2008). Erosion of the anticlinorium exposed Mesoproterozoic and Neoproterozoic granitoids in its core flanked on each side by Precambrian and Paleozoic metamorphosed sedimentary and volcanic rocks (fig. 6) (Mitra 1989).

The anticlinorium formed above a detachment fault or décollement that extends eastward beneath what is now the Piedmont province (Onasch 1986). The entire folded structure was subsequently transported westward along the North Mountain thrust fault during the Alleghany Orogeny (see the "Geologic History" section). The hanging wall of the North Mountain thrust fault includes the Massanutten synclinorium, parts of the Great Valley, and the Blue Ridge anticlinorium (figs. 14, 15, and 16) (Bailey et al., 2006). The rocks of the Blue Ridge were in turn thrust westward atop younger rocks of the Page and Great valleys along faults such as the Elkton, Stanley, and Front Royal faults that are part of the Blue Ridge fault system (Southworth et al. 2009).

Structures along the limbs of the anticlinorium suggest multiple phases of folding and metamorphism. For example, the "cleavage" pattern (how the rock fractures) has a different orientation than that of the overall anticlinorium suggesting different episodes of movement and deformation (Trombley and Zynjuk 1985; Onasch 1986). Folds are visible in Chilhowee Group outcrops

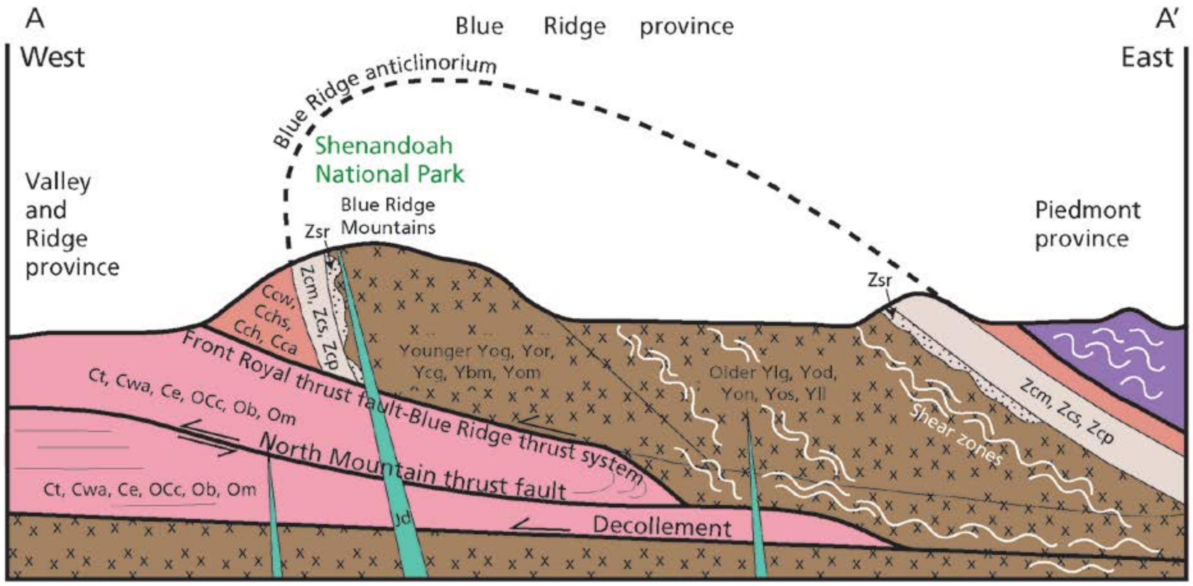


Figure 14. Schematic cross section of the Blue Ridge anticlinorium. Location of the cross section line is the orange arrow on figure 16. Some units are grouped for clarity. Diagram is not to scale. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after an unnumbered graphic in Bentley (2008), figure 4 in Bailey et al. (2006), and with information from A. Merschat (geologist, US Geological Survey, written communication, 16 July 2013).

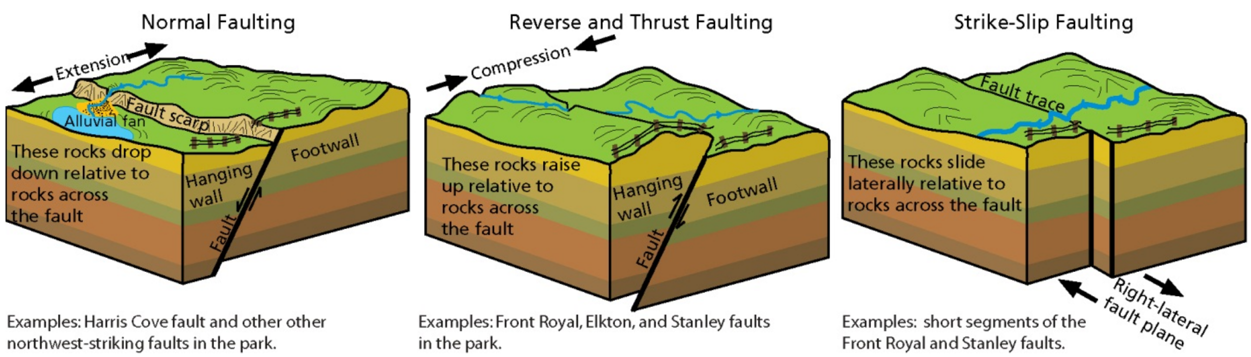


Figure 15. Schematic graphics illustrating different fault types. Footwalls are below the fault plane, hanging walls are above. In a normal fault the hanging-wall moves down relative to the footwall. Normal faults result from extension (pulling apart) of the crust. Grabens and horsts develop during extension due to faulting along normal faults. In a reverse fault the hanging wall moves up relative to the foot wall. A thrust fault is similar to a reverse fault only the dip angle of a thrust fault is less than 45°. Reverse faults occur when the crust is compressed. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. If the movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. If 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).

(Ccw, Cch, Cchs, and Cca), predominantly in the southern sections of the park (Harris et al. 1997) and several phases of folding predate the pervasive lower temperature and pressure metamorphism associated with the Alleghany Orogeny and therefore may represent prior Taconic or Acadian orogenic deformation (Onasch 1986). Structures like these provide evidence for the multiple Appalachian orogenies.

Faults influenced landform development within Shenandoah National Park. Several large low- to high-angle thrust faults dip to the southeast along the length of the park; some are visible as narrow brecciated zones, but most traces are covered with slope talus and other debris. These faults are largely parallel with the major Front Royal, Stanley, Elkton, and North Mountain faults (S. Southworth, geologist, US Geological Survey, personal communication, March 2005; Bailey et al. 2006). Steeply inclined, strike-slip faults (figs. 15 and 16) dissect the parallel thrust fault blocks, trending northwestward across the Blue Ridge. Movement along these faults caused the pattern of uneven summits, dissected ridges, and irregular stepwise ("lobe and embayment") patterns of the bedrock visible in map view along the eastern edge of the park (Harris et al. 1997).

Bedrock Outcrop Habitats

Rare plant communities are closely associated with prominent bedrock outcrops within the park. These communities are highly susceptible to human disturbances as described in the "Bedrock Outcrop

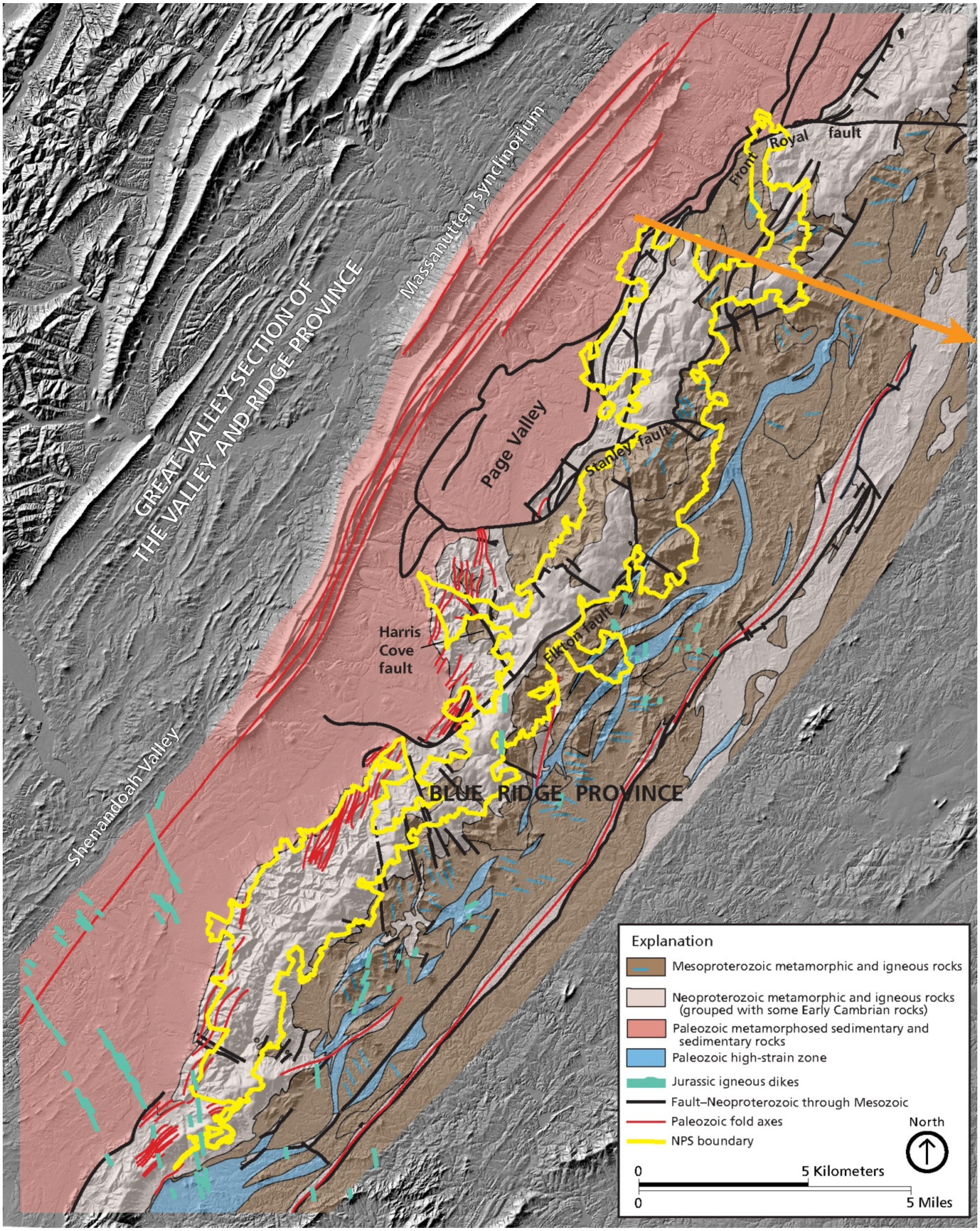


Figure 16. Geologic structures and rock types of the Shenandoah National Park region. Orange arrow depicts the approximate location of the cross section A-A' in figure 14 which extends off the map view and is not to scale. Rock types are draped over shaded relief imagery from ESRI. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after maps presented in Southworth et al. (2009).

Management" section. Soil properties (water-yielding), slope aspect, and topographic location are other key factors determining the location of the communities (Grote and Blewett 2000). The location and nature of bedrock outcrops are affected by myriad factors including the composition (lithology) of the bedrock, geologic processes that acted on the bedrock, such as faulting, metamorphism, folding, and weathering, and age of the rock (Butler 2006). In Shenandoah, three common bedrock compositions—greenstones, granitic gneisses, and metasedimentary rocks—yield different rock morphologies. According to the detailed rock outcrop study by Butler (2006), outcrops of greenstone (e.g., geologic map units Zcp, Zcs, and Zcm) occur most commonly as lines of cliffs and ledges with some open talus areas. In the older, granites and gneisses (e.g., Yom, Ybm, Ycg, Yor, Yog, Yll, Yos, Yon, Yod, and Ylg) smooth rock faces and barrens (including prominent rounded boulders) are common and ledges and cliffs are rare. Metasedimentary rocks (e.g., Zsr, Ccw, Cchs, and Cca) tend to form mixtures of cliffs, isolated outcrops, and ledges, and most commonly, large, open talus fields. Eleven natural community types, listed in table 2, are associated with the 50 bedrock outcrops assessed in the Rock Outcrop Management Plan (ROMP) (Fleming et al. 2007). Nine of the 11 natural community types are globally rare and two are entirely endemic to Shenandoah National Park. Twenty-one state rare plant species are found within these 11 rare plant communities. The preponderance of globally rare and environmentally restricted natural communities in the

Table 2. Natural community types and geology at 50 park bedrock outcrop study sites

Community	Representative or Significant Species	ROMP Site	Geology
Central Appalachian basic woodland	White ash (*Fraxinus americana*) Pignut hickory/cliff muhly (*Carya glabra/Muhlenbergia sobolifera*) Woodland sunflower (*Helianthus divaricatus*) Elm-leaf goldenrod (*Solidago ulmifolia*)	Dickey Ridge	Metabasalt Granitic complex Calcareous sandstone
Central Appalachian heath barren	Mountain-laurel (*Kalmia latifolia*) Early lowbush blueberry (*Vaccinium palladium*)	Marys Rock	Granitic complex Quartzite/sandstone
Central Appalachian acidic boulderfield	Lichen (*Lasallia* [*papulosa*, *pensylvanica*]) Lichen (*Dimelaena oreina*) Lichen (*Melanelia culbersonii*)	Blackrock South District	Quartzite Metabasalt
Central Appalachian mafic boulderfield	Lichen (*Lasallia papulosa*) Lichen (*Stereocaulon glaucescens*) Yellow lichen (*Chrysothryx chlorina*)	Franklin Cliffs overlook	Metabasalt
Central Appalachian circumneutral barren	Eastern red cedar (*Juniperus virginiana*) White ash/Pennsylvania sedge (*Fraxinus americana/Carex pensylvanica*) Hairy lipfern (*Cheilanthes lanosa*)	Dickey Ridge	Metabasalt Amphibolite Calcareous shale
Sweet-birch-chestnut oak talus woodland	Sweet birch (*Betula lenta*) Chestnut oak/Virginia creeper (*Quercus prinus/Parthenocissus quinquefolia*)	Blackrock South District	Quartzite/sandstone Metabasalt Granitic complex
Central Appalachian high-elevation boulderfield forest	Yellow birch/American mountain ash (*Betula alleghaniensis/Sorbus americana*) Mountain maple/Appalachian rock polypody (*Acer spicatum/Polypodium appalachianum*)	Hawksbill summit	Metabasalt Granitic complex Quartzite/sandstone
High-elevation outcrop barren	Black chokeberry (*Photinia melanocarpa*) Black huckleberry/Pennsylvania sedge (*Gaylussacia baccata/Carex pensylvanica*)	Pass Mountain	Metabasalt Granitic complex Rhyolite
Central Appalachian mafic barren	White ash/ninebark/Pennsylvania sedge (*Fraxinus americana/Physocarpus opulifolius/Carex pensylvanica*) Nodding onion (*Allium cernuum*) Appalachian phacelia (*Phacelia dubia*)	Little Devils Stairs	Metabasalt Granitic complex
High-elevation greenstone barren	Northern bush-honeysuckle (*Diervilla lonicera*) Rand's goldenrod (*Solidago randii*) Wavy hairgrass (*Deschampsia flexuosa*) Allegheny stonecrop (*Hylotelephium telephioides*) Michaux's saxifrage (*Saxifraga michauxii*)	Stony Man Summit	Metabasalt
Central Appalachian xeric chestnut oak-Virginia pine woodland	Chestnut oak (*Quercus prinus*) Virginia pine (*Pinus virginiana*) Table-mountain pine/little bluestem (*Pinus pungens/Schizachyrium scoparium*) Starved panic grass (*Dichanthelium depauperatum*)	Whiteoak Canyon	Metabasalt Granitic complex Sandstone

Information is from Fleming et al. (2009). Green rows denote natural community types endemic to Shenandoah National Park.

park stems from its rare confluence of geologic (granitic and metabasaltic rocks), climatic patterns, landforms, and biologic elements (Fleming et al. 2007).

Characteristic boulderfield and outcrop habitats (e.g., Central Appalachian Mafic Boulderfield, Central Appalachian Acidic Boulderfield, High Elevation Greenstone Barren, and Central Appalachian Heath Barren community types), yielded approximately 90 lichen taxa—five of which are potentially new to science and remain undescribed or lack sufficient features for identification (*Chrysothrix* sp., *Fuscidea* sp., *Lecanora* sp., *Lepraria* sp., *Opegrapha* sp.) (Fleming et al. 2007; W. Cass, Shenandoah NP, botanist, written communication, 16 September 2013). Erwin Bodo, a premier North American lichenologist, identified a previously unknown yellow crust as *Calvitimela talayana*, a species new to North America (W. Cass, written communication, 16 September 2013).

Greenstone talus deposits are preferred by the Shenandoah salamander (*Plethodon shenandoah*); rare lichens (*Buellia stellulata*, *Poripidia lowiana*, *Cladonia coccifera*, *Parmelia omphalodes*, and *Poripidia tuberculosa*) thrive on high elevation bedrock outcrops; high-elevation greenstone barrens have Rand's goldenrod (*Solidago simplex* spp. *randii*); cliffs provide Peregrine falcon (*Falco peregrinus*) habitat; and the shale-barren blazing star (*Liatris turgida* Gaiser) reflects the flower's preferred habitat (Thornberry-Ehrlich 2005; Fleming et al. 2007; W. Cass, written communication, 16 September 2013).

Chestnut oak (*Quercus prinus*, a xeric species) and red oak (*Quercus rubra*) are common on ridgetops and higher elevation locations underlain by Catoctin Formation greenstones (geologic map units Zcp, Zcs, Zcr, and Zcm). Yellow poplar (*Liriodendron tulipifera*, a mesic species) and black birch (*Betula lenta*) populate the lower areas with gentler slopes (<20%) (Grote and Blewett 2000; W. Cass, written communication, 16 September 2013). Ash (*Fraxinus* spp.), red oak, and basswood (*Tilia americana*) dominate shaded cove-like areas (cove hardwood forest) and black locust (*Robinia pseudoacacia*) trees are common in areas of obvious human disturbance.

The GRI digital geologic data provide a tool for GIS analysis to determine ecosystem relationships (Young et al. 2001, 2009). Examples of park GIS data include topography (digital elevation data), moisture patterns, and vegetation and soils data. As this report was being prepared (fall 2013), digital elevation and moisture pattern data were available, the park soils map is still in process (via the NPS Soil Resources Inventory), and the vegetation map is complete (Young et al. 2009). The vegetation map is particularly relevant document, because it was generated using environmental gradients, multi and hyperspectra imagery, and plant composition data, in conjunction with geologic information, to map 35 vegetation community types.

Surficial Deposits

With the exception of bedrock outcrops, most of the land surface within Shenandoah National Park is covered with unconsolidated, residual soil and surficial deposits of transported material. Much of this material was derived from weathering of the local bedrock. Surficial deposits document the most recent chapter of the ongoing geologic history at the park (Southworth et al. 2009). The distribution and types of surficial deposits and associated landforms are directly linked to their geologic setting and local bedrock. Colluvium and debris fans (geologic map units Qc, Qb and Nd) occur in highland areas with steep slopes and hollows, whereas broad alluvial fans, alluvial plains, and fluvial terraces (Qa, Np, Nt, and Nf) collect in lowland areas. (Southworth et al. 2009). In areas underlain by gneiss or metabasalt, debris-fan deposits (Nd) are abundant. Areas underlain by metamorphosed sandstone and quartzite support block-fields (Qb), whereas carbonate bedrock is mostly mantled by alluvial-fan deposits (Nf) (Southworth et al. 2009).

As described in the "Slope Movements" section, surficial deposits are grouped primarily by their process of deposition and resulting geomorphology. The surficial deposits mapped within the park resulted from the following processes: flowing water (Qa, Nt, Np, and Nf); slope failure (Qdf and Nd); and frost-wedging (Qb and Qc). They are described in detail in the "Map Unit Properties Table".

Periglacial Features

The great continental ice sheets of the Pleistocene ice ages did not reach Shenandoah National Park; the southern terminus was in central Pennsylvania. However, the colder global climates associated with the glacial events (and to a lesser extent, modern winters) profoundly affected the Blue Ridge landscape. The term "periglacial" describes features that were never buried by glaciers, but were subject to cold climates and associated frost weathering. Frost weathering occurs via the freezing and thawing of water within rocks or minerals. As described in Walder and Hallet (1985), Hallet (2006), and Matsuoka and Murton (2008), under sustained freezing and temperature ranges of -4°C to -15°C (25°F to 5°F), water seeps into fractures within the rock. When it freezes and expands, the rocks are wedged apart and fall downslope (fig. 17). Volumetric expansion (as water turns to ice) and ice segregation are the two main processes of frost weathering (Matsuoka and Murton 2008). The ice segregation process occurs as progressive microcracking in moist, porous rocks. Ice lenses expand into the microcracks and further pry the rocks apart (Matsuoka and Murton 2008). Frost weathering occurs today, but was especially active during the sustained, colder climates of Pleistocene glacial periods.

Four types of periglacial landforms are present at Shenandoah: (1) rock columns (pinnacles and tors), (2) boulder-covered slopes, (3) side-slope stone (or talus) "streams", and (4) steps as patterned ground features. The wedging action of water in fractures breaks apart the rock to produce columns (pinnacles and tors) of rock standing isolated from the neighboring slope. Tors occur on Old Rag Mountain, Rocky Mountain, and Stony Man (Morgan et al. 2003; Butler 2006). Thousands of boulders and smaller rocks, called colluvium or talus, that broke off from the columns are strewn across the surrounding slopes.

Boulder-covered slopes are characterized by boulders up to 6 m (20 ft) in diameter spaced less than 15 m (50 ft) apart. Extensive boulder fields occur in the upper headwaters of the Rapidan River and at Little Stony Man (Morgan et al. 2003; Butler 2006). Frost heaving slowly moves large boulders downslope. In areas such as Old Rag, large, rounded boulders creep downslope under the force of gravity after frost heaves imperceptibly move them (Hackley 2000).

Side-slope stone "streams" are roughly linear deposits of smaller boulders averaging 1 m (3 ft) in diameter spaced less than 0.6 m (2 ft) apart. Although similar in appearance to fluvial stream bottoms, stone streams contain angular rather than rounded boulders. A characteristic stone stream is visible near Blackrock (Morgan et al. 2003). Stone streams form when water-saturated talus slides downslope, particularly when the ground is frozen, via a process called "solifluction" (fig. 17) (Means 1995). This can also occur in masses of unconsolidated material as slump-like movements.

Step features typically form as lobate (spoon-shaped) solifluction terraces on moderate slopes. As the lobe slides downslope, it bulges, forming a localized terrace. The terraces form a perched, relatively flat surface and trap unconsolidated sediments above steep slopes. Patterned ground is typically manifested as the distinct, and often symmetrical, geometric shapes found anywhere that freezing and thawing of regolith alternate. Frost heaving causes expansion as wet, fine-grained, and porous soils freeze. Patterned ground can be found in a variety of forms—polygons, circles, steps, and stripes. Typically, the form or type of patterned ground in a given area is controlled by the prevalence of larger stones in local soils and the frequency of freeze-thaw cycles (Easterbrook 1999).

Periglacial features are best-preserved over quartzites, greenstones, and granites (Morgan et al. 2003; Thornberry-Ehrlich 2005). Periglacial stone streams and boulder-covered slopes host rare vegetation communities and burrowing animal habitat as described in the "Bedrock Outcrop Habitats" section (Shenandoah NP staff, conference call, 11 December 2012).

The periglacial features at Shenandoah National Park have yet to be comprehensively inventoried, described, or mapped (Shenandoah NP staff, conference call, 11 December 2012). The GRI GIS data include colluvium (geologic map unit Qc) and quartzite block fields (Qb), the bulk of both units likely formed via periglacial processes (Southworth et al. 2009). It is unclear if the soils at Big Meadows were derived from glacial loess (windblown silt) (fig. 18).

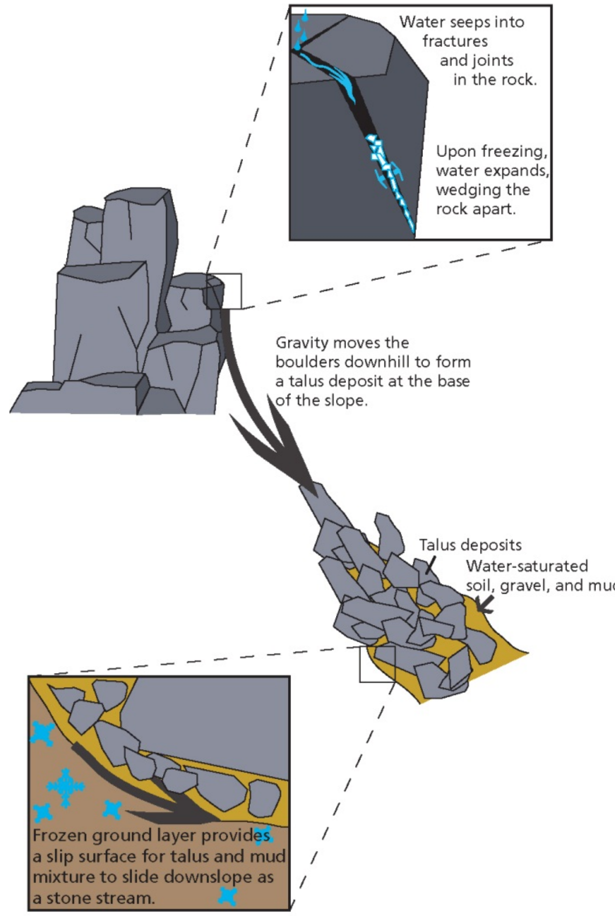


Figure 17. Frost weathering in fractured bedrock. Pinnacles or chimneys of rock remain standing whereas talus and stone streams litter the hillside below. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 18. Big Meadows. Big Meadows provides a natural open space within the heights of Shenandoah National Park. Much of the meadow is wetland habitat. Soils in the meadow are relatively deep and may be derived from windblown deposits such as periglacial loess. National Park Service photograph.

This may be an excellent opportunity for a Geoscientist-in-the-Parks (GIP) project as well as many other possibilities exploring the periglacial features at Shenandoah National Park. For more information about the GIP program, visit http://www.nature.nps.gov/geology/gip/.

Paleontological Resources

As would be expected for a park with a preponderance of very old metamorphic and igneous rocks, fossils are rare in Shenandoah National Park. The metamorphosed greenstones, granites, and gneisses contain no fossil resources. However, the Paleozoic sedimentary rocks exposed within the park contain some of the oldest fossils in the Appalachian Mountains. The Cambrian Harpers and Antietam formations (geologic map units Cch, Cchs, and Cca) of the Chilhowee Group, contain trace fossils more than 500 million years old (Gathright 1976; Kenworthy et al. 2006; Southworth et al. 2009). The trace fossils are identified as *Skolithos*, linear features most likely created by a worm burrowing through tidal flat sediments (fig. 19; Alpert 1974). These vertical burrows in quartzite helped geologists determine the original shallow marine environment of deposition and orientation of bedding. *Skolithos* tubes, once underwater in an ancient ocean are now visible at the heights of the Blue Ridge at Rockytop Overlook and at Calvary Rocks as well as along Skyline Drive in building stone (Badger 1999; Bentley 2011). Other early Paleozoic units within the park include the Tomstown Formation (Ct), the Waynesboro Formation (Cwa), the Elbrook Limestone (Ce), the Conococheague Limestone (OCc), and the Beekmantown Group (Ob). These units are not particularly fossiliferous within the park, but do contain some bioturbated beds, algal bioherms, and algal limestone. Younger, Neogene age surficial deposits may contain fossils; such remains would be rare.

Figure 19. *Skolithos* fossils. These vertical tubes were likely created by worms burrowing in tidal flat (beach) sediments, which are now the quartzite of the Antietam Formation. Pencil for scale. National Park Service photograph by Eric Butler (Shenandoah National Park).

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 (February 2014) being developed. Santucci et al. (2009)—the paleontological resources chapter in *Geological Monitoring*—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. Park staff has an interest in preventing degradation of fossil resources. (J. Schaberl, Chief, Natural and Cultural Resources Division, Shenandoah NP, written communication, 4 September 2013).

Cave and Karst Features

The term "karst" is derived from a Slavic word that means "barren, stony ground." Dissolution of carbonate rocks, such as limestone and dolomite, produces sinkholes, caves, disappearing streams, and other features characteristic of a karst landscape (Palmer 1984). Dissolution occurs when acidic water reacts with carbonate rocks along cracks and fractures. Most meteoric water is of relatively low pH ("acidic") 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^-); that is, "rocks in solution" or "dissolved rocks." Over hundreds of thousands of years, dissolution creates larger and larger voids that become caves or collapse into sinkholes (fig. 20).

The Great Valley section of the Valley and Ridge Province west of the Blue Ridge are rich in carbonate rocks (geologic map units DSu, Oeln, Ob, Os, OCc, Ce, Cwa, and Ct) and to varying degrees host karst features. The GRI GIS data include locations of more than 500 sinkholes, both large (>50 m diameter) and small (≤50 m diameter) throughout the map area. The largest sinkhole occurs near Luray and is 305 m (1,000 ft) in diameter (Southworth et al. 2009). The Beekmantown Group (Ob) contains the popular commercial caves Luray Caverns and Skyline Caverns. Karst processes are ongoing and sinkholes continue to develop. Sinkholes are commonly covered by a thin veneer of gravel (Southworth et al. 2009).

Connections with Park Stories

The geology and resultant landscape of what is now Shenandoah National Park played an important role in the history of the area. As discussed in the "Disturbed Lands" section, natural resource extraction—from American Indians obtaining quartzite, greenstone, and jasper (Nash 2009) to later mining—has long been associated with Shenandoah. Early settlers faced rocky soils and often harsh climate and terrain. Stone chimneys, foundations, and rock walls attest to their development of the area.

The local topography also held strategic value during the American Revolution and Civil War. George Washington planned to use what is now termed "Fort Valley" within the Massanutten synclinorium as a defensive position if the British had successfully taken Yorktown, Virginia (Southworth 2008). During the Civil War, strategic landforms were used by both Union and Confederate forces. For example, Signal Knob, on the north end of Massanutten Mountain, was used as a lookout and

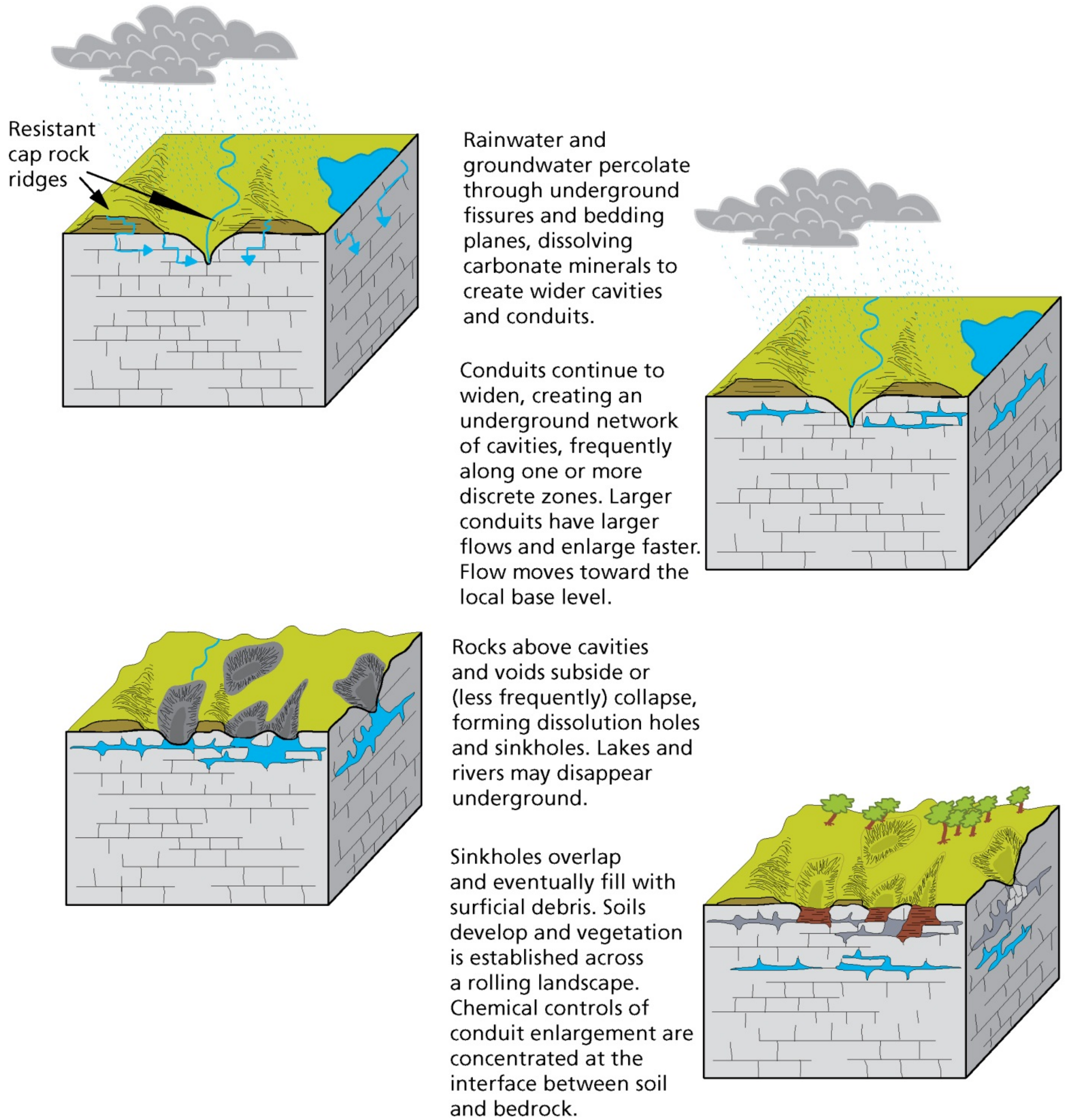


Figure 20. Schematic, three dimensional illustration of sinkhole development. Sinkholes are common in the Valley and Ridge province, particularly west of the park. Sinkhole development continues today. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

signaling post by Confederate scouts (Badger 1999). New Market Gap is visible to the west from Little Stony Man. Confederate general Thomas Jonathan "Stonewall" Jackson marched his troops through the gap on several occasions in the early part of the Civil War. He also used Fishers Gap in November 1862 while moving from Antietam to Richmond; this break in the Blue Ridge is visible from Franklin Cliffs (Badger 1999). Gaps in the Blue Ridge form where zones of weakness, commonly due to the presence of a major fault (e.g., Thornton Gap), smaller fault (e.g., Hawksbill Gap), or large fracture, weather more rapidly than surrounding bedrock (fig. 21) (Butler 2006).

By the early 1900s, the scenic views of and from the Blue Ridge, as well as the associated cliffs, waterfalls, knobs, hills, pinnacles, barrens, and hollows, were becoming increasingly valued. The failure of an old copper mine provided an opportunity for development of Skyland Lodge, which became a popular turn-of-the-century resort where visitors sought the cooler temperatures, sparkling spring waters, and spectacular views f of the Blue Ridge Mountains. Geologists (as well as President

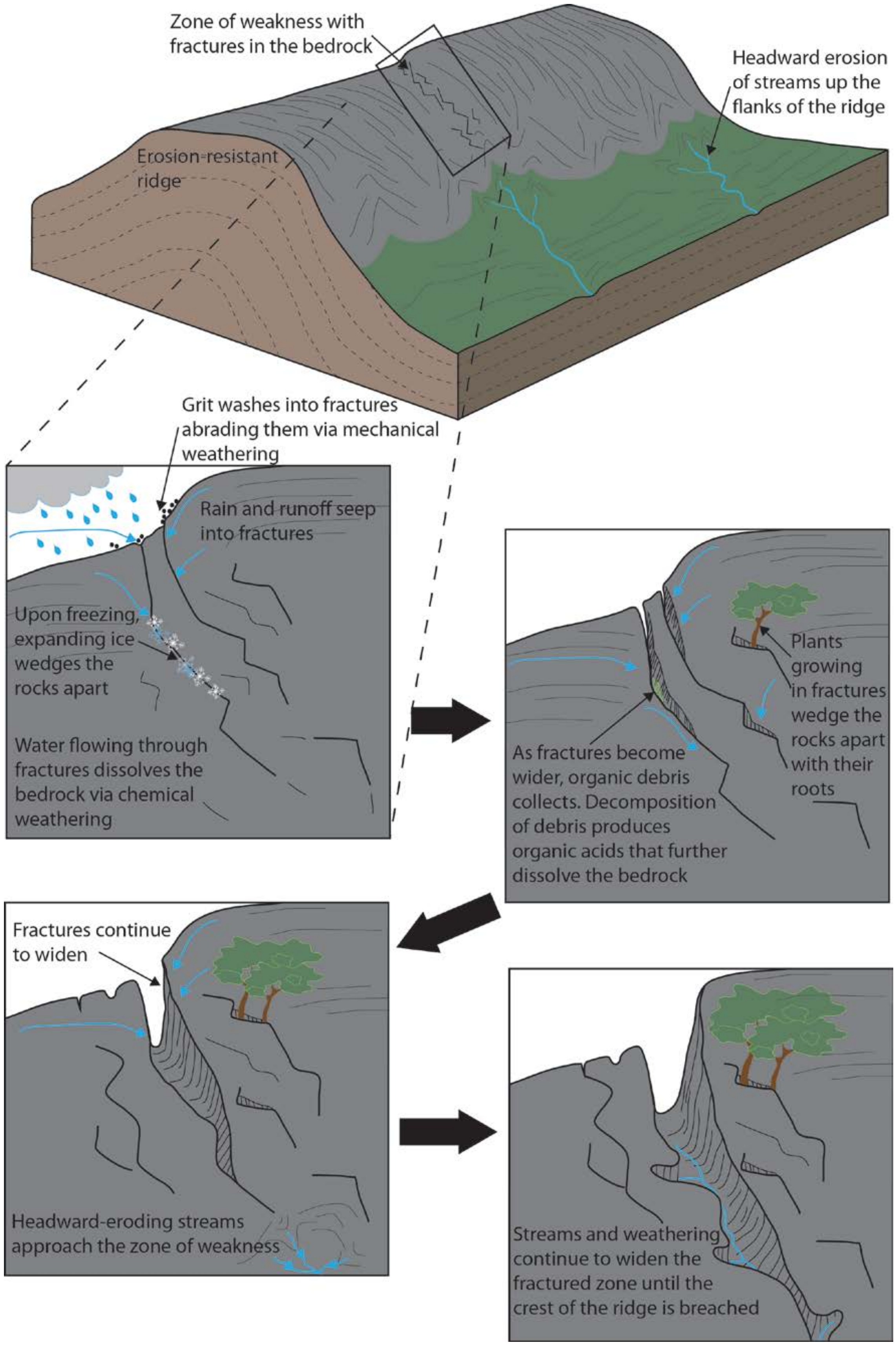


Figure 21. Schematic illustration of gap formation. Weathering processes preferentially remove material from areas of weakness that result from processes such as faulting, fracturing, or folding in bedrock. Streams may or may not flow through gaps. Examples of gaps within the park include Thornton Gap and Rockfish Gap. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

and First Lady) Herbert and Lou Henry Hoover, chose the peace and quiet of the headwaters of the Rapidan River to build their rustic retreat, Rapidan Camp, as an escape from Washington, DC.

During World War I, prospectors excavated shafts, tunnels, dumps, and pits in search of iron ore (Stose et al. 1919; Thornberry-Ehrlich 2005; Southworth et al. 2009). An iron smelter was at the Mount Vernon Furnace, now located on a restricted fire road (Thornberry-Ehrlich 2005; Engle 2013). In the south district, the Mount Vernon/Miller Ironworks is just inside the park boundary across the creek from the Madison Run fire road (Horning 2007; Sally Hurlbert, written communication, 8 November 2013. Seventy percent of the massive stone furnace structure was intact with some associated rubble. No mines were nearby, only roads, trenches, and ditches (Cloues and Sharrow 1990).

The Depression-era Civilian Conservation Corps (CCC) constructed the stone overlooks and guardrails along Skyline Drive, as well as other park infrastructure (fig. 22) to provide opportunities to access views of, and afforded by, the Blue Ridge rocks. The CCC sourced local rocks for buildings, guardrails, and other structures. Examples of this include The Byrd's Nest at Old Rag Mountain, constructed with Old Rag granite (geologic map unit Yor). Flagstones in front of the building may have come from local quartzites (Ccw or Cca) (Hackley 2000).

The park is a classic stop for Appalachian geology field trips. Given the bounty of diverse rocks within Shenandoah National Park, the park may consider establishing an interpretive collection of representative rocks from throughout the park (Thornberry-Ehrlich 2005). For example, bedrock from each of the four broad categories: (1) metamorphic and igneous rocks from the Mesoproterozoic Era; (2) metamorphic and igneous rocks of the Neoproterozoic Era; (3) metamorphosed sedimentary and sedimentary rocks from the Paleozoic Era; and (4) Jurassic-age igneous rocks, would be correlative with distinct episodes of Shenandoah National Park's geologic history. Samples of surficial deposits would also demonstrate the active processes of landform development and change. Other interesting bedrock teaching specimens may include samples of unakite or *Skolithos* tubes.

Badger (1999, updated in 2012) presents a geologic tour of Shenandoah National Park through detailed descriptions of geologic features, processes, and/or history at 26 locations along Skyline Drive. This tour covers the length of the park and this provides additional interpretive content beyond the scope of this report. The selected locations are from north to south

- Signal Knob Overlook—vesicles and amygdules within greenstones; Civil War history
- Indian Run Overlook—columnar jointing within thick basalt flows
- Range View Overlook
- Little Devils Stairs Overlook—feeder dikes for basaltic lava flows
- Hogback Overlook—metamorphic rocks and paleotopographic high point
- Thornton River Trail parking area—sedimentary cross-beds
- Marys Rock Tunnel—wide feeder dike for basaltic lava flows
- Hazel Mountain Overlook
- Pinnacles Overlook—protruding rock outcrops
- Stony Man Overlook—profile of Stony Man's face formed by the weathering and erosion of 5 lava flows
- Little Stony Man parking area—columnar jointing within thick basalt flows
- Little Stony Man cliffs—volcanic breccias
- Crescent Rock Overlook—talus fields and cliffs; view of Hawksbill Mountain
- Old Rag Mountain
- Hawksbill Gap parking area—gap formation
- Franklin Cliffs Overlook—view of Fishers Gap; Civil War history
- Dark Hollow Falls parking area—vesicles and amygdules within greenstones; pillow structures
- Big Meadows area, Blackrock—columnar jointing within thick basalt flows
- Bearfence Mountain parking area—thick talus deposits
- Bacon Hollow Overlook—extensive cliffs
- Loft Mountain Overlook—greenstone cliffs
- Rockytop Overlook—*Skolithos* tubes
- Doyles River Overlook—sedimentary cross-beds
- Blackrock parking area—sedimentary cross-beds
- Horsehead Mountain Overlook
- Riprap parking area
- Sawmill Ridge Overlook

Wayside exhibits and orientation shelters interpret geologic features, processes, and history to visitors. They are currently (2012) undergoing a complete replacement (Shenandoah NP staff, conference call, 11 December 2012). A geology training manual for park interpreters is also being developed through Oregon State University (see Kelly 2011 for the thesis version). Shenandoah National Park is in the process of developing a new Long Range Interpretive Plan. One of the new interpretive themes details the stories of how people used the land for their livelihoods before the park existed, which includes the topic of mining (Sally Hurlbert, written communication, 8 November 2013).

Building Stone Quarries and Skyline Drive Restoration

During the 1930s, the CCC used local quarried stones in constructing many of the familiar visitor use facilities and

Skyline Drive (fig. 22). In the south district, near the entrance station is a small quarry excavated for building stones (Thornberry-Ehrlich 2005). Some of the features along Skyline Drive were designed in the 1930s and are no longer adequate for the amount of use they receive and are degrading due to their age. Problems include rotting timbers, inadequate and improper fill, inadequate culverts, and bulging rockwalls and retaining walls. The park is interested in developing a remediation plan for the cultural landscape to preserve the historic structures, reduce impacts to natural resources, and increase visitor safety.

Figure 22. Civilian Conservation Corps construction in Shenandoah National Park. During the 1930s, the Civilian Conservation Corps (CCC) built much of the park's infrastructure including masonry walls along Skyline Drive (top) and trails (bottom). National Park Service photographs available online: http://www.nps.gov/shen/historyculture/skylinedrive.htm (top) and http://www.nps.gov/shen/photosmultimedia/photogallery.htm (bottom), both accessed 6 February 2014.

Geologic Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Shenandoah National Park. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2005 scoping meeting and 2012 conference call, the following geologic resource management issues were identified:

- Slope movements
- Bedrock outcrop management
- Surface water and sediment loading
- Groundwater quantity and quality
- Disturbed lands
- Earthquakes
- Cave and karst hazards

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 movements (fig. 23) along trails, roads, and Skyline Drive are among the most serious geologic hazards in the park. The presence of debris-flow deposits (geologic map unit Qdf), quartzite block-field deposits (Qb), colluvium (Qc), and debris-fan deposits (Nd) in the digital geologic map data by Southworth et al. (2009) attest to past, ongoing, and potential widespread slope movements in the park.

Debris Flows

Debris flows are catastrophic landslides of vegetation, soil, regolith, and bedrock that move rapidly downslope, entraining more material in their paths. Debris-flow deposits contain boulders and cobbles that are suspended in a finer-grained matrix of jumbled sand, silt, and clay. Collecting over time, they fill the lower reaches of many of the stream valleys and hollows draining the Blue Ridge in the park area (Morgan et al. 2003). Debris flow initiation requires abundant precipitation, steep hill slopes, and preexisting stream channels draining steep slopes (Morgan et al. 1997). Debris flows commonly follow severe storm events that deliver excessive precipitation (greater than 13 cm [5 in] in 24 hours) to a particular area. The saturated surficial material detaches and slides downslope over the bedrock surface as a viscous, highly fluid form of rapid mass wasting. Over the past 50 years, storms resulting in debris flows have occurred approximately every 10 to 15 years in the Appalachians (Wieczorek et al. 2004).

One of the most damaging storms in recent history occurred in June 1995. Over the course of a few hours, the storm dropped 700 mm (28 in.) of rain in a small area (130 km^2 [50 mi^2]) causing flooding and significant mass wasting activity, including debris flows, mudflows, slumps, and blowouts (Morgan and Wieczorek 1996; Morgan et al. 1997; Karish et al. 1997). Fourteen drainages on the east side and four drainages on the west side of the park were impacted (Karish et al. 1997). This storm triggered approximately 1,000 debris flows in Madison County, others in Albemarle and Greene counties, and nearly 100 slides in an area of about 13 km^2 (5 mi^2) within the drainage basin of Moormans River in Shenandoah National Park (Morgan and Wieczorek 1996; Wieczorek et al. 2006; Sally Hurlbert, Shenandoah NP, park ranger, written communication, 8 November 2013). These debris flows seemed to occur where colluvium collected in hollows on upper slopes. Many began as soil slips or small debris slides that coalesced downslope into debris flows. Velocities of the flows reached upwards of 24 m/sec (79 ft/sec) (Morgan et al. 1997). The flows destroyed forests, roads, trails, and riparian habitat along the drainage of Moormans River (fig. 24; Morgan and Wieczorek 1996). Devegetated scars from these flows were still visible in Shenandoah National Park more than a decade later in 2012 (Shenandoah NP staff, conference call, 11 December 2012). Areas scoured to bedrock may take hundreds of years to fully recover (Karish et al. 1997).

Because debris flows are triggered in part by high precipitation, climate change patterns are important to understand. Climate models predict severe storms will increase in frequency and intensity. Climate models also suggest variations in the quantity and timing of precipitation, and increased frequency and severity of weather-related disturbances such as floods and droughts (Karl et al. 2009). Sea surface temperatures in the Atlantic Ocean are rising and this correlates with an increase in hurricane power (peak wind speeds, rainfall intensity, and storm surge height and strength) (Karl et al. 2009). As climate continues to change, geologic issues associated with precipitation including debris flows will be exacerbated thereby increasing the level of concern for park staff. In the Appalachian Mountains, catastrophic storms have a recurrence interval of just once every three years and this interval does not include cloudbursts (similar to the 1995 event) or tropical storms that affect the park about once a year (Thornberry-Ehrlich 2005).

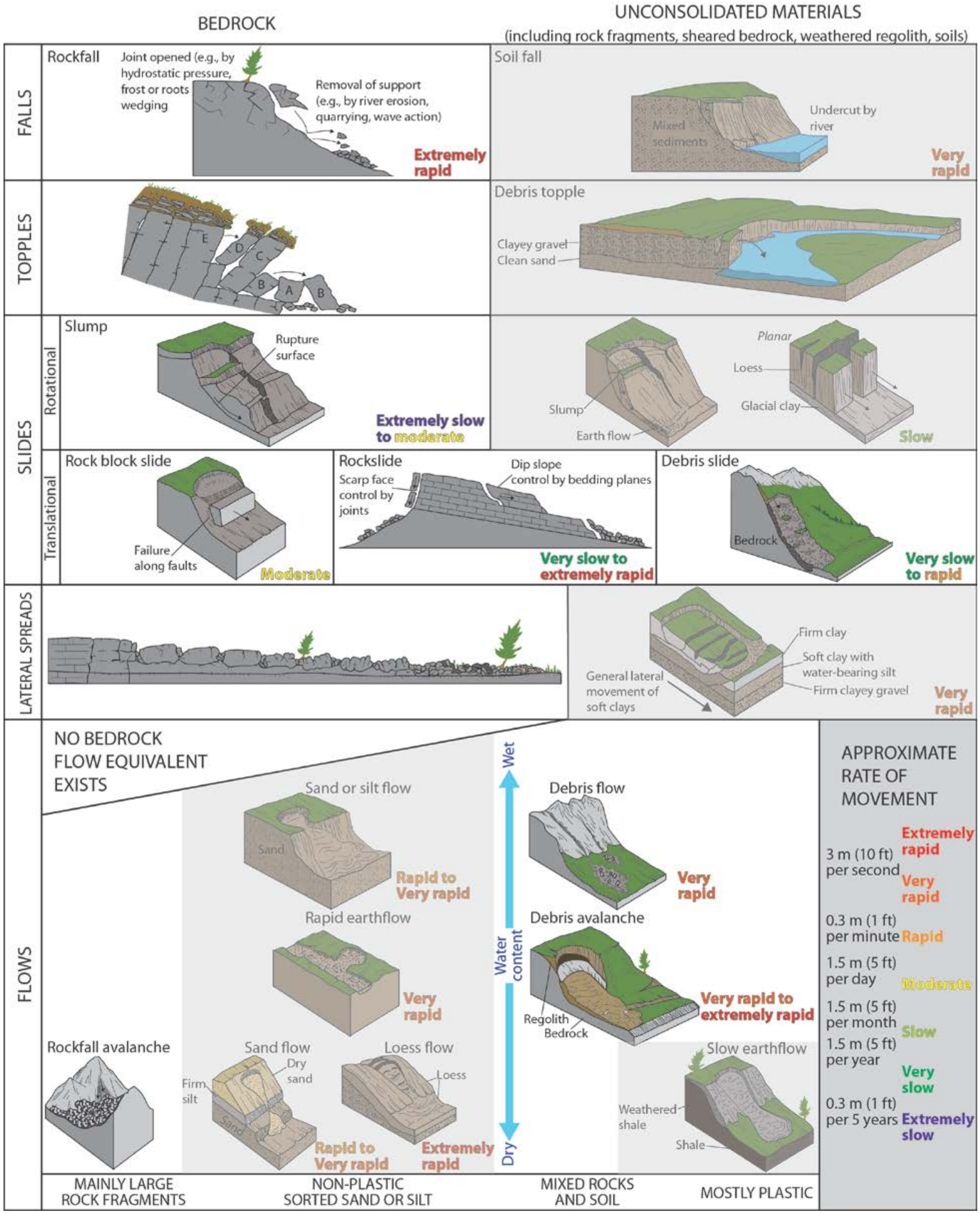


Figure 23. Schematic illustrations of slope movements. Grayed areas depict conditions that are not likely to exist within Shenandoah National Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978) and Cruden and Varnes (1996).

Figure 24. Debris flow damage in Shenandoah National Park. The debris flows in 1995 heavily impacted at least 18 drainages in the park. National Park Service photographs by David Steensen (Geologic Resources Division).

Generally, the probability of debris flow recurrence within any given drainage is quite small. Recurrence intervals for debris flows of about 3,000 to 4,000 years were determined from radiocarbon (carbon-14 or "C-14") dates for specific drainages in Nelson County, Virginia (Morgan and Wieczorek 1996). The challenge remains to determine the areas that are most prone to experience extreme mass wasting events in the future. According to Morgan and Wieczorek (1996), morphology of the landscape has a direct correlation with the possibility of debris flow formation An accumulation of loosened, unconsolidated material is necessary to form a debris flow on any given slope (Morgan and Wieczorek 1996). Areas where the bedrock has weathered to produce thick mantles of unconsolidated regolith are more prone to debris flow development than more intact bedrock under the same conditions. In 1995, debris flows developed from individual large or coalescing soil slips on slopes of about 30° or from massive debris slides within saprolite on slopes between 19° and 26°. Several large failures occurred on the noses of hills instead of within hollows (fig. 25). The bedding or layering within the local bedrock dips toward the east and also served to concentrate the majority of debris flows on the west side of the Moormans River valley, funneling them down the dipslope of the bedrock. In the Moormans River area, the bedrock of the Catoctin Formation (geologic map units Zcp, Zcs, Zcr, and Zcm) was deeply weathered to produce a thick mantle of clay-rich saprolite (Morgan and Wieczorek 1996). This material absorbed the heavy precipitation and ultimately started to slide downslope.

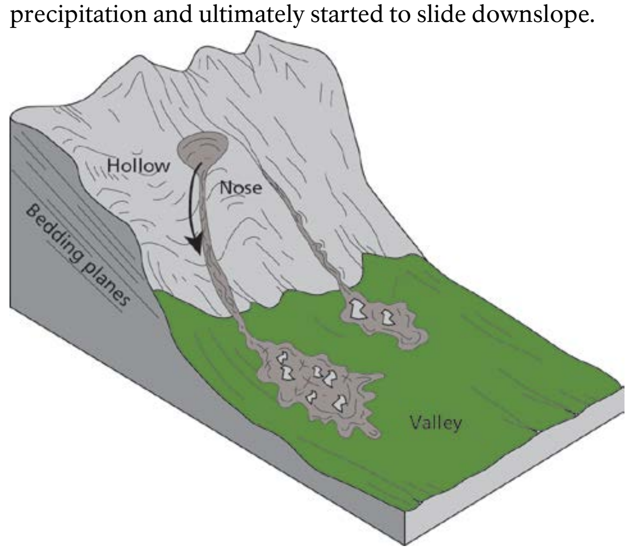


Figure 25. Schematic graphic showing debris flows initiating on the nose of a hill. Once the debris flow is initiated, it moves downslope and commonly follows stream drainages. In 1995, the east-dipping bedding or layering within the local bedrock served to concentrate the majority of debris flows on the west side of the Moormans River valley, funneling them down the dipslope of the bedrock (Morgan and Wieczorek 1996). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Landslides, Slumps, Rock Fall, and Frost Weathering

Compared to massive debris flows, landslides, rotational slumps, and rock falls are typically more localized slope movements, but still impact visitor safety and access along trails, embankments, and road cuts, including along Skyline Drive. Commonly, the displaced material slides, rotates (slumps), or falls along or from a discrete surface or confined zone. The scale, composition, and morphology of these movements vary greatly from single blocks of rock sliding or falling to slumps involving an entire hillside.

Because water and ice can saturate earthen material (making it heavy) or dislodge masses of earth and rock—particularly during frost weathering—they play an important role in triggering slope movements or creating the potential hazard. As described in the "Periglacial Features" section, the processes of frost weathering, wherein rocks experience a temperature fluctuation across the freezing point in the presence of moisture, are particularly active agents of landform change within the higher elevations of the park (fig. 17). For example, runoff and flow from springs near Marys Rock tunnel percolates through the fractured bedrock. In winter, when this water freezes and expands, the rocks are forced apart, and frequently fall to the roadway. The icicles that form also cause regular road closures (fig. 26) (Shenandoah NP staff, conference call, 11 December 2012).

Figure 26. The tunnel at Marys Rock. Fractures within the bedrock oriented perpendicular to the tunnel channel groundwater, which then freezes, causing icing problems for the roadway. When the ice freezes and expands within the fractures, it wedges loose blocks of rock. Fracture planes above the tunnel opening are shaded orange. Photograph by Trista Thornberry-Ehrlich (Colorado State University).

Landslides are responsible for maintenance issues, particularly along the major roads within the park. Trail crews manage slides on park trails on a recurring, park-wide basis (J. Schaberl, written communication, 4 September 2013). Slides were active along Meadow Run during flood events in 1937, 1972, 1993, 1997, and 1999 (Wieczorek et al. 2006; Southworth et al. 2009). "Soil sloughing" occurs in other areas, such as the east side of Thornton Gap (Thornberry-Ehrlich 2005). In 2003, a rockfall forced the closure of Skyline Drive at mile 67 and required blasting to clear the road of large debris (Thornberry-Ehrlich 2005; Sally Hurlbert, written communication, 8 November 2013). Moveable concrete barriers ("Jersey barriers") were installed at an area of repeated sliding along Skyline Drive in the south district. In one particularly problematic area, the park constructed a catch basin to collect debris. Park maintenance crews clear the area of debris regularly and are interested in a longer term solution (Shenandoah NP staff, conference call, 11 December 2012). At Little Stony Man, rock debris funnels down a chute onto the trail below and frequently needs to be removed by maintenance staff (Shenandoah NP staff, conference call, 11 December 2012).

Managing and Monitoring Slope Movements

Refer to Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), and http://landslides.usgs.gov/ for background information regarding slope movements, monitoring, and mitigation measures, as well as guidance and tools for hazard map development. As of the writing of this report the park does not have a comprehensive, formal inventory of areas affected by slope movements nor a monitoring plan for such areas.

In order to determine areas susceptible to debris flows, several factors must be taken into account: (1) the morphology of the given area (e.g., slope steepness [greater than 30°], shape, extent, etc.); (2) the amount of loosened, unconsolidated material present; (3) the type of bedrock (i.e. deeply weathered, fractured); (4) the orientation of the underlying bedrock; (5) climate patterns (rainfall threshold curves); (6) the presence, amount, and age of previous debris flows and flood deposits; and (7) the presence of channels that may act as flow paths (Morgan and Wieczorek 1996; Morgan et al. 1997).

Once areas known to be susceptible to debris flows are identified, avoiding development in those areas is critical to mitigate debris flow threats. Mitigation strategies may also reduce potential impacts to existing infrastructure. Structures such as debris basins and barriers may protect local areas. Zoning and grading ordinances are key to preventing loss of life and destruction of property from debris flows (Morgan et al. 1997).

Matsuoka and Murton (2008) described new techniques to monitor moisture contents and crack movements in near-surface hard jointed bedrock in order to evaluate seasonal rockfall activity at high elevation settings where frost weathering is common. Field observations, laboratory experiments, and theoretical developments may aid in the prediction of large-scale rockfalls and rock avalanches triggered by frost weathering. Field observations include rockwall retreat, new crack growth, and rockfall monitoring. Laboratory experiments include simulating ice segregation, modeling rock slip, and measuring rock properties. Theoretical contributions such as volumetric expansion, capillary theory, and heat conduction models are the products of advances in frost-weathering studies.

Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslides; (2) landslide causes and triggers; (3) geologic materials in landslides; (4) measurement of landslide movement; and (5) assessing landslide hazards and risks. The 2005 scoping participants suggested the following:

- Identify areas near failed debris flows that may be susceptible to continued or future failure (e.g., Big Run per Morgan and Wieczorek 1996; Morgan et al. 1997; and Morgan et al. 1999 for Madison County, Virginia). Morgan et al. (1997) may provide a guide to forthcoming hazard maps to show the slopes that failed and the slopes that potentially might fail in the future.
- Perform systematic surveys of roadcuts along Skyline Drive looking for particular fracture geometries that may cause failure (e.g., where fractures parallel a slope, or where overhanging blocks have fractures perpendicular to slope and/or bedding [see fig. 26]).
- Analyze precipitation and storm surge patterns to aid in prediction of debris flow events. Coordinate with local agencies and media to broadcast weather warnings on the park website and social media.

For climate pattern research, the NPS Climate Change Response Program (CCRP, based in Fort Collins, Colorado) facilitates servicewide climate change science, adaptation, mitigation, and communication (National Park Service 2012). The CCRP developed a climate change response strategy and climate change action plan for the NPS. Refer to their website (http://www.nps.gov/orgs/ccrp/index.htm) for additional information and to download the plans. Karl et al. (2009) summarizes climate data, projections, as well as regional impacts across the United States.

Bedrock Outcrop Management

Waterfalls, cliffs, and bedrock outcrops provide much of the quintessential scenery and landscapes of the park. Cliffs and high bedrock outcrops also provide important habitat and host several rare and unique biologic communities. Slow-growing flora, unique to rock outcrops in the park, are part of a fragile natural ecosystem. They commonly grow in scant to nonexistent soils, are subject to extreme drainage (i.e., very little soil water-retention capacity), wind desiccation, and high levels of solar irradiation, not to mention low winter temperatures, ice storms, and high winds (Fleming et al. 2007). For example, 76 rare plant populations in 11 natural community types are associated with 50 inventoried bedrock outcrops within the park (see "Bedrock Outcrop Habitats" section). Nine of them are globally rare and two are entirely endemic to Shenandoah National Park (high-elevation greenstone barren and high-elevation outcrop barren) (Fleming et al. 2007). Extremely rare natural communities, plants, and animals are associated with 15 bedrock outcrop sites. As such sensitive habitats, they are particularly vulnerable to human disturbance (fig. 27). The foremost impact to the park's rock outcrops is visitor trampling via climbing, hiking, and camping. Trampling crushes plants, compacts the soil, contributes to erosion, and may distribute invasive plant species' seeds (Fleming et al. 2007). Reducing vegetation increases the likelihood that soils may be eroded away by wind or water, leaving behind coarser-grained "lag deposits". The loss of finer-grained material changes the distribution of unconsolidated material including soils. Visitor use may also trigger rock falls, create social trails, polish or tarnish rock surfaces, and disturb lichen patterns (Butler 2006). Graffiti, litter, fire rings, and footprints are other visible impacts of human use. Visitor safety concerns are inherent with bedrock outcrops including rockfalls, falling, and slipping. Several slipping accidents occur at park waterfalls every year. Rockfall and slipping accidents also occur annually at Little Stony Man and Old Rag Mountain—areas popular for their bedrock outcrops (Thornberry-Ehrlich 2005). The Ranger Division maintains statistics about such accidents within the park (J. Schaberl, written communication, 4 September 2013).

The Old Rag area is a very popular location for bare-rock hiking and rock scrambling. The visitor-use impacts listed above are common at Old Rag because of its popularity. The rocks in the area are fractured, weathered granite (geologic map unit Yor). Balancing visitor access and natural resource protection in this designated wilderness area is a challenge (Shenandoah NP staff, conference call, 11 December 2012). In 2010, the Natural Resources staff moved some rocks on the summit to facilitate visitor movement and resource protection. Climbing at Old Rag Mountain is allowed, but the park would prefer guidelines in lieu of a permit process (Shenandoah NP staff, conference call, 11 December 2012).

In response to the challenges of facilitating visitor access while providing protection for the parks rock outcrops, a cooperative research effort called the Rock Outcrop Management Project (ROMP) was initiated in Shenandoah National Park in 2003. The purpose of ROMP was to inventory the biological, and geological resources present at 50 rock outcrop sites within the Park, and to assess the social use of, and impacts to, these rock outcrops, in an effort to find better ways to manage natural resources and visitor use. As of September 2013, the park is nearing completion of the ROMP (Shenandoah NP 2012). The plan followed inventories of rock outcrops by Wood et al. (2006), Butler (2006), Young et al. (2006), and Fleming et al. (2007) The proposed ROMP is an important component of other management plans and priorities for the park, including the Backcountry and Wilderness Management Plan, Comprehensive Plan for the Appalachian Trail, Rare Plant Monitoring, Exotic Plant Control, Gypsy Moth Control, Recovery Plan for the Shenandoah Salamander, and Peregrine Falcon Protection and Restoration.

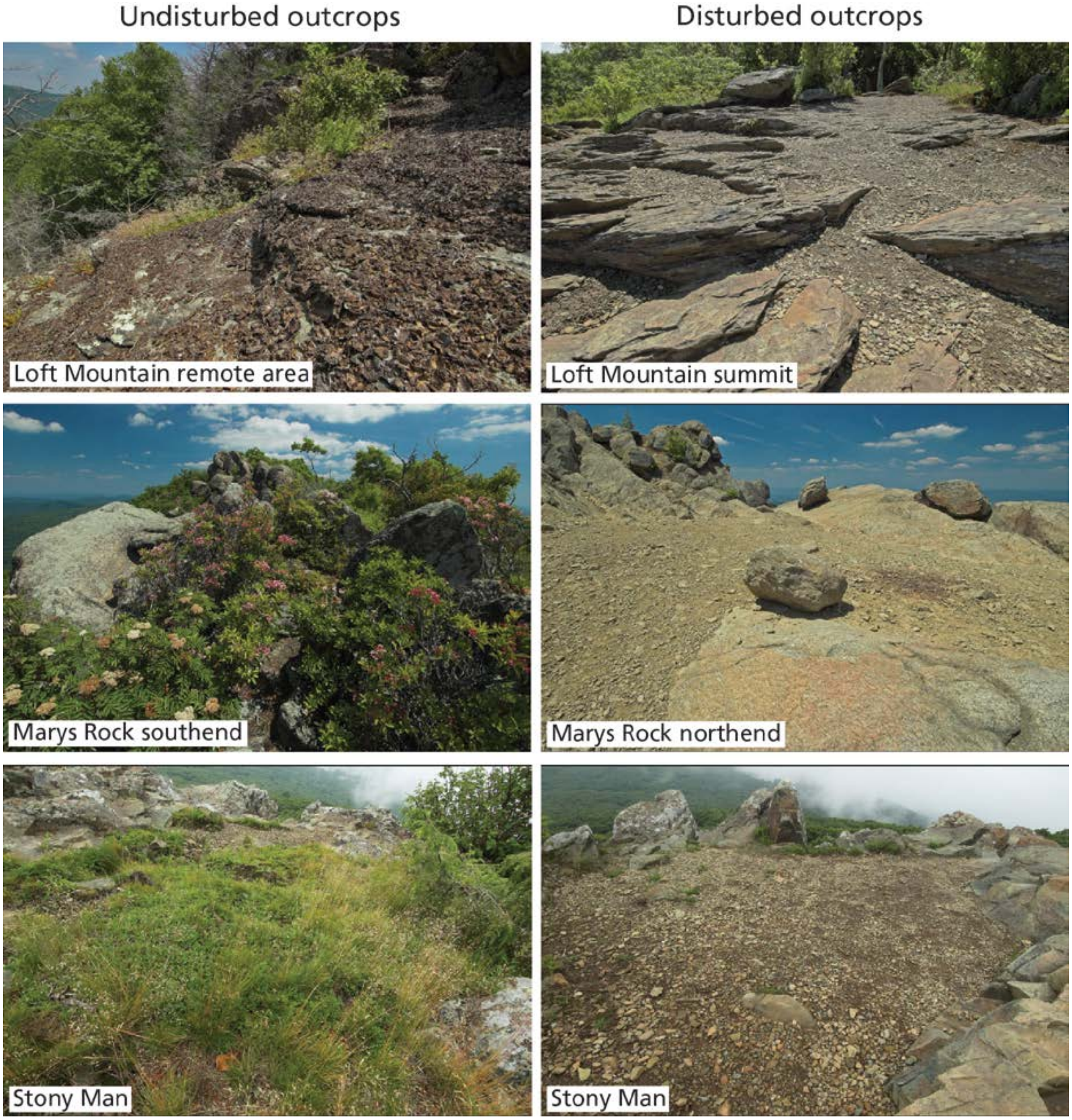


Figure 27. Undisturbed and disturbed bedrock outcrops. Note the dramatic changes in undisturbed outcrops versus areas where trampling has degraded vegetation, lichen communities, and soils. Photographs by Gary P. Fleming (Virginia Department of Conservation and Recreation Division of Natural Heritage) as part of the work for the ROMP study (Shenandoah NP 2012).

Fleming et al. (2007) identified 50 areas of significant bedrock outcrops (of 2,105 outcrops occurring within the park) where conflicts between resource preservation and visitor use are most likely to occur (fig. 28). Seven of these are metasedimentary rock outcrops (e.g., geologic map units Zsr, Ccw, Cchs, and Cca), 32 are greenstone sites (Zcm, Zcs, and Zcp), 10 are granite and/or gneiss (Yom, Ybm, Ycg, Yor, Yog, Yll, Yos, Yon, Yod, and Ylg), and one is mixed greenstone and igneous rocks (Butler 2006).

The ROMP divides the 50 outcrop sites into management categories as per table 3. This table describes management issues associated with each category. Management alternatives may include: (1) no action; (2) balance between natural resource protection and visitor use; (3) emphasis on natural resource protection; and (4) emphasis on visitor use. Proposed management actions vary by site and could include using low barriers to direct visitor movement, limiting access to certain sites, restricting and/or re-directing rock climbing and camping activities, re-routing trails, monitoring vegetation, monitoring visitor impacts, and installing educational signs to inform visitors about the need for resource management protection (Fleming et al. 2007; Shenandoah NP 2012).

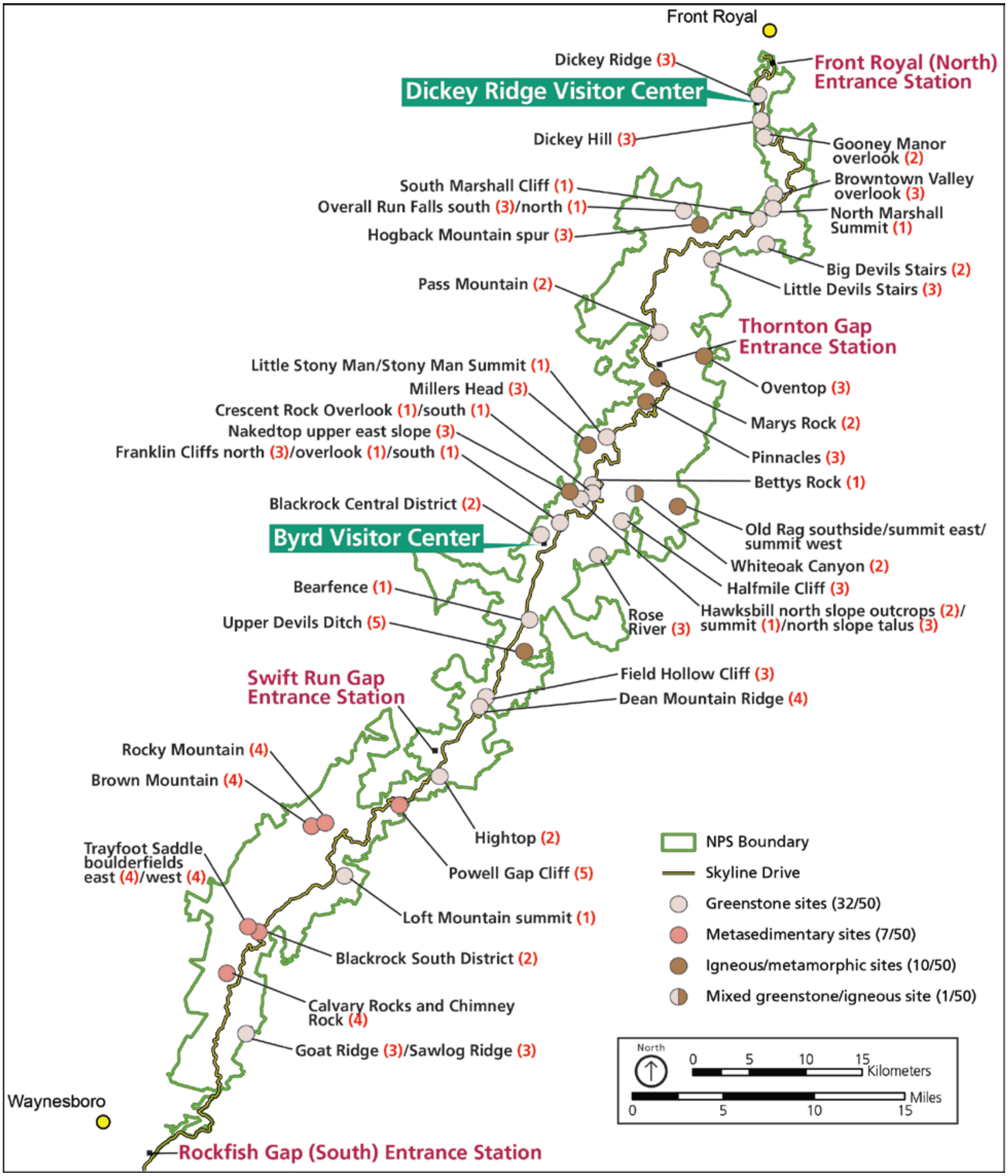


Figure 28. Locations and rock types of 50 selected outcrops. Outcrops were selected for targeted resource management with the ROMP. Red numbers after each outcrop name refer to resource management categories described in table 3. Note Little Stony Man and Old Rag Mountain consist of diverse sites and are their own management categories. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 1 in Butler (2006) with assistance from Georgia Hybels (NPS Geologic Resources Division).

Table 3. Rock outcrop management categories

Management Category	Bedrock Sites	Description of Management Issues
Little Stony Man Mountain	Diverse sites	Intense visitor use; strong public interest; and sensitive natural resources
Old Rag Mountain	Old Rag South Side Old Rag Summit East Old Rag Summit West	Heavy visitor use; strong public interest; and sensitive natural resources
Category 1	Bettys Rock Crescent Rock Overlook Crescent Rock South Franklin Cliffs Overlook Franklin Cliffs South Hawksbill Summit Loft Mountain summit North Marshall summit South Marshall cliff Stony Man Summit Overall Run Falls North Bearfence Mountain	Areas support globally rare flora and/or fauna; sustained widespread human impacts
Category 2	Big Devils Stairs Blackrock Central District Blackrock South District Gooney Manor Overlook Hawksbill North slope outcrops Hightop Marys Rock Pass Mountain White Oak Canyon	Areas support globally rare flora and/or fauna; sustained moderate human impacts
Category 3	Browntown Valley Overlook Dickey Hill Dickey Ridge Franklin Cliffs North Goat Ridge Halfmile Cliff Hogback Mountain spur Little Devils Stairs Millers Head Nakedtop Upper East Slope Oventop Overall Run Falls South Pinnacles Sawlog Ridge Hawksbill North slope talus Field Hollow Cliff Rose River Cliffs	Areas support globally rare flora and/or fauna; sustained minor human impacts
Category 4	Calvary Rocks – Chimney Rock Dean Mountain Ridge Rocky Mountain Trayfoot Saddle boulderfields east Brown Mountain Trayfoot Saddle boulderfield	Areas support state rare or watch-listed flora and/or fauna; sustained minor human impacts
Category 5	Powell Gap cliff Upper Devils Ditch	Contain no state or globally rare flora or fauna; human impacts present

Information from Shenandoah National Park (2012).

Surface Water and Sediment Loading

Shenandoah National Park contains the headwaters for 231 watersheds in central Virginia (fig. 29) (Rice et al. 2007). Because of this, the condition of the watersheds in the park is of great importance. In addition to the effects of acid precipitation described below, impervious surfaces, soil compaction, vegetation disturbances, and road and trail maintenance, impact water sources in the park. The geologic map units associated with modern and ancient drainages are alluvium, terrace deposits, and alluvial-plain deposits (geologic map units Qa, Nt, and Np) (Southworth et al. 2009).

Figure 29. Whiteoak Canyon. The stream cascading down boulder-strewn slopes is characteristic of the headwater streams flanking both sides of the Blue Ridge Mountains of Shenandoah National Park. National Park Service photograph.

Impervious surfaces and soil compaction

Soil compaction occurs within the park, primarily as a result of high visitation (see "Bedrock Outcrop Management" section). Compaction lessens the ability of the soil to absorb seasonal precipitation. This combined with impervious surfaces such as roads, parking lots, and high-use trails, increases seasonal runoff as sheet flows. In areas where runoff is managed by culverts, drains, or bridges, vegetation often obscures the structures making management of them difficult, particularly in remote areas (Thornberry-Ehrlich 2005).

Flooding and Sediment Loading

Flooding and erosion are natural processes of landscape change within Shenandoah National Park. Severe storms cause significant flooding and stream channel morphology changes. In some areas such as Big Meadows, flooding and channel erosion impact important wetland habitat and visitor-use facilities such as campgrounds (Thornberry-Ehrlich 2005). The 1995 storm, described in the "Slope Movements" section, altered the morphology and channel substrate of several of the park's rivers including the Staunton River and North Fork Moormans River (Karish et al. 1997). Such severe storms and subsequent flooding and erosion are projected to increase in frequency and severity as climate continues to change as described in the "Debris Flows" section.

Erosion of sediment into waterways increases sediment loads which affects channel morphology and aquatic habitats by increasing the proportion of fine-grained sediments along stream bottoms. Gravel-dwelling organisms and fish that lay eggs in the spaces between coarse gravels require habitats with little finer-grained sediment (Castro and Reckendorf 1995). Suspended sediment increases water turbitity, decreasing the degree to which sunlight filters through the water, in turn impacting aquatic flora.

Natural and anthropogenic alterations to park vegetation are changing the nature and morphology of park waterways. A gypsy moth (*Lymantria dispar*) infestation killed thousands of hectares of trees within the park. An exotic aphid-like insect, the Hemlock wooly adelgid (*Adelges tsugae*) is impacting hemlocks within the park, destroying shaded riparian habitat along streams (Morton et al. 2001). In some drainages, including the forks of the Rapidan River that coalesce at Rapidan Camp, trees killed by these pests have fallen into streams, creating pinchpoints and increasing the potential for major flooding (Shenandoah NP staff, conference call, 11 December 2012). The loss of these trees and their stabilizing roots also increases sedimentation in nearby streams and could contribute to slope movements (Thornberry-Ehrlich 2005; Jonas et al. 2012). Similarly, natural or anthropogenic fires, such as the Fultz Run fire in 2002 and the Smith Run fire in 2011, remove stabilizing vegetation on the steep slopes of the park. This can increase erosion and subsequent sediment loads in the nearby streams (Thornberry-Ehrlich 2005). Sediment loads are also increasing in streams near visitor-use areas such as horse trails, hiking trails, heavily visited campgrounds, as well as access roads or other disturbed areas (fig. 30) (Thornberry-Ehrlich 2005).

Figure 30. Backcountry campsite. Note the diminished vegetation, bare soils, and exposed roots indicative of frequent trampling and use. National Park Service photograph.

Surface Water Acidification

Researchers have studied acid precipitation in the park since the 1970s and the pH of local precipitation averages at 4.2 to 4.6 versus average rainwater at 5.6, meaning precipitation in the park is 10 times more acidic than "average" rainwater (Rice et al. 2006). The sources of the acidification are the sulfates and nitrates from air pollution which react with water to produce acids

(Badger 1999; Rice et al. 2007). Current acid deposition rates are still high in the park (Shenandoah NP staff, conference call, 11 December 2012). Individual measurements of pH values of rain at the park have been below 4.0 since testing began in 1981 (Rice et al. 2007). Acid rain impacts the ecosystem in four ways: (1) acidification of surface waters; (2) loss of aquatic biota; (3) depletion of soil nutrients; (4) impairment of forest health (Deviney et al. 2006). This is a challenging threat to resource managers because the park has 231 headwater streams and very limited influence over the air pollution that envelops the region (Rice et al. 2007).

Though the same precipitation is falling throughout the park, acidification in individual watersheds varies dependent on factors including bedrock type and slope of topography. Siliciclastic bedrock (sandstones or shales) lacks the buffering properties of other rocks and does not neutralize the acidity of the stream water (Badger 1999). Alternatively, carbonate rocks (limestones) and the pyroxene and feldspar-rich (greenstones or altered basalts) Catoctin Formation neutralize acid precipitation. In the park, streams flowing over these rocks have pHs between 6.6 and 7.3. Streams in watersheds underlain by granites and gneisses have intermediate buffering capacity and as a result yield pHs between 6.0 and 7.1 (Badger 1999). Chilhowee Group rocks with lesser pyroxene and feldspar minerals lack acid-neutralizing capabilities. Streams within watersheds underlain by Chilhowee Group rocks such as Paine Run, (visible from the Horsehead Mountain Overlook), have pHs between 4.8 and 6.2 and are increasingly toxic to sensitive life forms (Badger 1999).

Local features within stream drainages, in addition to varying buffering capacities, may be contributing to the acidification of park streams. For example, run-off from sulfide minerals exposed to weathering within mines or mine tailings may lower pHs in park streams through acid-mine drainage (Trexler et al. 1975; Thornberry-Ehrlich 2005). Acid-mine drainage is a significant problem for the National Park Service at Friendship Hill National Historic Site, 130 km (80 mi) northwest of Shenandoah National Park. Mitigation efforts there are ongoing (for more information see Thornberry-Ehrlich 2008). Additionally, the Chilhowee Group may locally contain high amounts of iron sulfide minerals that would increase the acidification of a stream or watershed, especially in areas that were disturbed by mining for iron-bearing minerals described in the "Disturbed Lands" section. Specific units that might contain greater amounts of sulfides and decrease the pH of streams may include the ferrigunous metasandstone of the Harpers Formation (Cchs) and beds in the Weverton Formation (Ccw). Some sedimentary units in the Catoctin Formation may also contain significant amounts of sulfides (A. Merschat, geologist, US Geological Survey, written communication, 16 July 2013).

Steeper slopes leave precipitation and runoff less time to interact with potentially-neutralizing bedrock. In this way, a small stream, near the crest of a mountain on a steep slope underlain by siliciclastic rocks would have much more acidic water than a larger stream on a gentler slope underlain by greenstones (altered basalt) (Rice et al. 2007). Topography layered with geologic mapping in a GIS would help to determine the buffering potential of the bedrock, the interaction between acidic meteoric water and the underlying geology, and the response of the ecosystem to changes in water chemistry (Thornberry-Ehrlich 2005; Rice et al. 2007). Once the extent of problem streams are identified and quantified, resource managers can determine management alternatives on a stream-by-stream basis. Acid rain studies and models developed by Rice et al. (2004); Webb (2004); and Deviney et al. (2006) are valuable sources for future research and resource management efforts.

Surface Water Resource Management

Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related "vital signs", including: (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. Vana-Miller and Weeks (2004) also evaluate the hydrologic system (including stream chemistry) and effects of acidic deposition on aquatic biota within the park. The Natural Resources Conservation Service prepared a working paper detailing the effects of sediment on the aquatic environment that also contains a comprehensive bibliography of resources and potential actions to improve aquatic habitats (Castro and Reckendork 1995). In 2005, scoping participants suggested the following action items:

- Inventory wetlands within the park.
- Monitor sediment loads to determine seasonality and impacts to aquatic and riparian biota. Meadow Run was suggested as a focus area.
- Accurately map park administrative roads and runoff engineering structures (i.e. culverts), then target streams and areas of erosion for remediation.
- Map dead tree areas using techniques described by Morton et al. (2001) to focus erosion control measures.
- Layer GRI digital geologic data (surficial and bedrock geologic units) with water monitoring data (e.g., pH and stream categories) to develop an acid-buffering potential, rock-type model for stream condition and health. Apply this technique to the future soils map from the Soil Resources Inventory (http://www.nature.nps.gov/geology/soils/SRI.cfm).

Groundwater Quantity and Quality

Groundwater in Shenandoah National Park resides in, and is transported via, bedrock fractures. Fracture density decreases with depth, and few wells yield water from depths greater than 90 m (300 ft) (Plummer et al. 2001). In part because the groundwater is mostly shallow and flow along open fractures can be rapid, the water is relatively young, meaning it has not been stored for great lengths of time in underlying aquifers or had the opportunity to chemically react much with adjacent bedrock. For this reason, surface disturbances such as the introduction of contaminants are reflected quickly in groundwater. Plummer et al. (1999, 2001) determined residence times of spring water in the range of 0–3 years and well water in the range of 0–25 years. The park also serves as a large recharge area for adjacent watersheds and the aquifers of neighboring valleys (Thornberry-Ehrlich 2005).

The park obtains most of its potable water from groundwater springs and wells (fig. 31). Approximately 850 springs and seeps occur throughout the park (Plummer et al. 2000). Springs and seeps occur primarily in bedrock where fractures funnel the water to discrete outlets. Springs and seeps also occur at the tops of slope wash (not mapped) deposits because their high clay content restricts groundwater flow as an "aquitard" below perched water tables (Morgan et al. 2003).

The potential for groundwater contamination and contaminant transportation is high (Plummer et al. 2000) particularly from roads such as Skyline Drive and at lower elevations from increasing surrounding development. Water discharged from shallow, unconfined springs is easily compromised by surficial contaminants. Contaminant introduction and transportation in deeper groundwater is difficult to predict due to the unknown interconnectivity of the fractures that serve as flow paths. Groundwater pumping can exacerbate these properties by causing rapid transport of contaminants over large distances within the system (Plummer et al. 2000).

Although karst areas are limited in extent (see "Cave and Karst" sections), within the park, they are extensive within the Great Valley west of the park. Subsurface conduits typical of karst areas rapidly transport water and contaminants. Dye tracing tests could illustrate the effects of karst features on the hydrogeologic system in the park area. Previous work focused on the Dickey Ridge Trail area (Thornberry-Ehrlich 2005).

Siting of facilities during the development of the park in the 1930s focused on areas near springs and also in higher-altitude areas, for example Skyline Drive passes near approximately 70 springs. Thus, the park's water supplies are also near the most populated areas increasing potential for surface contamination. Other infrastructure is far from productive water sources (Plummer et al. 2000). Hydrogeologic models would help manage the groundwater resource in the park and predict the response of the system to contamination, drought, and excess precipitation. The latter two are expected to increase as climate continues to change. Wells in the park could serve useful in park-wide monitoring efforts and hydrogeologic studies.

Groundwater quality and management specifics are beyond the scope of this report; refer to Vana-Miller and Weeks (2004) and contact the NPS Water Resources Division (Ft. Collins, Colorado) at http://www.nature.nps.gov/water/ for more information and assistance.

Disturbed Lands

Disturbed lands are those where natural conditions and processes were impacted by human development or agriculture. Humans have long used the natural resources of the Shenandoah area. American Indians were the first to extract minerals in the Shenandoah area. They obtained chert from nodules of Paleozoic clastic and carbonate rocks (geologic map units DSu, Ob, Os, and Oeln), as well as jasper from hydrothermally-altered carbonates from the Beekmantown Group (Ob) in what is now the Flint Run Archeological District (Southworth et al. 2009). During the 19th and 20th centuries, miners targeted iron, manganese, and copper (Rickard and Roberts 1937; Allen 1963). After the park was established, local rocks were used as building stones. An extensive road network is now mostly abandoned. Energy transmission infrastructure affects the park viewshed. Some energy corridors may be restored to natural conditions.

Agriculture

European Americans began establishing farms and communities along the slopes of the Blue Ridge and the Shenandoah Valley in the 1700s. Farming and homesteading involved construction of irrigation canals, removal of soil and rocks, construction of stone fences, clearing of pastures for grazing, and extensive logging, especially in the western edge fans and stream hollows (Thornberry-Ehrlich 2005).

Iron, Manganese, and Copper Mining

The iron-ore minerals limonite and goethite form by the chemical weathering of iron-rich sulfide minerals hematite, magnetite, olivine, pyroxene, amphibole, and biotite. As early as 1836, prospectors began mining limonite and goethite for iron ore in and around what would become Shenandoah National Park. Mining for manganese ore and manganese-rich oxides (such as psilomelane, pyrolusite, and manganite minerals) began in 1884 (Southworth et al. 2009). During World War I, prospectors excavated shafts, tunnels, dumps, and pits in search of iron ore (Stose et al. 1919; Thornberry-Ehrlich 2005; Southworth et al. 2009). An iron smelter was at the Mount Vernon Furnace, now located on a restricted fire road (Thornberry-Ehrlich 2005; Engle 2013). In the south district, the Mount Vernon/Miller Ironworks is just inside the park boundary across the creek from the Madison Run fire road (Horning 2007; Sally Hurlbert, written communication, 8 November 2013). No mines were nearby, only roads, trenches, and ditches (Cloues and Sharrow 1990).

Manganese ore occurs along the western side of Shenandoah National Park. Originally, the manganese minerals occurred as iron-carbonate components of the Tomstown Formation (geologic map unit Ct). Bicarbonate-saturated groundwater circulated through the rocks, dissolved the iron-carbonate minerals, and as the solution percolated upwards, the manganese

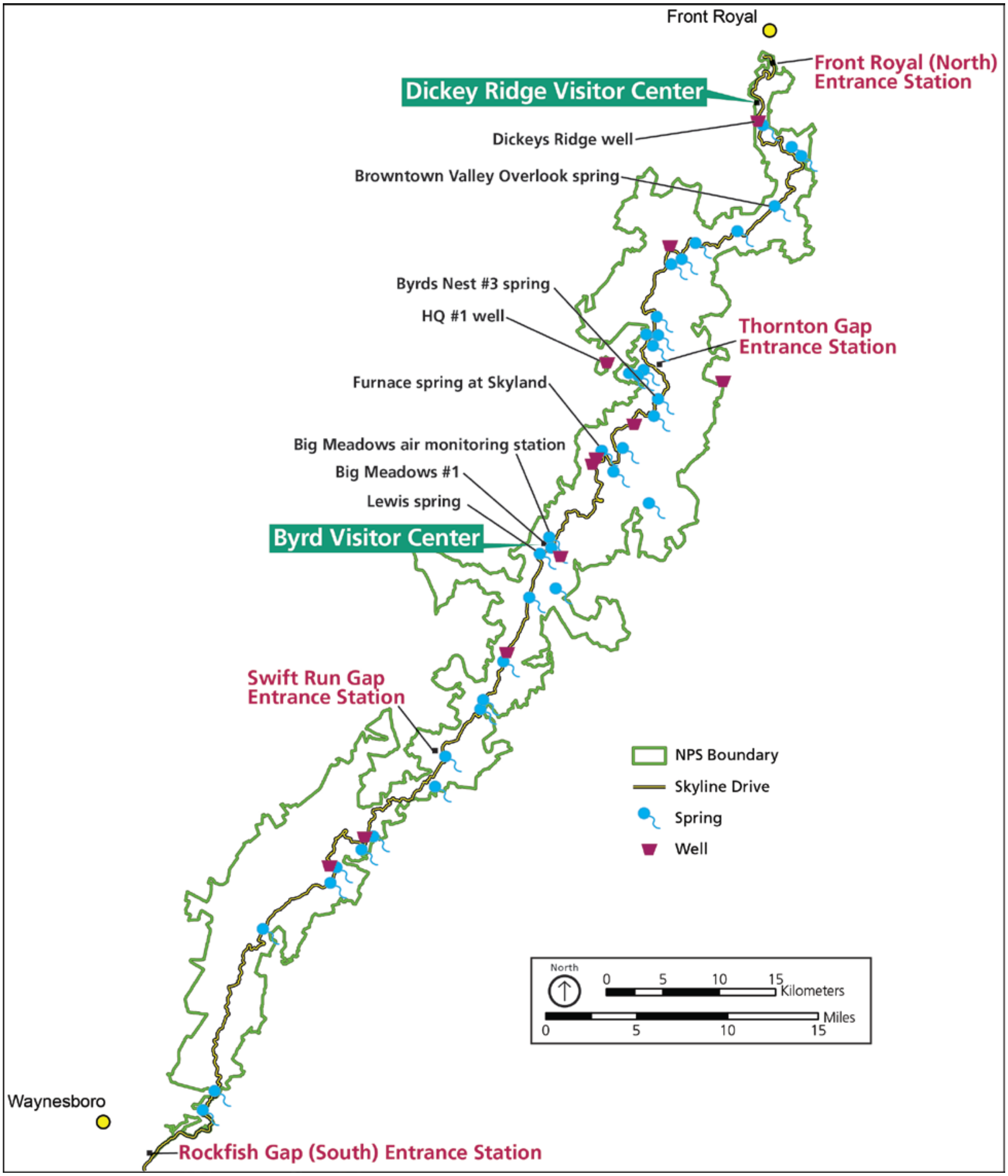


Figure 31. Location of springs and wells within Shenandoah National Park. These features were sampled during the study by Plummer et al. (2001). Not all springs and wells present within the park are named or located on the map. Graphic after figure 1 in Plummer et al. (2001) by Trista L. Thornberry-Ehrlich (Colorado State University) with assistance from Georgia Hybels (NPS Geologic Resources Division).

minerals precipitated out of solution to be redeposited as manganese oxides in overlying clay-rich regolith and sandstone breccias(mapped as breccia point features in the digital geologic map data) (Southworth et al. 2009).Manganese is an important component of steel. During both world wars, there was great interest in the manganese deposits on the west slope of the Blue Ridge, especially near Elkton and in the Page Valley (Stose et al. 1919; King 1950; Southworth et al. 2009). Manganese-bearing nodules in the Tomstown Formation (geologic map unit Ct) were of particular interest. Alluvial fans (Nf) also provided a “trap” for manganese deposits weathering out of carbonate units in the Page Valley.

The manganese mining legacy is visible throughout the park. A series of ponds along the western side of the south district are likely WWII-era manganese prospects and exploration pits (King 1950; Allen 1963; Southworth et al. 2009). Manganese breccias were mined at the Compton Mine along Dry Run near Luray. Trenches, prospects, assay pits, open-cut mines, and shafts occur within or west of the park. Many are filled with water and resemble ponds or flooded sinkholes (Southworth et al. 2009). Of these, the Crimora Mine, the largest local open-cut manganese mine, is visible from Crimora Lake Overlook (flooded mine feature is situated just to the left of the lake) on Skyline Drive (Southworth et al. 2009). The lake was formed by damming a stream in Dorsey Hanger Hollow to provide water for processing the manganese ore (Heatwole 1988).

To a lesser extent, copper mining occurred at several places in or near Shenandoah National Park from the 1850s to the 1940s. Copper oxides, sulfides, and native copper occur sporadically in the metabasalt of the Catoctin Formation (Zcm) throughout this part of the Blue Ridge (Rader and Biggs 1975; Southworth et al. 2009). Copper may have concentrated in this unit during volcanism associated with the deposition of the Catoctin metabasalts or during metamorphism and deformation associated with Appalachian mountain building (Allen 1963; Southworth et al. 2009).

The copper ore was processed primarily at Furnace Springs near Skyland. Copper mining in the Catoctin Formation occurred primarily in eight areas (not all of which occur within park boundaries): (1) Dickey Ridge; (2) Stony Man crest; (3) between Dark Hollow Falls and Rose River Falls, north of the Rose River Loop Trail; (4) northwest of Ida; (5) west of Fletcher; (6) on Hightop; (7) on the Mathews Arm Trail; and (8), along Virginia Route 662 east of Rileyville (Southworth et al. 2009).Copper prospects also exist in Mesoproterozoic gneissic rocks (including Yor and Yos) in 4 locations: (1) southeast of Compton; (2) southeast of Pinnacle Overlook; (3) northwest side of Catlett Mountain along the Catlett Mountain Rail; and (4), west of Dickey Ridge. The Dickey Ridge deposit also contains gold and silver in a mineralized fracture zone above the Front Royal Fault (Rader and Biggs 1975; Southworth et al. 2009).

Although no active mining occurs within the park, mine features pose several issues for resource managers including, but not limited to visitor safety, mineral theft, and acid-mine drainage (see "Surface Water and Sediment Loading" section). Open shafts, old mine works, and loose tailings are present, they pose a threat to visitor safety (Burghardt et al. 2013). Within the park, most of the mine features that pose a threat to public safety have been blocked or filled, including the gate at the Rose River copper mine (Shenandoah NP staff, conference call, 11 December 2012). Other areas such as the abandoned mineral lands site at Hannah Run are largely vegetated and reclaimed naturally (Cloues and Sharrow 1990). Cloues and Sharrow (1990) conducted site assessments at a few of the mine-feature locations. For example, the mine at Stony Man was abandoned before 1850 and is now largely revegetated and may have been recommissioned as Furnace Spring (Cloues and Sharrow 1990). The Rose River site consists of a large concrete foundation, adits, underground workings, waste rock piles, and pits. One adit, now gated, is habitat for brown bats. A deep pool of water was also present near the opening (Cloues and Sharrow 1990).

The stability of tailing piles is not yet determined (Thornberry-Ehrlich 2005) although they may contain interesting or valuable minerals to collectors. Park staff members are aware of mineral theft of copper ore minerals such as azurite and malachite on top of Stony Man (Thornberry-Ehrlich 2005). Other rare rock types at risk of theft include unakite (product of contact metamorphism between Catoctin lava flows and underlying bedrock), hydrothermally weathered granite with epidote and blue quartz crystals, large garnet crystals in the Old Rag Granite (Yor), magnetite, red jasper in the Catoctin Formation (Zcp, Zcs, Zcr, and Zcm), and metasedimentary rocks with *Skolithos* burrows (Cch, Cchs, and Cca) (Thornberry-Ehrlich 2005; Southworth et al. 2009)

Run-off from mine features has the potential to contribute to the lowered pH in park streams through acid mine drainage as described in the "Surface Water and Sediment Loading" section. Mine run-off also has the potential to contribute contaminants such as mercury. Monitoring is beginning at Shenandoah to assess the deposition of and impacts from mercury (Thornberry-Ehrlich 2005; National Park Service 2013).

The NPS Geologic Resources Division conducted an abandoned mineral lands inventory in 2011–2012. As of March 2013, the NPS Abandoned Mineral Lands (AML) database documents 27 AML features at 17 sites within Shenandoah National Park. According to Burghardt et al. (2013) none of those sites are considered "high priority" for mitigation; 14 are medium or low. The remainder are not yet prioritized. The Virginia Department of Mines, Minerals, and Energy (available at: http://www.dmme.virginia.gov/) maintains additional databases of mine features and documentation for mines, as well as information about the history and future of mining in Virginia. Many of the features are in remote, backcountry areas. Most do not require a gate, but this need should be evaluated (Shenandoah NP staff, conference call, 11 December 2012).

Abandoned Roads

Upon its establishment, Shenandoah National Park inherited a road network (e.g., Tanners Ridge Road, Lewis Springs Road, Meadows School Road, and Rose River Road) that has since been repurposed or modified, and in some cases abandoned, to facilitate visitor and/or park staff access and protect natural resources (Greco 2000; Sally Hurlbert, written communication, 8 November 2013). This road system impacted the natural hydrology associated with slope movements such as debris flows. As described in the "Debris Flows" section, debris flows are a natural, common occurrence in the Blue Ridge. Bridges and culverts create "pinch points" along streams that are subject to logjams and blockages. These in turn divert flows and shift the hazard to adjacent areas. Highly compacted roadfill may disrupt natural hydrologic processes and contribute to slope instability (Greco 2000) by causing water saturation in adjacent, possibly unstable areas.

Greco (2000) recommended a roads analysis to help identify areas of hazard within the inherited road network. Subsequent road treatments might include road upgrading (removing earth from locations at risk of landslides), modification of road drainage, reconstructing stream crossings, installation of water bars, and removal of roads and hillslope recontouring. GIS inventories can help identify areas that are the most sensitive to prioritize road treatments (Greco 2000).

Energy Transmission

Because the park is amidst a high population area, viewsheds are compromised by mobile phone transmission towers, power line corridors, and other surrounding development (Shenandoah NP staff, conference call, 11 December 2012). Three electric companies and at least one gas company have lines that intersect park lands (J. Schaberl, Shenandoah NP, written communication, 4 September 2013). These companies obtain permits to conduct regular maintenance, including removal of vegetation (native and non-native) to maintain the right-of-way corridor. This requires a pattern of repeat disturbances to maintain the vegetation (J. Schaberl, written communication, 4 September 2013). An environmental assessment is currently (March 2013) underway to evaluate potential impacts from upgrading and rehabilitating the Dooms-Bremo corridor in the south district. This will include a vegetation restoration plan and maintenance more in adherence to NPS policies (J. Schaberl, written communication, 4 September 2013). A gas pipeline also traverses the park and the potential exists for additional energy transmission projects.

Earthquakes

Earthquakes are uncommon in Central Virginia but do occur. Like many people throughout the eastern United States, Shenandoah National Park staff and visitors felt the magnitude 5.8 earthquake of August 2011. The earthquake epicenter was about 50 km (30 mi) east of Charlottesville, Virginia. Prior to that, the largest regional earthquake measured by the Central Virginia Seismic Center was magnitude 4.5 in 2003 (US Geological Survey 2003). Ancient fault zones are found throughout the east coast and faults are mapped in the GRI GIS data. Although major damage to park infrastructure is not likely due to earthquakes, rockfalls and other slope movements may be triggered by earthquakes.

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.

Caves and Karst Hazards

As described in the "Caves and Karst Features" section, approximately 8 ha (20 ac) of the park contains documented karst features and other areas are underlain by carbonate rocks with potential for karst feature development (Hubbard 1988; Thornberry-Ehrlich 2005; Southworth et al. 2009). Depressions in alluvial-fan deposits (geologic map unit Nf) attest to sinkhole formation (Southworth et al. 2009). GRI scoping meeting participants identified the need to comprehensively inventory karst features in the park to better manage this resource and provide for visitor safety (Thornberry-Ehrlich 2005). For example, an unnamed cave on the northwest side of the park is a "bad air" cave with dangerously high carbon dioxide (CO_2) concentrations. Currently, the cave is closed and the park is not monitoring the feature (Shenandoah NP staff, conference call, 11 December 2012).

White-Nose Syndrome (WNS) is a disease killing bats throughout the eastern United States and Canada. The disease continues to spread westward. No cases have yet been reported in Shenandoah National Park, but caves in the Blue Ridge and Valley and Ridge of Virginia have confirmed cases. For more information visit the NPS Cave and Karst Program website for WNS: http://nature.nps.gov/biology/WNS/index.cfm or http://www.whitenosesyndrome.org/ (both accessed 20 November 2013).

Land et al. (2013) provided a summary of cave and karst management issues throughout the NPS. Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology such as microclimate and air composition of the cave; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, drip rate, drip volume, drip water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Shenandoah National Park.

The geologic history (fig. 4) of Shenandoah National Park includes the early construction of the North American continent more than one *billion* years ago, several major mountain-building events (orogenies) that led to the formation of the Appalachian Mountains and the assembly of the supercontinent Pangaea hundreds of millions of years ago, as well as evidence of Pangaea rifting apart (fig. 32). Much younger rocks and deposits (thousands to a few million years old) result from the continuous processes of weathering and erosion sculpting the landscape. Gathright (1976), Badger (1999), Hackley (2000), Bentley (2008), and Kelly (2011) provide summaries of the park's geologic story. Morgan et al. (2003) describes the younger, unconsolidated surficial deposits attesting to the earth surface processes active on the park's landscape today.

Mesoproterozoic Era (1.3 Billion to 1.0 Billion Years Ago)

Grenville Orogeny and the Supercontinent Rodinia

The bedrock underlying parts of the Blue Ridge Mountains in Shenandoah National Park is among the oldest in the eastern United States, dating back to the Mesoproterozoic Era, or nearly 1.2 billion years ago (Tollo et al. 2006). At the time, the granitic gneisses and granitoids ("Y" geologic map units) were emplaced , metamorphosed, and deformed during several phases of the Grenville Orogeny (Harris et al. 1997; Bailey et al. 2006; Tollo et al. 2006). The Grenville Orogeny spanned from approximately 1,300 to 900 million years ago (fig. 33A) (Tollo et al. 2006; Southworth et al. 2010; M. Heller, geologist, Virginia Division of Geology and Mineral Resources, written communication, 16 July 2013) and ultimately resulted in the formation of the supercontinent Rodinia. Rodinia encompassed most of the continental crust in existence at the time, including what would become North America.

The Grenville-era, Mesoproterozoic rocks form a geologically complex basement upon which all other rocks of the Appalachians were deposited (Southworth et al. 2008b).The rocks are now highly deformed, as a result of extremely high pressure metamorphism, faulting, and high strain that took place during multiple orogenies, spanning millions of years (Tollo et al. 2004; Butler 2005; Southworth 2005; Southworth et al. 2009).

Neoproterozoic Era (1.0 Billion to 541 Million Years Ago)

During continued tectonic activity of the Grenville Orogeny, the Mesoproterozoic rocks were uplifted and eroded. Early Neoproterozoic sediments (Zp map unit) shed from the Mesoproterozoic rocks covered the eroded surface after about 960 million years ago (fig. 33B) (Southworth et al. 2009). Those sediments in turn were buried, metamorphosed and uplifted to the surface before deposition of younger Neoproterozoic sediments (map units Zmr and Zsr) between about 700 and 575 million years ago (Southworth et al. 2009).

Failed Rifting

Approximately 730 to 700 million years ago, the ancient continent experienced a rifting event that ultimately failed and did not result in the breakup of the landmass. Associated with this continental extension, the Robertson River Igneous Suite (a series of granitoids, "Zr" geologic map units) intruded the local bedrock—possibly along a preexisting fault or other boundary, such as a series of igneous plutons (fig. 33B) (Tollo and Aleinikoff 1996; Bailey et al. 2006; Southworth et al. 2009). Volcanism accompanied this intrusive event from 714 to about 700 million years ago in addition to intermittent sedimentary deposition, although rocks from this time period are not mapped within park boundaries in the GRI GIS data (Tollo and Hutson 1996; Bailey et al. 2007; Southworth et al. 2009). A successful rifting event was forthcoming.

Rifting of Rodinia and Opening of the Iapetus Ocean

Following a period of erosion or nondeposition, sediments were deposited into basins (perhaps a graben or half-graben, as shown in fig. 15) and covered the eroded surface of older metamorphic and igneous rocks. Those sediments would become the Mechum River and Swift Run formations (Zmr and Zsr, respectively) (Bailey 2007). The Swift Run Formation contains diverse material from several sources including the Grenville highlands and earliest volcanic debris and ash from eruptions that also produced the Catoctin Formation ("Zc" units) (Butler 2005).

During the late Proterozoic, approximately 600 million years ago, crustal extension began to pull apart Rodinia (fig. 33C). Weathering and erosion reduced the highlands that formed during the Grenville Orogeny to low-rolling hills similar to the modern Piedmont (Butler 2005). As the supercontinent rifted, a basin formed that eventually became the Iapetus Ocean. In an extensional setting, analogous to a modern-day East African rift and the Red Sea, many normal faults (see fig. 15) develop to accommodate the stretching of the crust. Igneous rocks, such as flood basalts and rhyolite travelled through cracks in the ancient granitic gneisses ("Y" units) of the Blue Ridge core and erupted onto the land surface during the break-up of Rodinia (Southworth et al. 2008b). Today these flood basalts are part of the Catoctin Formation ("Zc" units), that support the highlands of Shenandoah National Park. The Catoctin Formation is

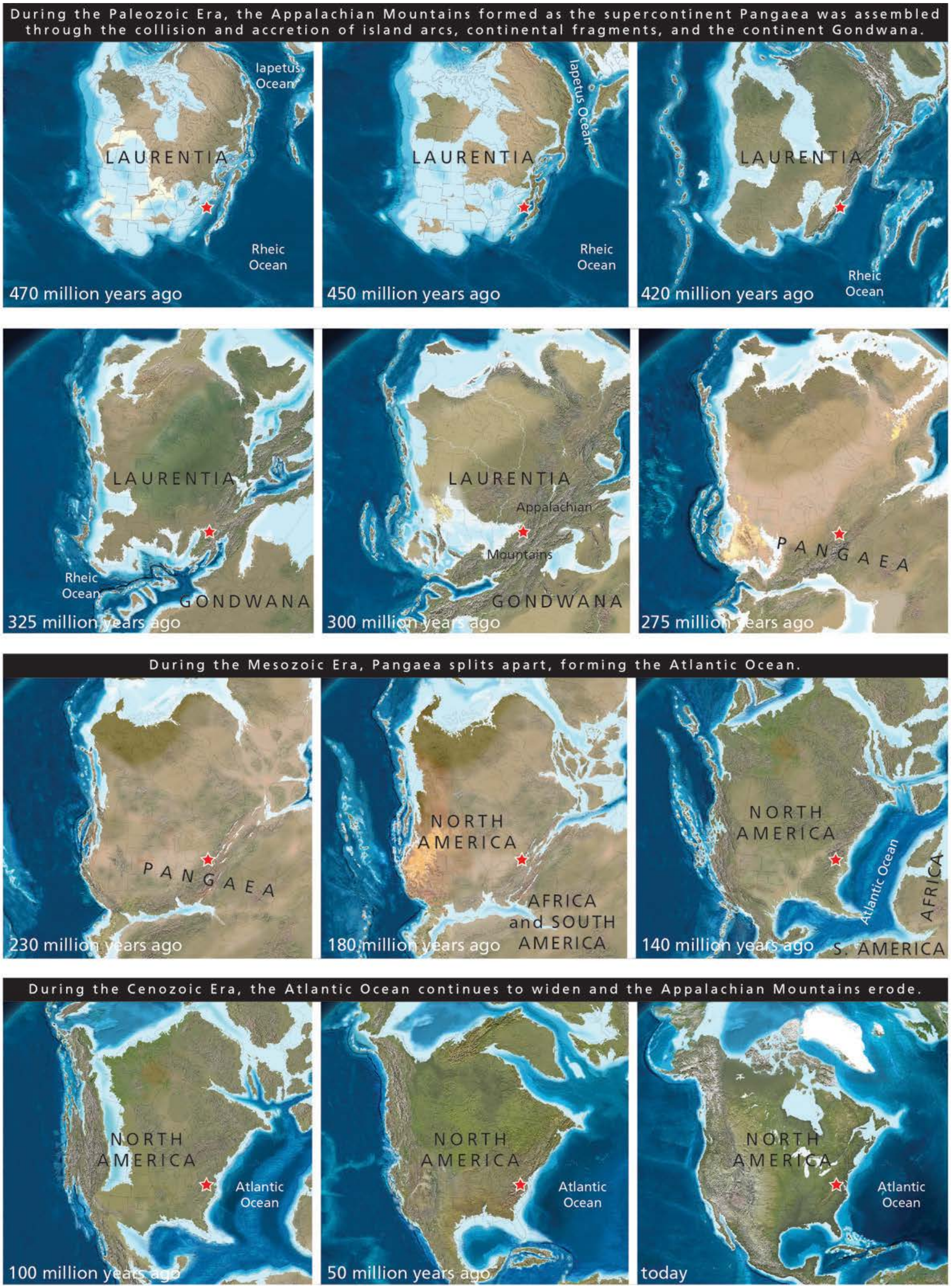


Figure 32. Paleogeographic maps of North America. The red star indicates the approximate location of Shenandoah National Park. Graphic complied by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 25 January 2012).

named for outcrops within and near Catoctin Mountain Park, Maryland (for additional information see Thornberry-Ehrlich 2009). They are the youngest Precambrian rocks in the park, and date to approximately 570 million years ago (Southworth et al. 2009).

Paleozoic Era (541 Million–252 Million Years Ago)

Continued Opening of the Iapetus Ocean and Transition to a Passive Margin

At the dawn of the Paleozoic Era, the rifted continental margin began to stabilize as the Iapetus Ocean grew wider. The passive margin collected sediments eroded from the highlands in a series of riverine and nearshore marine environments on an irregular topographic surface developed atop the Proterozoic rocks (fig. 33D) (Southworth et al. 2009). Today these units include the metamorphosed sedimentary rocks of the Chilhowee Group (the Weverton, Harpers, and Antietam formations, "Cc"geologic map units) deposited nonconformably atop the eroded Catoctin Formation ("Zc" units). The conglomerates and other coarse, clastic sediments of the Weverton Formation (Ccw) are evidence of rivers flowing and eroding the new landscape. As the Iapetus Ocean transgressed over the continental shelf, lagoons formed, and deposited finer grained sediments of the Harpers Formation (Cchs and Cch). As the Iapetus continued to widen, lagoons gave way to a beach-barrier island system (fig. 33E), similar to the modern barrier islands along the east coast, preserved in the sandstones of the Antietam Formation (Cca) (Bulter 2006).

Passive Margin

The broad continental shelf along what would become the eastern margin of North America collected an 8 km (5 mi) thick stack of Cambrian and Ordovician sediments (Bailey et al. 2008). At this time, the margin faced southward (W. Kelly, geologist, Virginia Division of Geology and Mineral Resources, written communication, 16 July 2013). An expansive carbonate platform developed during Cambrian through Early Ordovician time (fig. 33F). Within the park, the carbonate rocks of the Tomstown and Waynesboro formations (Ct and Cwa), Elbrook and Conococheague limestones (Ce and OCc), and Beekmantown Group (Ob) were deposited as part of that platform. Organisms flourished in the tropical setting, as evidenced by bioturbation and marine fossils in Cambrian and Ordovician rocks, respectively.

Taconic Orogeny

The carbonate platform was not to last as tectonic unrest began anew. The continental margin transitioned from a passive margin to a convergent margin as an arc of volcanic islands collided with ancient North America (Laurentia in fig. 32) during the Taconic Orogeny (approximately 440 million–420 million years ago in the central Appalachians).The siliciclastic rocks of the Martinsburg Formation (Om) signal this change in depositional setting as the carbonate rocks were buried by sediments shed from the new highlands to the east (Southworth et al. 2009). Oceanic crust and portions of the volcanic arc were shoved onto the eastern edge of the North American continent (Laurentia in fig. 32) along major thrust faults.

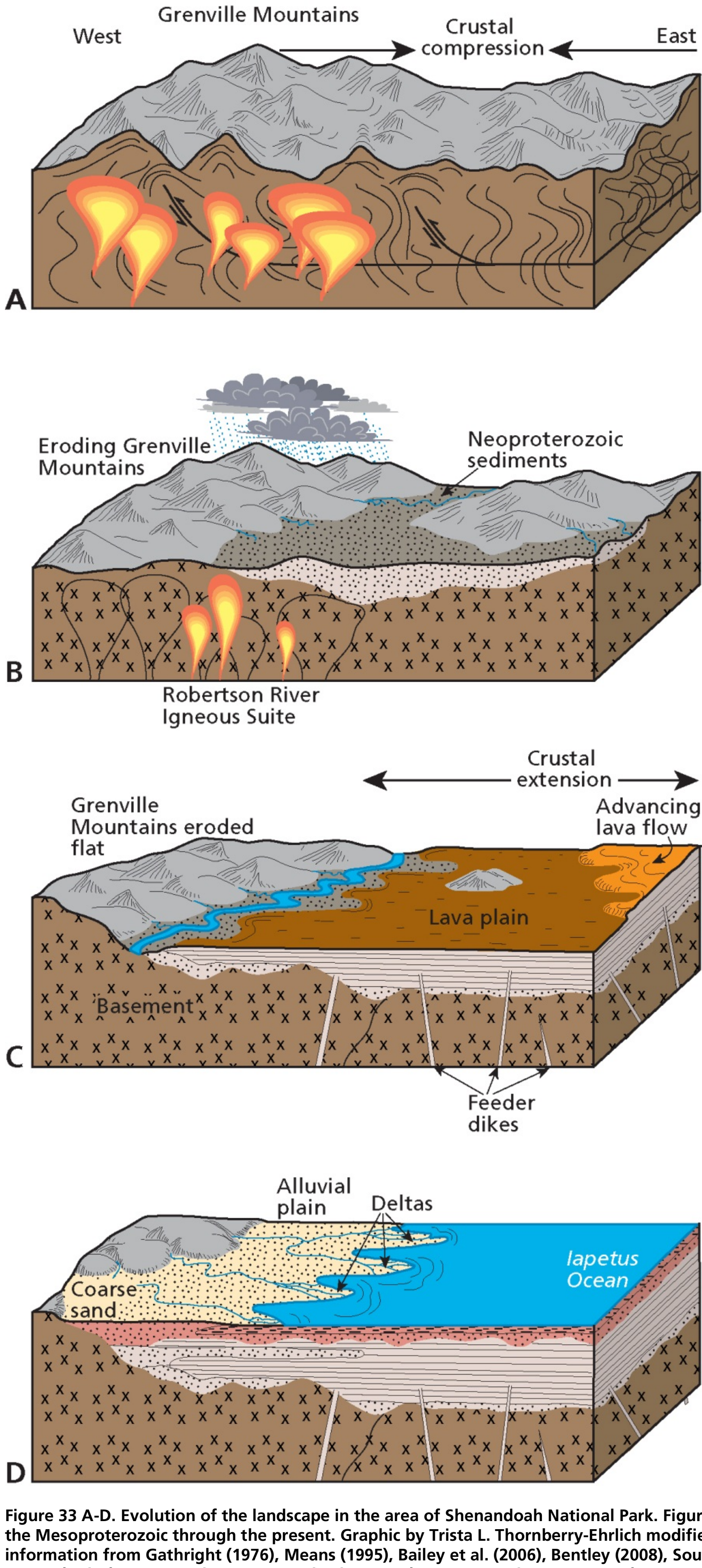
In response to the increased weight of the thickening crust of eastern North America, the crust bowed downwards to the west creating a deep basin by about 450 million years ago. The basin—centered on what is now West Virginia—formed where the carbonate platform once stood (Harris et al. 1997; Southworth et al. 2008b). Deposition of increasingly siliciclastic and terrestrial sediments ensued into an epicontinental sea as highlands rose to the east (fig. 33G) (Southworth et al. 2009, W. Kelly, written communication, 16 July 2013). The highlands were also eroding, eventually forming a thick sequence of Late Ordovician (Oeln, Om), Silurian (Sm), and Devonian (DSu) rocks. These rocks underlie the Valley and Ridge province to the west of Shenandoah National Park (Fisher 1976). For example, erosion-resistant sandstones and clastic rocks of Sm and DSu support the ridges of Massanutten Mountain (Southworth et al. 2009).

Acadian-Neoacadian Orogeny (410 Million–355 Million Years Ago)

The Acadian Orogeny (approximately 360 million years ago) followed the mountain building of the Taconic Orogeny as the African continent approached North America (Laurentia and Gondwana, respectively in fig. 32) (Harris et al., 1997). Similar to the Taconic Orogeny, the Acadian Orogeny involved land mass collision, mountain building, and regional metamorphism (Means 1995). This event was focused in New England; however, a deformation event between pre-360 million and 310 million years ago produced high-strain zones ("Paleozoic high-strain zones" in the GRI GIS data) and folded near-surface rocks of the Blue Ridge (fig. 33H) (Bailey et al. 2006). The Tioga Ash Beds (mapped within DSu) reflect regional volcanic island-arc activity. Though, this event occurred between the classically accepted Appalachian orogenies, evidence suggests a pervasive crustal-shortening event occurred in the Blue Ridge at this time—the "Neoacadian" Orogeny (Kunk et al. 2005; Bailey et al. 2006; Merschat and Hatcher 2007). Initial metamorphism of the Catoctin volcanic rocks into metabasalts and metarhyolites, as well as the Chilhowee Group sedimentary rocks into metasiltstones, quartzites, and phyllites likely began during the Devonian, but culminated later during the Alleghany Orogeny (Southworth et al. 2009).

Alleghany Orogeny (325 Million–265 Million Years Ago)

The Iapetus basin closed during the Late Paleozoic as the North American and African continents (Laurentia and Gondwana, respectively in fig. 32) collided during the Alleghany Orogeny, about 325 million to 265 million years ago (fig. 33I). This was the last major orogeny to contribute to the Appalachian Mountains evolution, forming a mountain chain perhaps rivaling the modern



1,300 to 900 million years ago–Grenville Orogeny and the formation of supercontinent, **Rodinia**; extensive metamorphism, deformation, and pluton intrusion

960 to 680 million years ago–Uplift and erosion; sediments shed from Grenville Mountains; Robertson River Igneous Suite intruded 730 to 700 million years ago as part of a failed rift event; deposition of Mechum River and Swift Run formations at about 730 to 680 million years ago

600 million years ago–**Rodinia** rifted apart; *Iapetus Ocean* began to open; widespread volcanic activity; Catoctin Formation deposited atop Grenville basement and sedimentary deposits

*colors in cross section represent different periods of time (see stratigraphic column)

541 million years ago–world-wide explosion and diversification of sea life at the base of the Cambrian; sand and mud deposited in lagoons to become the Weverton and Harpers formations atop the Catoctin Formation

Figure 33 A-D. Evolution of the landscape in the area of Shenandoah National Park. Figure continues on subsequent pages. Time spans from the Mesoproterozoic through the present. Graphic by Trista L. Thornberry-Ehrlich modified from Gathright (1976) (figures C–F) with information from Gathright (1976), Means (1995), Bailey et al. (2006), Bentley (2008), Southworth et al. (2009), and A. M. Merschat, geologist, US Geological Survey, written communication 16 July 2013. Drawings not to scale.

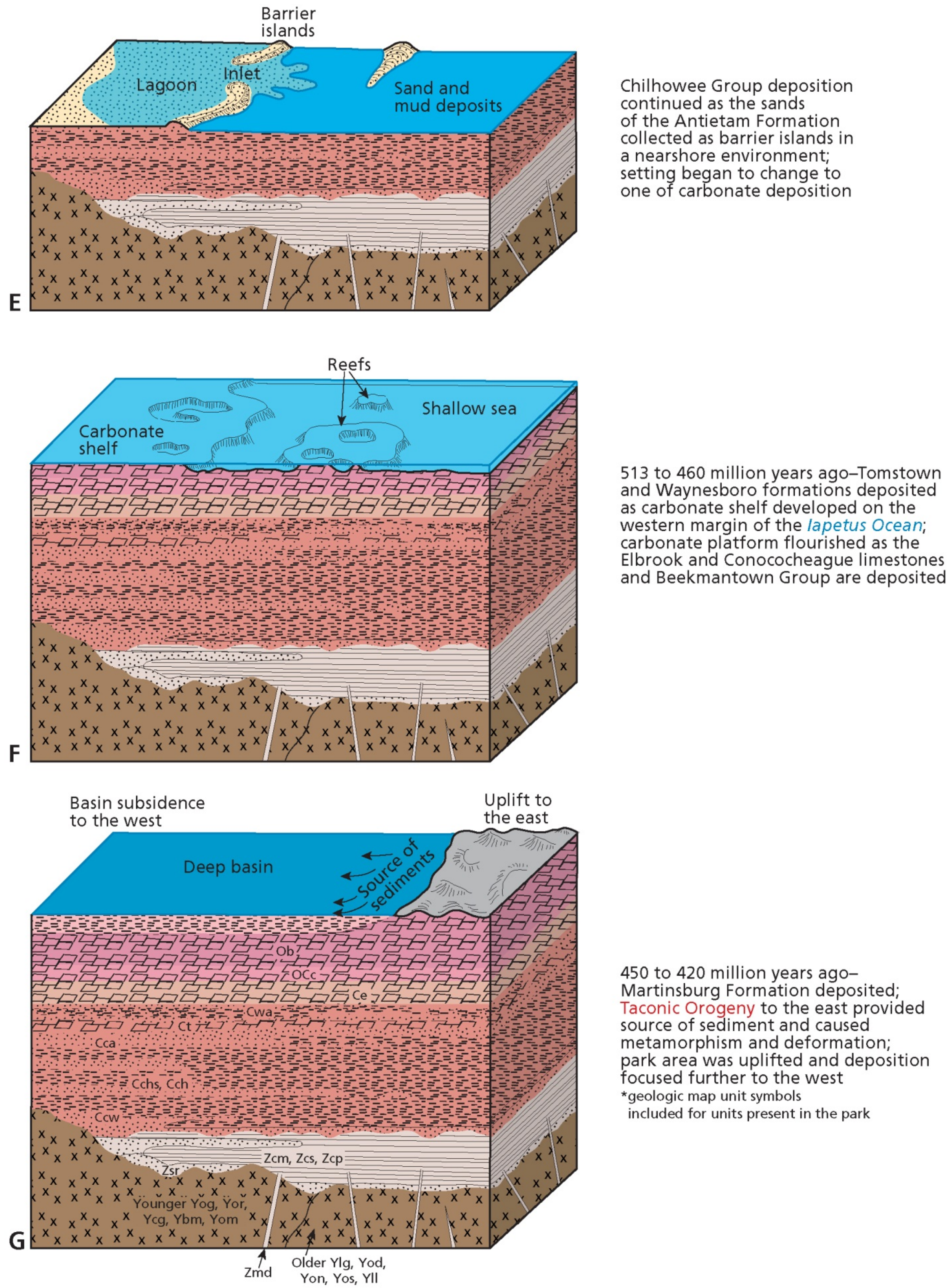


Figure 33 E-G. Evolution of the landscape in the area of Shenandoah National Park, continued. Graphic continues on subsequent pages. Graphic by Trista L. Thornberry-Ehrlich modified from Gathright (1976) (figures C–F) with information from Gathright (1976), Means (1995), Bailey et al. (2006), Bentley (2008), Southworth et al. (2009), and A. M. Merschat, geologist, US Geological Survey, written communication 16 July 2013. Drawings not to scale.

Himalayas with elevations potentially exceeding 6,100 m (20,000 ft) (Means 1995). Erosion and weathering may have removed about 6.5 km (4.0 mi) of rock since the Alleghany Orogeny (Southworth et al. 2009). The Alleghany Orogeny culminated with the assembly of all the major continents into the supercontinent Pangaea (fig. 32).

During the Alleghany Orogeny, folding and faulting produced the Blue Ridge-South Mountain anticlinorium, the Massanutten synclinorium, and the parallel folds of the Valley and Ridge province (fig. 33I) (Southworth et al. 2008b; 2009). Blue Ridge and Piedmont rocks were transported westward along the North Mountain thrust fault atop rocks of the Valley and Ridge province. The trace of this structure is on the west side of the Great Valley (Southworth et al. 2009; Orndorff 2012). The Blue Ridge thrust fault system (Front Royal, Stanley, and Elkton faults, locally) subsequently transported and buckled the Blue Ridge rocks and Chilhowee Group rocks, as the leading edge, atop younger Paleozoic rocks along the eastern edge of the Great Valley.

The amount of southeast-to-northwest crustal contraction associated with folding and faulting during the Alleghany Orogeny was extreme. Estimates are of 50–70 % total shortening which translates into 125–350 km (75–125 mi) of lateral movement and the rocks now underlying Shenandoah would have been located closer to Richmond, Virginia (Hatcher 1989; Harris et al., 1997; Southworth et al. 2009).

Mesozoic Era (252 Million–66 Million Years Ago)

Pangaea Separation, Atlantic Ocean Formation, and Appalachian Mountains Erosion

During the Late Triassic, approximately 80 million years after the Alleghany Orogeny (Southworth et al. 2009), the supercontinent Pangaea began rifting apart into landmasses that would form the modern continents. As the African continent moved away from North America and the Atlantic Ocean began to form (fig. 32), extension of the Earth's crust formed down-dropped basins (grabens; see fig. 15) along the eastern margin of North America (Harris et al. 1997; Southworth et al. 2008b). The Culpeper basin east of Shenandoah National Park is one example. As with previous episodes of rifting, dikes of molten material were commonly associated with crustal extension (fig. 33J). Such dikes intruded the park's bedrock about 200 million to 150 million years ago during the Jurassic (geologic map unit Jd) (Southworth et al. 2009).

Because collisional tectonic forces had ceased, the Appalachian Mountains were no longer being pushed upward and erosion became the dominant process shaping the mountains. Immense amounts of gravel, sand, and silt were eroded and carried eastward to accumulate in the Atlantic Coastal Plain, of Shenandoah National Park (Duffy and Whittecar 1991; Whittecar and Duffy 2000; Southworth et al. 2008b). The amount of material removed from the now-exposed metamorphic mountain core must have been immense. Many of the rocks exposed at the surface were buried at least 20 km (12 mi) below the surface prior to regional uplift and erosion.

Cenozoic Era (The Past 66 Million Years)

Appalachian Mountain Erosion and Ice Age Glaciation

Since the Mesozoic breakup of Pangaea, the North American plate has moved westward. The eastern margin of the continent became passive again, collecting sediments eroding from the Appalachian Mountains (fig. 32). The topographic expression of the modern Blue Ridge Mountains developed during the late Cenozoic (fig. 33K) (Naeser et al. 2006; Duxbury et al. 2007; Southworth et al. 2009). Continuous erosion and slope movements formed debris-fan deposits (geologic map unit Nd) in the highlands, whereas terrace deposits (Nt), alluvial-plain deposits (Np), and alluvial-fan deposits (Nf) were deposited along rivers in the flanking lowlands (Southworth et al. 2009).

During the Pleistocene Epoch, global climate shifts brought alternating periods of prolonged cold—ice ages—and relative warmth similar to modern climate. Continental ice sheets descended south from the Arctic reshaping the landscape of much of northern United States. Though glaciers from the Pleistocene ice ages never reached the central Virginia area (the southern terminus was in central Pennsylvania), the colder climates of the ice ages played a role in the formation of the landscape at Shenandoah National Park. Within what would become the park, periglacial conditions included discontinuous permafrost, tundra-like vegetation, and frost weathering (Braun 1989). Frost weathering wedged untold numbers of boulders and small rocks from the bedrock to form stone streams, quartzite block-field deposits (Qb) and colluvium (Qc) (Morgan et al. 2003; Southworth et al. 2009).

When warmer climates resumed during the Holocene Epoch erosion of Shenandoah National Park's steep slopes continued. Debris-flow deposits (Qdf) record rapid episodes of mass wasting (Morgan et al. 2003; Southworth et al. 2009). The youngest geologic unit on the park's landscape is the alluvium (Qa) collecting along streams and rivers (Southworth et al. 2009).This process occurs throughout the region as the Potomac, Rappahannock, Rapidan, and Shenandoah rivers meander across their floodplains transporting and depositing material eroded from the Appalachian Mountains and Coastal Plains. Today, visitors enjoy the picturesque landscape of Shenandoah National Park. The park's beautiful vistas, mountains, hollows, and valleys record a geologic history where supercontinents were created and destroyed, oceans opened and closed, and mountains rose and were worn away (fig. 34).

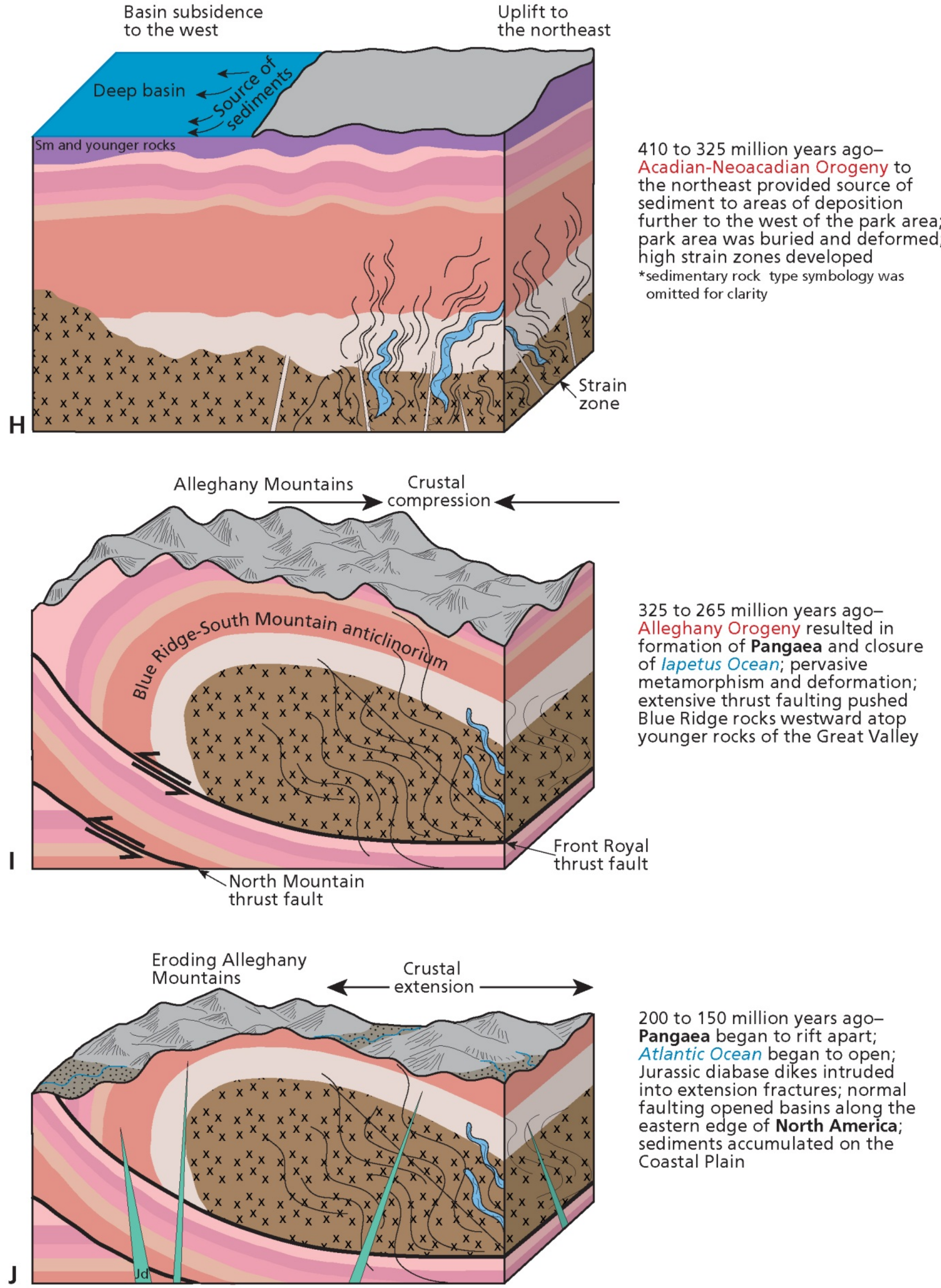
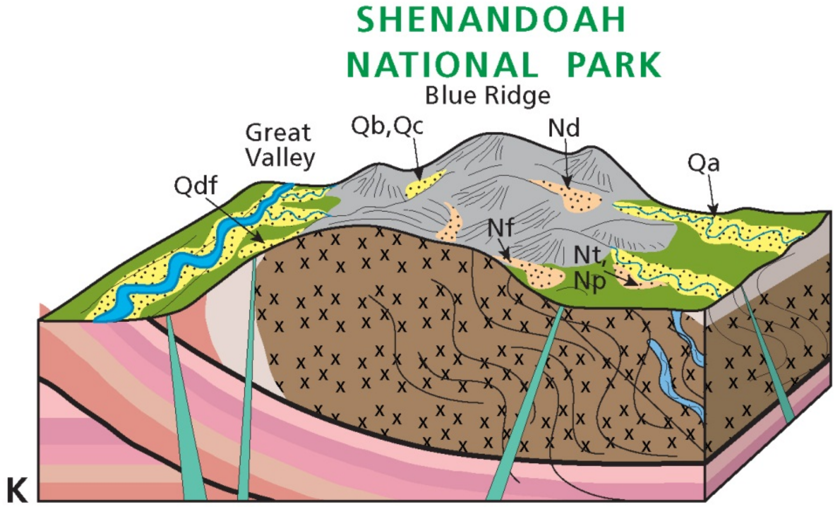


Figure 33 H-J. Evolution of the landscape in the area of Shenandoah National Park, continued. Graphic continues on subsequent pages. "Alleghany Mountains" in figures 33I and 33J refer to the mountains formed during the Alleghany Orogeny, which resulted in the modern Appalachians. Graphic by Trista L. Thornberry-Ehrlich modified from Gathright (1976) (figures C–F) with information from Gathright (1976), Means (1995), Bailey et al. (2006), Bentley (2008), Southworth et al. (2009), and A. M. Merschat, geologist, US Geological Survey, written communication 16 July 2013. Drawings not to scale.



Past 66 million years–*Atlantic Ocean* continued to widen; erosion and weathering continued to wear away the Blue Ridge highlands; slope deposits accumulated during ice ages; modern streams deposited alluvium

Figure 33 K. Evolution of the landscape in the area of Shenandoah National Park, continued. Graphic by Trista L. Thornberry-Ehrlich modified from Gathright (1976) (figures C–F) with information from Gathright (1976), Means (1995), Bailey et al. (2006), Bentley (2008), Southworth et al. (2009), and A. M. Merschat, geologist, US Geological Survey, written communication 16 July 2013. Drawings not to scale.

Figure 34. Old Rag Summit view. A visitor takes in the view from Old Rag Summit where the landscape records the assembly of supercontinents, the existence of ancient oceans, and the rise and fall of ancient mountain ranges. National Park Service photograph available online: http://www.nps.gov/shen/photosmultimedia/photogallery.htm (accessed 6 February 2014).

Geologic Map Data

This section summarizes the geologic map data available for Shenandoah National Park. The Geologic Map Graphics (in pocket) display the map data draped over imagery 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://go.nps.gov/gripubs.

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, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are 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, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following source to produce the digital geologic data set for Shenandoah National Park. These sources also provided information for this report.

Southworth, S., J. N. Aleinikoff, C. M. Bailey, W. C. Burton, E. A. Crider, P. C. Hackley, J. P. Smoot, and R. P. Tollo. 2009. Geologic Map of the Shenandoah National Park Region, Virginia (scale 1:100,000). Open-File Report 2009-1153. US Geological Survey, Reston, Virginia, USA.

GRI 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 at 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 Shenandoah National Park using data model version 2.1. The GRI website provides more information about GRI map products: http://www.nature.nps.gov/geology/inventory/geo_maps.cfm.

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 are part of the data set:

- A GIS readme file (.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format
- Layer files with feature symbology (table 4)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth (table 4).

Table 4. Geology data layers in the Shenandoah National Park GIS data

Data Layer	Data Layer Code	On Map Graphics?	Google Earth Layer?
Geologic Cross Section Lines	SEC	No	No
Geologic Attitude Observation Localities	ATD	No	No
Age-Date Localities	GSL	No	No
Breccia	GPF	No	No
Stratified Slope Deposits	GOL	Yes	No
Small Sinkholes	HZP	No	No
Mines	MIN	No	No
Large Sinkhole Boundaries	HZAA	Yes	Yes
Large Sinkholes	HZA	Yes	Yes
Surficial Contacts	SURA	Yes	Yes
Surficial Units	SUR	Yes	Yes
Faults	FLT	Yes	Yes
Deformation Area Boundaries	DEFA	No	Yes
Deformation Areas	DEF	No	Yes
Bedrock Contacts	GLGA	Yes	Yes
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. Not all GIS feature classes may be included on the graphics (table 4). Geographic information and selected park features have been added to the graphics. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the Geologic Map Graphic. Based on the source map scale (1:100,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 51 m (167 ft) of their true locations.

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age (in years) of a fossil, rock, feature, or event; commonly refers to a radiometrically determined age. See "radiometric age."
abyssal plain. A flat region of the deep ocean floor, usually at the base of the continental rise.
active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary), or slide past one another (transform boundary). Typically associated with earthquakes and, in the cases of convergent and divergent boundaries, volcanism. Compare with "passive margin."
adit. A horizontal passage from the surface into a mine.
aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.
alkalic. Describes a rock that is enriched in sodium and potassium.
alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows into a hydraulically unconfined area (commonly from a mountainous area into a valley or plain).
alluvium. Stream-deposited sediment.
altiplanation. Soliflucation and related mass movements that tend to produce flat or terrace-like surfaces, especially at high elevations and latitudes.
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.
amygdule. A gas cavity or vesicle in an igneous rock, which is filled with secondary minerals ("amygdaloidal" describes rocks with amygdules).
andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.
angular unconformity. An unconformity in which the rock layers above and below are oriented differently. Also see "unconformity."
anticline. A convex ("A"-shaped) fold. Older rocks are found in the center. Compare with "syncline."
anticlinorium. A large, regional feature with the overall shape of an anticline. Composed of many smaller folds.
aphanitic. Describes the texture of fine-grained igneous rock in which different components are not distinguishable by the unaided eye.
aphyric. Describes the texture of a fine-grained or aphanitic igneous rock that lacks coarse (large) crystals.
aquiclude. See "confining bed."
aquifer. A rock or sedimentary unit that is sufficiently porous 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."
arkose. A sandstone with abundant feldspar minerals, commonly coarsegrained and pink or reddish.
ash (volcanic). Fine material ejected from a volcano.Also see "tuff."
asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.
augen. Describes large lenticular mineral grains or mineral aggregates that are eye-shaped 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 foldalong the boundary between its two limbs.
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. Streamflow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.
base level. The lowest level to which a stream channel can erode. 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 scale, into which sediments are deposited.
batholith. A very large (more than 100 km^2 (40 mi^2), discordant pluton, often formed from multiple intrusions of magma.
bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (39.4 to 78.7 in) 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.
bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.

block (fault). A crustal unit bounded completely or partially by faults.

bioherm. A mound-like, dome-like, lens-like, or reef-like mass of rock built up by sedentary organisms, composed almost exclusively of their calcareous remains and enclosed or surrounded by rock of different lithology.

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

bioturbation. The reworking of sediment by organisms.

Bouma cycle. A fixed, characteristic succession of five intervals that makes up a complete sequence of a turbidite. One or more intervals may be missing. The five intervals are, from bottom to top (oldest to youngest): a) graded, b) lower parallel laminations, c) current ripple laminations, d) upper parallel laminations, and e) pelitic. Named after Arnold Bouma, Dutch sedimentologist. Also see "turbidite."

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

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material, such as tuff or ash.

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

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

calc-silicate rock. A metamorphic rock consisting mainly of calcium-bearing silicates and formed by metamorphism of impure limestone or dolomite.

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

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 providing more stability in the current environment.

chert. An 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). Also see "epiclastic."

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 with 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 weakness in the crystal structure.

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

clinopyroxene. A subgroup of pyroxene minerals crystallizing in the monoclinic system. Important rock-forming minerals; common in igneous and metamorphic rocks.

columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep. Usually collects at the base of a gentle slope or hillside.

concordant. Describes a stratum with contacts parallel to the orientation of adjacent strata.

concretion. A hard, compact aggregate of mineral matter, subspherical to irregularly shaped; formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock. The composition of a concretion generally differs from that of the rock in which it occurs.

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) in diameter.

contact metamorphism. Changes in rock as a result of contact with an igneous body.

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 of 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 in contrast 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 collide.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

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.

crossbedding. 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 graphic interpretation of geology, structure, and/or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

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."

cryptocrystalline. Describes a rock texture in which very small individual crystals cannot be recognized or distinguished with an ordinary microscope.

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

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

dacite. A fine-grained extrusive igneous rock similar to andesite, but with fewer calcium-plagioclase minerals and more quartz.

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

décollement. A markedly displaced (kilometers to tens of kilometers), shallowly dipping to subhorizontal fault or shear zone. See "detachment fault."

deformation. A general term for the processes of rock faulting, folding, and shearing 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.

depocenter. An area or site of maximum deposition; the thickest part of any specified stratigraphic unit in a depositional basin.

detachment fault. Synonym for décollement used widely to describe a regionally extensive, gently dipping normal fault that is commonly associated with extension in a metamorphic core complex.

detritus. A collective term for loose rock and mineral material that is worn off or removed by mechanical processes.

diabase. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.

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

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

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

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

dip-slip fault. A fault with measurable offset in which the relative movement is parallel to the dip of the fault. Compare with "strike-slip fault."

disconformity. An unconformity in which the bedding of strata above and below is parallel.

discordant. Describes a contact between strata that cuts across or is set at an angle to the orientation of adjacent rocks.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

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

dome. General term for any smoothly rounded landform or rock mass. More specifically, refers to an elliptical uplift in which rocks dip gently away in all directions.

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

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

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

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal,""parabolic," and "transverse" (see respective listings).

entrainment. The process of picking up and transporting sediment, commonly by wind or water.

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

epiclastic rock. A rock formed at Earth's surface by consolidation of fragments of pre-existing rocks.

epidote. A yellowish-green, pistachio-green, or blackish-green mineral.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or mass movement. Also called a "scarp." The Blue Ridge escarpment does not coincide with a fault, but is a steep topographic break between the erosion resistant rocks of the Blue Ridge and lower elevations of the Piedmont.

extension. A type of strain resulting from "pulling apart" forces. 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. A fan delta differs from a delta in that it forms next to a highland, typically at an active margin.

fault. A break in rock characterized by displacement of one side relative to the other.

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

felsic. Describes an igneous rock containing abundant light-colored minerals such as quartz, feldspar, or muscovite. Compare with "mafic."

felsite. A general term for any light-colored, fine-grained extrusive rock composed chiefly of quartz and feldspar.

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.

fold. A curve or bend in an originally flat or planar structure, such as a rock stratum, bedding plane, or foliation; 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 lower wall of a fault. Compare with "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 by freezing in fractures.

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

garnet. A hard mineral with a glassy luster, often with well-defined crystal faces; garnet occurs in 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.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

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

Gondwana. Late Paleozoic supercontinent that comprised much of the Southern Hemisphere continental crust. Combined with Laurasia to form Pangaea.

gradient. See "slope."

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; a locus of sedimentary deposition. Also see "horst."

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.

greenschist. A metamorphic rock with a green color due to the presence of the mineral chlorite, epidote, or actinolite; corresponds to metamorphism at temperatures of 300 to 500°C (570 to 930°F).

greenstone. A general term for any compact, dark-green, altered or metamorphosed basic igneous rock with a green color due to chlorite, actinolite, or epidote mineral content.

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

hanging wall. The upper wall of a fault. Compare with "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 form.

horst. An area of relatively high topography between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin and Range province of Nevada, where the basins are grabens and the ranges are weathered horsts. Also see "graben."

hydraulic conductivity. Measure of permeability coefficient (the ease with which water moves through spaces or pores in soil or rock).

hydrogeologic. Describes geologic influences on groundwater and surface water composition, movement, and distribution.

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

igneous. Describes a rock or mineral that originated from molten material; one of the three main classes of rock—igneous, metamorphic, and sedimentary.

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.

isotopic age. An age (in years) 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 planar break in rock without relative movement of rocks on either side of the fracture surface.

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.

karst window. A collapse sinkhole opening into a cave.

labradorite. A colorless or dark mineral of the plagioclase feldspar group often with a pearly luster.

lamination. Very thin, parallel layering.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

latite. A porphyritic extrusive volcanic rock with large crystals of plagioclase and potassium feldspar minerals in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass.

Laurasia. Late Paleozoic supercontinent that comprised much of the Northern Hemisphere continental crust. Combined with Gondwana to form Pangaea.

lava. Molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the left. Synonymous with sinistral fault.

lens. A sedimentary deposit characterized by converging surfaces, thick in the middle and thinning out toward the edges, resembling a convex lens.

leucogranite. A light-colored intrusive igneous rock rich in potassium feldspar and aluminum.

limb. One side of a structural fold.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lithic. A sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

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 characteristics such as color, mineral composition, and grain size.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 mi) thick, that encompasses the crust and uppermost mantle.

lithostratigraphy. The aspect of stratigraphy that investigates the lithology of strata, their organization into units based on lithologic characteristics, and their correlations.

loess. Windblown silt-sized sediment, generally of glacial origin.

mafic. Describes dark-colored rock, magma, or mineral rich in magnesium and iron. Also see "ultramafic," compare with "felsic."

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

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.

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 an igneous rock or poorly sorted clastic sediment or rock. Also refers to rock or sediment in which a fossil is embedded.

meander. Sinuous lateral curve or bend in a stream channel; a meander's original pattern is preserved with little modification. An entrenched meander is incised (carved downward) into the surface of its valley.

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.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

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

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

meteoric water. Water of recent atmospheric origin.

metavolcanic. Informally describes a volcanic rock that shows evidence of metamorphism.

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

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; exhibits 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.

monzonite. A group of plutonic (intrusive igneous) rocks of intermediate color containing approximately equal amounts of alkali feldspar and plagioclase, little or no quartz, and commonly augite as the main mafic mineral. Intrusive equivalent of latite.

morphometry. Quantitative measurement of a feature's shape.

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

muscovite. A colorless to pale-brown mineral of the mica group; common in metamorphic rocks such as gneiss and schist, igneous rocks such as granite and pegmatite, and sedimentary rocks such as sandstone.

mylonite. A fine-grained, foliated rock typically found in localized zones of ductile deformation and high strain, often formed at great depths under high temperature and pressure.

mylonite structure. A flow-like appearance, characteristic of mylonite that is produced by intense small-scale crushing, breaking, and shearing of rock.

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

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall. Compare with "reverse fault" and "thrust fault."

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

olivine. An olive-green mineral rich in iron, magnesium, and manganese that is commonly found in low-silica (basaltic) igneous rocks.

orogeny. A mountain-building event.

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

paleofill. Ancient sediment that filled caves and sinkholes, existing before the present cave passages formed.

Pangaea. A supercontinent that existed during the Permian and Triassic periods and included much of Earth's continental crust. Split into Gondwana and Laurasia.

parent material. The unconsolidated organic and mineral material in which soil forms.

parent rock. Rock from which soil, sediment, or other rock is derived.

passive margin. A margin at which no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America. Compare with "active margin."

pebble. Generally, a small rounded rock particle with a diameter of 4 to 64 mm (0.16 to 2.52 in).

pegmatite. An exceptionally coarse-grained intrusive igneous rock with interlocking crystals, usually found in irregular dikes, lenses, and veins, especially at the margins of batholiths.

pelitic. Describes a sedimentary rock composed of clay (pelite) or a metamorphic rock derived by metamorphism of pelite.

perched aquifer. An aquifer containing unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone.

peridotite. A coarse-grained plutonic (intrusive) rock composed chiefly of olivine and other mafic minerals; commonly alters to serpentinite.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or sediment.

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.

plastic. Describes a material capable of being deformed permanently without rupture.

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

platy. Describes a sedimentary particle with a length more than three times its thickness. Also describes a sandstone or limestone that splits into thin (2 to 10 mm [0.08 to 0.4 in]) layers.

plume. A persistent, pipe-like body of hot material moving upward from Earth's mantle into the crust.

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

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander, where flow velocity slows.

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

porphyry (porphyritic).(Describes) an igneous rock consisting of abundant coarse (large) crystals in a fine-grained matrix.

porphyroclast. A partly crushed, or deformed rock fragment or mineral within a finer-grained matrix in a metamorphic rock.

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

protolith. The parent or unweathered and/or unmetamorphosed rock from which regolith or metamorphosed rock is formed.

pseudomorph. A mineral whose outward crystal form resembles that of another mineral; described as being "after" the mineral whose outward form it has (e.g., quartz after fluorite).

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 characterized by short, stout crystals.

quartzite. Metamorphosed quartz sandstone.

quartz monzonite. A plutonic rock with 5% to 20% quartz and an alkali feldspar: total feldspar ratio of 35% to 65%. Intrusive equivalent of rhyodacite.

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

radiometric age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products. See "absolute age" and "isotopic age."

recharge. Infiltration process that replenishes groundwater.

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

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

rhyodacite.A volcanic rock intermediate between rhyolite and dacite. Extrusive equivalent of quartz monzonite.

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

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.

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right. Synonymous with dextral fault.

ripple marks. The undulating, approximately parallel and usually small-scale pattern of ridges 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.

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

rock fall. The most rapid mass-wasting process, in which rocks are dislodged and move downslope rapidly.

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, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

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

saprolite. Soft, often clay-rich, decomposed rock formed in place by chemical weathering.

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 split readily into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity," to the rock.

schistose. Describes a rock displaying schistosity, or foliation, which imparts a silky sheen.

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

sericite. A white, fine-grained potassium mica occurring in small scales and flakes as an alteration product of various aluminosilicate minerals, having a silky luster, and found in various metamorphic rocks.

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

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

shear zone. A zone of rock that has been crushed and brecciated by many parallel fractures due to shear strain.

sheet flow. An overland flow or downslope movement of water,in the form of a thin, continuous film, over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sheetwash (sheet erosion). The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water, rather than by a stream flowing in a well-defined channel.

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

silicic. Describes a silica-rich igneous rock or magma.

siliciclastic. Describes noncarbonate clastic rocks.

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; 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 failure surface and subsequent backward rotation relative to the slope.

sodic. Describes a mineral or igneous rock containing a relatively high proportion of sodium.

soil. The unconsolidated mineral or organic matter on the surface of the earth that has been affected by climate (water and temperature) and organisms (macro and mico), conditioned by relief, acting on parent material over a period of time. Soil differs from the material from which it is derived in many ways.

solifluction. The slow downslope movement of waterlogged soil, normally at rates of 0.5 to 5.0 cm (0.2 to 2 in) per year; especially, the flow occurring at high elevations in regions underlain by frozen ground that acts as a downward barrier to water percolation, initiated by frost action and augmented by meltwater resulting from alternate freezing and thawing of snow and ground ice.

spreading center. A divergent boundary where two lithospheric plates are spreading apart; 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.

stone stream. An accumulation of boulders or angular blocks over solid or weathered bedrock, colluvium, or alluvium.

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 bench surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).
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. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right. Compare with "dip-slip fault."
structure. The attitudes and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusion.
subaerial. Describes a condition or process that exists or operates 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) fold with layers that dip inward; stratigraphically younger rocks are found in its core. Compare with "anticline."
synclinorium. A composite synclinal structure of regional extent composed of lesser folds.
talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.
tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.
tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.
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. Describes a feature, process, or organism related to land, Earth, or its inhabitants.
thrust fault. A contractional dip-slip fault with a shallowly dipping (less than 45°) fault surface where the hanging wall moves up and over relative to the footwall. Compare with "normal fault" and "reverse fault."
topography. The general morphology of Earth's surface, including relief and locations of natural and human-made features.
trace (fault). The exposed intersection of a fault with Earth's surface.
trace fossil. A fossilized feature or material, such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself.
trachyte. A group of fine-grained, generally porphyritic, extrusive rocks containing alkali feldspar and minor mafic minerals.
transform fault. A strike-slip fault that links two other faults or plate boundaries (e.g., two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other.
trend. The direction or azimuth of elongation of a linear geologic feature.
tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.
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 location. The geographic location where a non-stratified (layered) metamorphic or igneous rock type is well displayed and formally defined. The place of original description, from which the unit derives its name.
type section. The geographic location where a layered stratigraphic unit or fossil is well displayed and formally defined. The place of original description, from which the unit or fossil derives its name.
ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron- and magnesium-rich) minerals.
unconfined groundwater. Groundwater that has a water table; i.e., water not confined under pressure beneath a confining bed.
unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time. Compare with "nonconformity."
uplift. A structurally high area in the crust produced by movement that raises the rocks.
vent. An opening at Earth's surface from which volcanic materials emerge.
vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.
vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was molten.
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.
volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, and deposited in any environment.
volcanogenic. Describes material formed by volcanic processes.
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.
xenolith.A rock particle, formed elsewhere, entrained in magma as an inclusion.
zircon. A common accessory mineral in siliceous igneous rocks, schist, and gneiss; also in sedimentary rocks. 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 valid as of January 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

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

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

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 variety of geologic parks): http://www.nature.nps.gov/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

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

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): http://nature.nps.gov/geology/monitoring/index.cfm

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

Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Virginia Department of Mines, Minerals, and Energy: http://www.dmme.virginia.gov/

US Geological Survey: http://www.usgs.gov/

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

American Geophysical Union: http://sites.agu.org/

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

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

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

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

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Shenandoah National Park, held on 22-23 March 2005, or the follow-up report writing conference call, held on 11 December2012. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2005 Scoping Meeting Participants

Name	Affiliation	Position
Chuck Bailey	College of William & Mary	Geologist
Eric Butler	Cliff Management project	Geologic intern
Wendy Cass	Shenandoah National Park	Botanist
Jim Comiskey	NPS Regional I&M Coordinator	I&M Coordinator
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Scott Eaton	James Madison University	Geologist
Matt Heller	Virginia Division of Mineral Resources	Geologist
Robert Higgins	NPS Geologic Resources Division	Geologist
Dan Hurlbert	Shenandoah National Park	GIS Specialist
Sally Hurlbert	Shenandoah National Park	Park Ranger
John Karish	NPS Northeast Region	Chief Scientist
Lindsay McClelland	NPS Geologic Resources Division	Geologist
Carolyn Mahan	Penn State University, Altoona	Associate Professor
Gordon Olson	Shenandoah National Park	Natural Resources Branch Chief
Gary Somers	Shenandoah National Park	
Scott Southworth	USGS	Geologist
Shane Spitzer	Shenandoah National Park	Physical Scientist
Trista Thornberry-Ehrlich	Colorado State University	Geologist
Dick Tollo	George Washington University	Geologist
John Young	USGS-Leetown Science Center	Research Biologist

2012 Conference Call Participants

Name	Affiliation	Position
Wendy Cass	Shenandoah National Park	Botanist
Tim Connors	NPS Geologic Resources Division	Geologist, GRI Maps Coordinator
Jennifer Flynn	Shenandoah National Park	Deputy Superintendent
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Rebecca Port	NPS Geologic Resources Division	Geologist, GRI Writer/Editor
Jim Schaberl	Shenandoah National Park	Chief, Natural and Cultural Resources Division
Trista Thornberry-Ehrlich	Colorado State University	Geologist, GRI Report Author

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS 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 January 2014. Contact the NPS Geologic Resources Division 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** states 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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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 (December 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
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 American Indian 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.
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 and 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 134/123841, February 2014

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

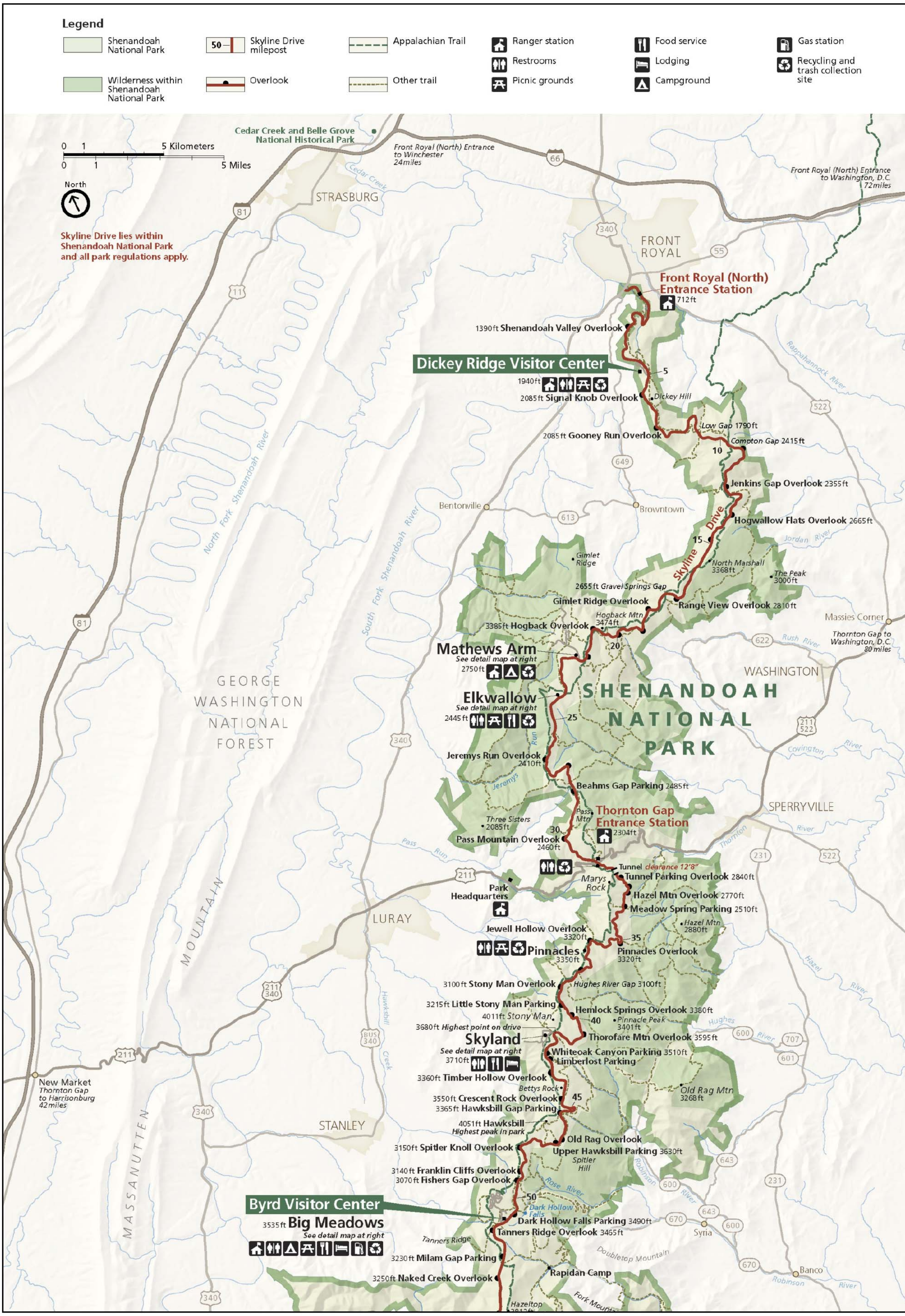


Plate 1. Map of Shenandoah National Park (continued on other side). National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=SHEN (accessed 13 November 2013). Detail maps for selected areas in the park are also available at that website.

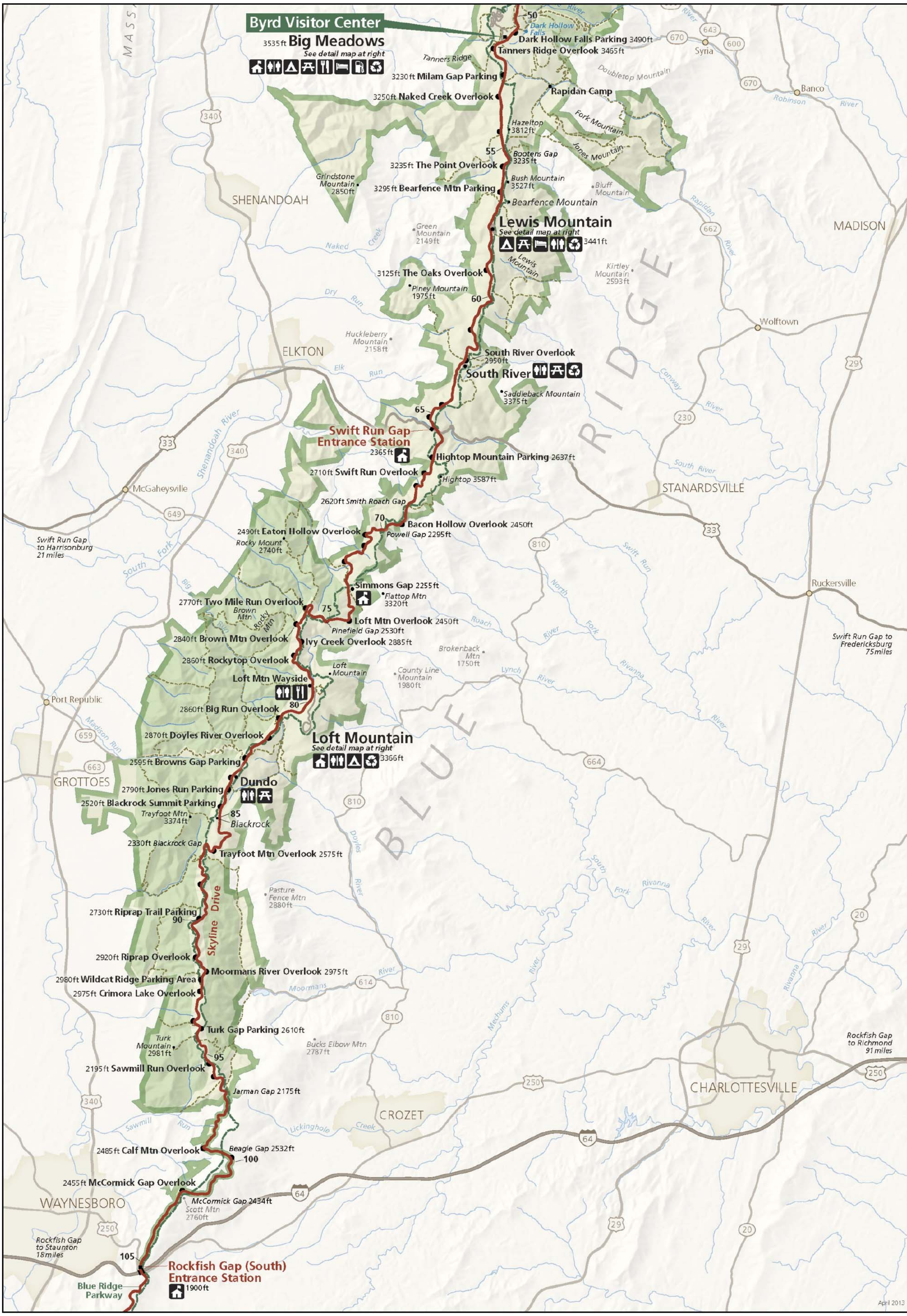
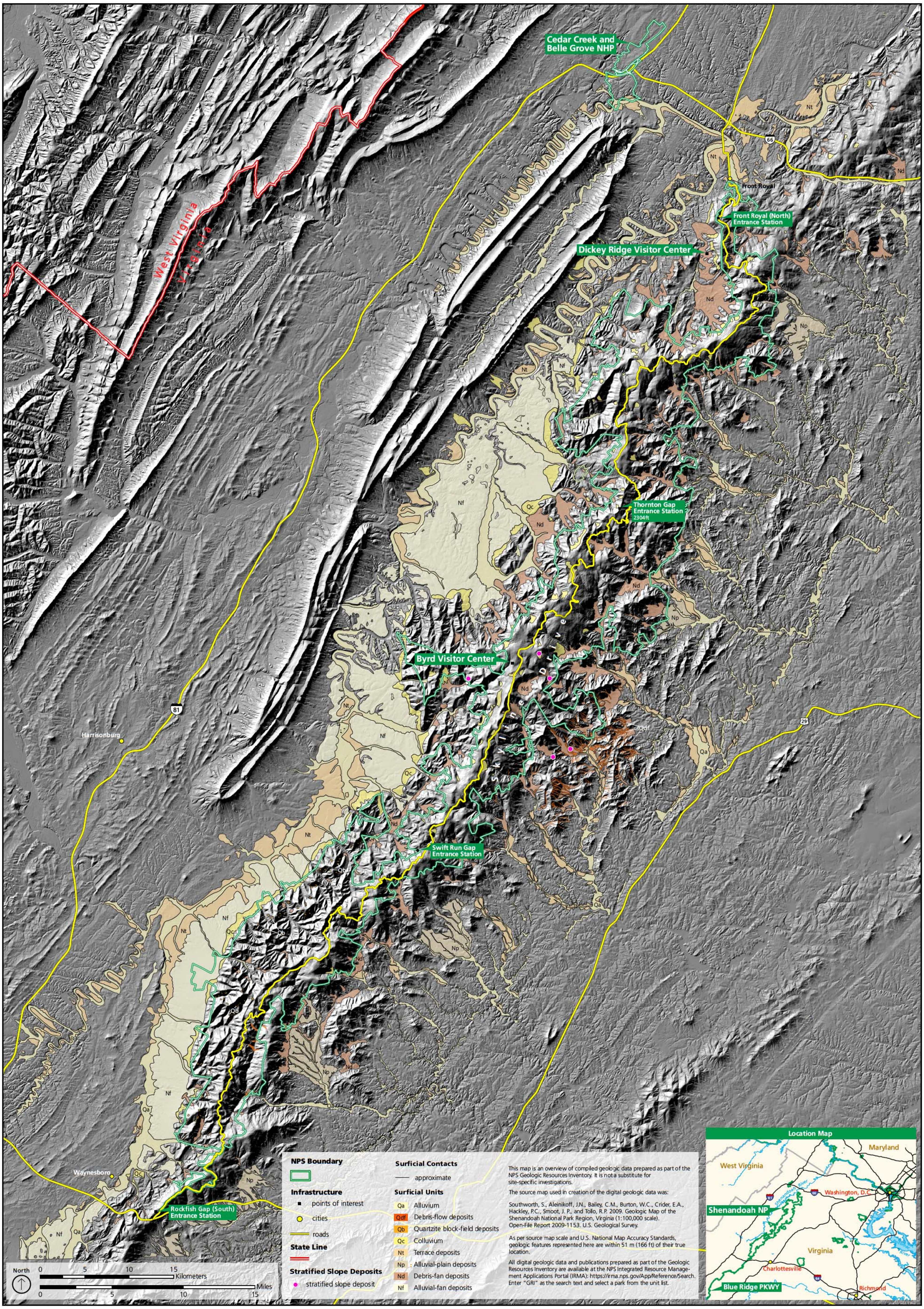


Plate 1 (continued). Map of Shenandoah National Park (continued from other side). See other side for legend and scale. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=SHEN (accessed 13 November 2013). Detail maps for selected areas in the park are also available at that website.

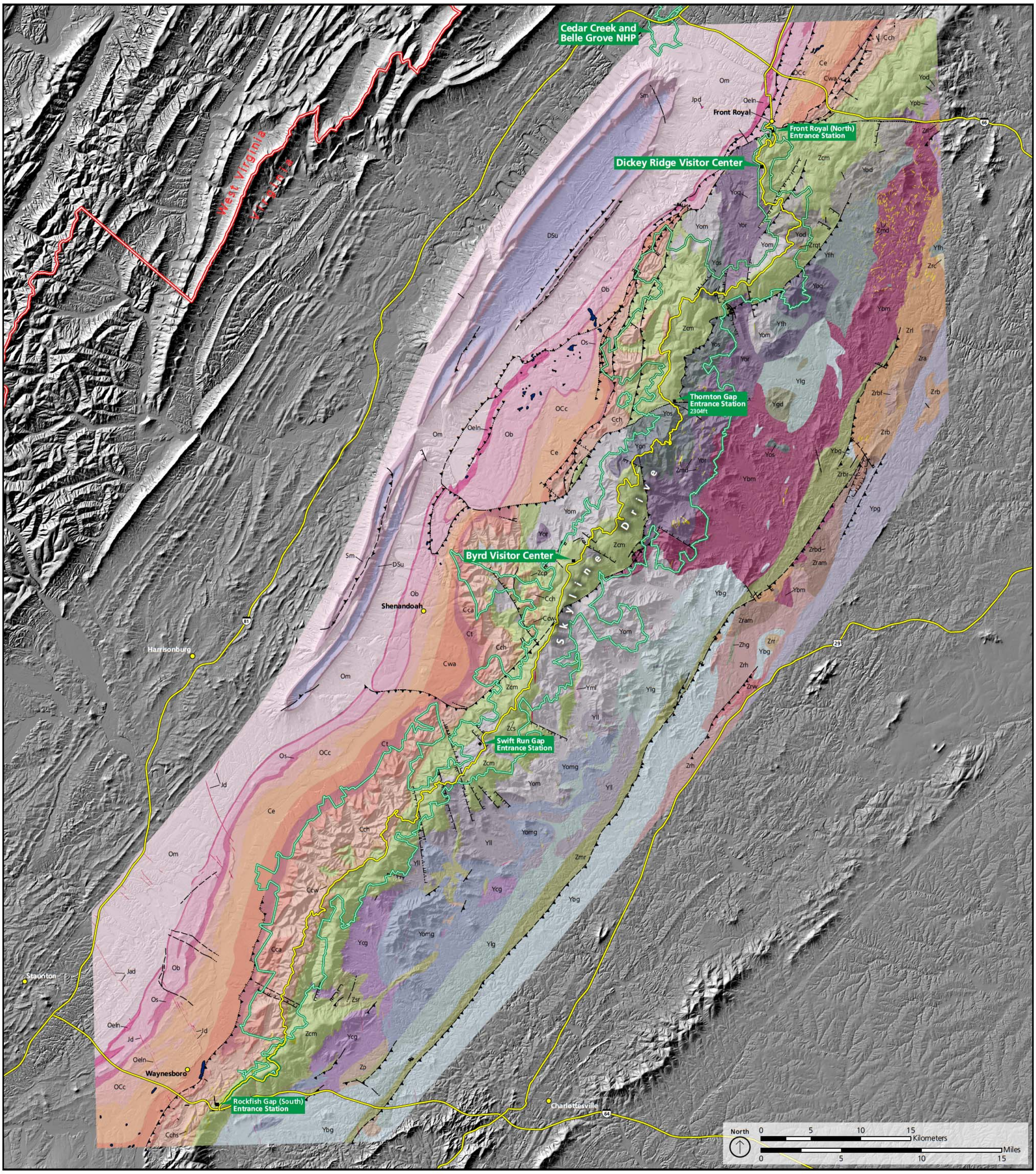
Geologic Resources Inventory

National Park Service
U.S. Department of the Interior

Surficial Geologic Map of Shenandoah National Park, Virginia



Bedrock Geologic Map of Shenandoah National Park, Virginia



NPS Boundary

Infrastructure

- points of interest
- cities
- roads

State Line

Faults

- unknown offset/displacement or tear fault
- normal fault, bar on downthrown side
- thrust fault, sawteeth on upper plate

dashed where approximately located; dotted where concealed; and queried where uncertain

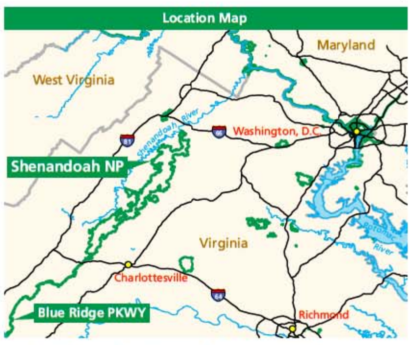
Karst Features

- large sinkholes

Bedrock Units

Jpd	Peridotite dike
Jad	Alkalic dike
Jd	Diabase dike
DSu	Devonian and Silurian rocks, undivided
Sm	Massanutten Sandstone
Om	Martinsburg Formation
Oeln	Edinburg Formation, Lincolnshire Limestone, and New Market Limestone, undivided
Ob	Beekmantown Group, undivided
Os	Stonehenge Limestone
OCc	Conococheague Limestone
Ce	Elbrook Limestone
Cwa	Waynesboro Formation
Ct	Tomstown Formation
Cca	Antietam Formation
Cch	Harpers Formation
Cchs	Harpers Formation, ferruginous metasandstone
Ccw	Weverton Formation
Zcp	Catoctin Formation, metavolcanic phyllite
Zcs	Catoctin Formation, metasandstone and laminated phyllite
Zcr	Catoctin Formation, metarhyolite
Zcm	Catoctin Formation, metabasalt
Zmd	Metadiabase dike
Zsr	Swift Run Formation
Zhg	Hornblende metagabbro dike and (or) sill
Zmr	Mechum River Formation
Zra	Amissville Alkali Feldspar Granite
Zrb	Battle Mountain Alkali Feldspar Granite
Zrbr	Rhyolite and metaconglomerate
Zrbf	Felsite
Zrbd	Felsic dike
Zrh	Hitt Mountain Alkali Feldspar Syenite
Zrqt	Quartz trachyte
Zrc	Cobbler Mountain Alkali Feldspar Quartz Syenite
Zrw	White Oak Alkali Feldspar Granite
Zrl	Laurel Mills Granite
Zram	Arrington Mountain Alkali Feldspar Granite
Zrr	Rivanna Granite
Zp	Garnet-graphite paragneiss
Ybg	Biotite monzogranite-quartz monzodiorite
Yom	Orthopyroxene monzogranite-quartz monzodiorite
Ypb	Megacrystic quartz monzonite
Ybm	Megacrystic biotite monzogranite
Ycg	Crozet Granite
Yor	Old Rag Granite
Yml	Porphyroclastic metagranitoid
Yog	Orthopyroxene granite-monzogranite
Yfh	Flint Hill Gneiss
Yll	Lineated leucogranite gneiss
Yomg	Orthopyroxene monzogranite-quartz monzodiorite gneiss
Yos	Megacrystic orthopyroxene syenogranite-monzogranite gneiss
Ygd	Granodiorite gneiss
Yoq	Orthopyroxene quartz diorite gneiss
Yon	Orthopyroxene syenogranite and monzogranite gneiss
Yod	Orthopyroxene granodiorite gneiss
Ypg	Foliated, garnetiferous, porphyroblastic monzogranite
Ylg	Leucogranite gneiss

Location Map



This map is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. It is not a substitute for site-specific investigations.

The source map used in creation of the digital geologic data was:

Southworth, S., Aleinikoff, J.N., Bailey, C.M., Burton, W.C., Crider, E.A., Hackley, P.C., Smoot, J. P., and Tollo, R.P. 2009. Geologic Map of the Shenandoah National Park Region, Virginia (1:100,000 scale). Open-File Report 2009-1153. U.S. Geological Survey.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are within 51 m (166 ft) 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.

Map Unit Properties Table: Shenandoah National Park

Gray-shaded map units are not mapped within Shenandoah National Park. Bold text refers to sections in report. Primary source for geologic descriptions is Southworth et al. (2009).

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene)	Alluvium (Qa)	**Qa** consists of unconsolidated (not solidified) deposits of (by increasing grain size) silt, sand, cobbles, and boulders with a total thickness up to 12 m (40 ft). This unit is associated with fluvial processes and is deposited along streams, floodplains, riparian areas, and alluvial plains. At higher elevations, coarser grain sizes such as boulders dominate units of **Qa**. Further downslope, the alluvium mixes with debris fans (see **Qdf** and **Nf**).	**Surficial Deposits**—Deposited by flowing water. Alluvium is ubiquitous along park streams and rivers reflecting the most recent part of the park's geologic history.	**Slope Movements**—unconsolidated units such as **Qa** are prone to erosion when exposed on slopes or undercut by streams. **Surface Water and Sediment Loading**—**Qa** is associated with surface water features such as streams and rivers. **Groundwater Quantity and Quality**—surface water percolates through **Qa** to recharge underlying aquifers. **Disturbed Lands**—sand and gravel resources occur within **Qa**. Locally, thick deposits of alluvium resulted from increased erosion during deforestation and agriculture of the 1800s.	**Appalachian Mountain Erosion and Ice Age Glaciation**—youngest geologic map units occurring on the landscape at Shenandoah National Park. These units reflect the ongoing processes of weathering and erosion within the Appalachian Mountains as sediments are transported downslope toward the Coastal Plain.
	Debris-flow deposits (Qdf)	**Qdf** consists of boulders and finer-grained matrix material deposited in chutes within bedrock and unconsolidated regolith. Tracks and scars scratched by the flow of these deposits occur in the Blue Ridge highlands. Flows of **Qdf** are triggered by high rainfall events.	**Surficial Deposits**—**Qdf** occurs at the base of coves and hollows on the upper to lower slopes of the Blue Ridge highlands. Deposited by slope movements.	**Slope Movements**—**Qdf** forms via mass wasting processes of debris flows and slides. When located in areas of infrastructure, debris flows can cause serious damage and threat to human safety. Measured velocities from 1995 debris flows were as much as 24 m/sec (79 ft/sec). Climate models predict more frequent and intense storm events for the park area; strong storms may trigger additional debris flows. Scars associated with the formation of **Qdf** can remain unvegetated for decades. **Surface Water and Sediment Loading**—heavy precipitation triggers debris flows on steep slopes of the Blue Ridge Mountains. **Earthquakes**—could trigger mass movements on steep slopes, particularly in wet conditions.	
QUATERNARY (Holocene and Pleistocene)	Quartzite block-field deposits (Qb)	**Qb** contains rather angular block and boulders of lichen-covered quartzite with very little interstitial (matrix) material between the blocks. Deposits of **Qb** tend to accumulate on nonvegetated slopes of ridges composed of erosion resistant quartzite of the Chilhowee Group (see **Ccw**, **Cchs**, **Cch**, and **Cca**). Thickness of **Qb** is variable.	**Surficial Deposits**—block fields are concentrated in the highland slopes of the park. They are well-developed on ridges underlain by metamorphosed sandstone and quartzite such as the Chilhowee Group (**Ccw**, **Cch**, and **Cca**). Typically formed by frost-wedging. **Periglacial Features**—**Qb** likely formed during cooler climates as frost wedging created quartzite blocks. **Paleontological Resources**—may contain Pleistocene-age fossils. **Connections with Park Stories**—quartzite was used by American Indians for tools. Only scant vegetation can develop on **Qb** and the unit was largely undisturbed during early settlement.	**Slope Movements**—**Qb** forms through mass wasting processes such as frost weathering. Rockfall and topples proceed as blocks are weathered from the bedrock outcrop and fall downslope. **Bedrock Outcrop Management**—the erosion-resistant quartzites that weather to produce deposits of **Qb** tend to form cliffs and ridges. **Earthquakes**—could trigger mass movements of blockfall- and topple-prone deposits on steep slopes.	**Appalachian Mountain Erosion and Ice Age Glaciation**—units reflect colder climatic conditions during the Pleistocene ice ages when frost weathering dislodged millions of blocks of rock from bedrock outcrops to litter the slopes below. Process continues at a subdued rate today.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
QUATERNARY (Holocene and Pleistocene)	Colluvium (Qc)	Colluvium is similar to **Qb** in that it contains clast-supported, rather angular to slightly rounded cobbles and boulders. As with **Qa**, **Qc** grades downslope into debris-fan deposits (see **Qdf** and **Nf**). Thickness of **Qc** can reach up to 30 m (100 ft).	**Surficial Deposits**—colluvium is concentrated in the highlands of the park. Typically formed by frost-wedging. **Periglacial Features**—most **Qc** is a relict deposit from the periglacial climates of the Pleistocene formed by forces and processes such as gravity, solifluction, freeze-thaw cycles, ice wedging, and frost heaving. **Paleontological Resources**—may contain Pleistocene-age fossils.	**Slope Movements**—**Qc** is formed by myriad mass wasting processes and is present at the base of slopes throughout the park area. **Bedrock Outcrop Management**—**Qc** collects at the base of steep slopes and cliffs. **Earthquakes**—could trigger mass movements on steep slopes.	**Appalachian Mountain Erosion and Ice Age Glaciation**—units reflect colder climatic conditions during the Pleistocene ice ages when frost weathering dislodged millions of blocks of rock from bedrock outcrops to litter the slopes below. Process continues at a subdued rate today.
NEOGENE	Terrace deposits (Nt)	**Nt** comprises unconsolidated, sorted sand, gravel, cobbles, and boulders. It is associated with major rivers in the park area. Deposits of **Nt** can reach 9 m (30 ft) in thickness. Terraces frequently occur as much as 9 m (30 ft) above the modern floodplain, but **Nt** also includes older terraces as much as 60 m (197 ft) in elevation above the active floodplain.	**Surficial Deposits**—deposited by flowing water. Terrace deposits are located along major rivers in the valleys of the park area. **Periglacial Features**—terraces may have formed as material destabilized from upland surfaces during following the colder climates of the Ice Age; frost-bound debris provided a pulse of increased sediment load of which the terraces are remnants. **Paleontological Resources**—may contain Neogene-age fossils.	**Slope Movements**—elevated terraces, perched some 60 m (197 ft) above modern floodplains may be prone to mass wasting. Much of the finer, unconsolidated material has already eroded away, leaving boulders and cobbles. **Surface Water and Sediment Loading**—**Nt** is associated with major rivers, flanking the sides of the valley. These are left perched along stretches of the valley to record previous, higher river levels.	**Appalachian Mountain Erosion and Ice Age Glaciation**—units reflect a long history of erosion and landscape change within the park area. These units formed through earth surface processes active from 23 to 2.6 million years ago.
	Alluvial-plain deposits (Np)	**Np** covers broad areas of coalescing terraces (**Nt**) along major rivers in the lowlands east of the Blue Ridge highlands. As such, it contains similar deposits and records the former locations of the major rivers meandering across the landscape.	**Surficial Deposits**—deposited by flowing water. Alluvial-plain and alluvial-fan deposits are located on the lower slopes and valleys on the western and eastern flanks of the Blue Ridge, respectively. **Paleontological Resources**—may contain Neogene-age fossils.	**Surface Water and Sediment Loading**—**Np** records the previous locations of major rivers meandering across the lowland topography. **Disturbed Lands**—sand and gravel resources occur within **Np**.	
	Debris-fan deposits (Nd)	**Nd** forms fans and sheets as much as 30 m (98 ft) thick on lower slopes and valleys. The deposits consist of a jumbled mixture of pebbles, cobbles, and boulders that are only partially rounded by weathering. These coarse components are supported in a matrix of unstratified and unconsolidated clay, silt, sand, and pebbles. All the deposits come from local bedrock, and their morphology and topographic setting vary with bedrock type. Some portions of **Nd** are actually terraces of debris fans as much as 36 m (118 ft) above adjacent fans and alluvium (**Qa**).	**Surficial Deposits**—deposited by slope movements. Debris-fan deposits are concentrated in coves and hollows on the upper to lower slopes within the park, particularly where underlain by gneiss of metabasalts. **Type Sections, Reference Locations, and Radiometric Ages**—radiocarbon (C^{14}) ages from fans along Kinsey Run ranged from 51,000 to 2,000 years before present, individual flow events recur on average of every 2,500 years. Cosmogenic Be^{10} and Al^{26} dates from exposed boulders in the same area suggest the fan surfaces are older than 500,000 years before present. **Periglacial Features**—**Nd** formed during glacial and interglacial transitions as warm and cold cycles fluctuated and severe storms were common. **Paleontological Resources**—may contain Neogene-age fossils.	**Slope Movements**—**Nd** forms downslope from debris flows and slides. This unit contains a valuable record of the history of mass wasting in the park area and is the dominant Cenozoic deposit of the unglaciated highlands of the Appalachians. **Disturbed Lands**—early settlers, while developing land for pasture, removed the boulders and cobbles making conical piles, terraces, and/or fences.	

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NEOGENE	Alluvial-fan deposits (Nf)	**Nf** contains unconsolidated sand, pebbles, cobbles, and boulders of quartzite and sandstone (derived from **Cca**, **Cch**, and **Cchs**). Fans and sheets of coalesce to form aprons extending from the lower west slope of Blue Ridge to the South Fork of the Shenandoah River. Thickness of **Nf** is variable, but can exceed 150 m (500 ft) in areas where the deposits have not been significantly reworked by later alluvial (stream) processes.	**Surficial Deposits**—deposited by flowing water. Alluvial-plain and alluvial-fan deposits are located on the lower slopes and valleys on the western and eastern flanks of the Blue Ridge, respectively. Commonly mantles carbonate (limestone or dolomite/dolostone) bedrock **Paleontological Resources**—may contain Neogene-age fossils. **Cave and Karst Features**—**Nf** has surface expressions of sinkholes and water-filled depressions.	**Slope Movements**—unconsolidated units such as **Nf** are prone to erosion when exposed on slopes or undercut by streams. **Groundwater Quantity and Quality**—surface water percolates through **Nf** to recharge underlying aquifers. These fans host the only aquifer of unconsolidated sediments west of the Coastal Plain province in Virginia. **Disturbed Lands**—sand and gravel resources occur within **Nf**. **Nf** also forms a "trap" for manganese deposits weathering out of carbonate units (**Ct** and **Cca**) along the western slope of the Blue Ridge (Page Valley area). **Cave and Karst Hazards**—sinkholes and water-filled depressions in **Nf** attest to karst formation in underlying bedrock.	**Appalachian Mountain Erosion and Ice Age Glaciation**—units reflect a long history of erosion and landscape change within the park area. These units formed through earth surface processes active from 23 to 2.6 million years ago.
JURASSIC (Late)	Peridotite dike (Jpd)	Peridotite is a silica-poor rock composed of olive and other mafic minerals with virtually no feldspar. Dikes are igneous intrusions that cut across the fabric of the local bedrock. **Jpd** occurs in a discrete, 182-m (597-ft) long, 46-m (151-ft) wide, elliptical igneous intrusion into **Om** west of Front Royal, Virginia. This localized unit contains olivine and pyroxene minerals which have altered to chlorite, phlogopite, biotite, ankerite, and talc.	**Ancient Bedrock**—molten material that would become dikes was emplaced in fractured rock, which formed as Pangaea rifted apart.	**Disturbed Lands**—peridotites often contain unusual minerals that may be targets for mining.	**Pangaea Separation, Atlantic Ocean Formation, and Appalachian Mountains Erosion**—of these units, the only Mesozoic rocks in the park are diabase dikes, **Jd**. They represent a shift in tectonic setting from plates coming together to the supercontinent Pangaea rifting apart. At this time, extension of Earth's crust was occurring along the eastern side of North America.
JURASSIC (Late)	Alkalic dikes (Jad)	**Jad** occurs in a series of discrete, northwest-trending vertical dikes consisting of nepheline syenite, teschenite, and teschenite-picrite. Similar to **Jpd**, **Jad** intrudes **Om**, but west of the Grottoes.	**Ancient Bedrock**—molten material that would become dikes was emplaced in fractured rock, which formed as Pangaea rifted apart. **Type Sections, Reference Locations, and Radiometric Ages**—**Jad** yielded an age of 157±8 to 148±7 million years ago.	None reported.	
JURASSIC (Early)	Diabase dikes (Jd)	**Jd** consists of medium to dark gray, crystalline (visible crystals) and equigranular (crystals of similar grain size), massive diabase (see **Zmd**) dikes. The diabase varies in composition between olivine-bearing and quartz-bearing and has clusters of calcic plagioclase feldspar in a fine-grained groundmass (matrix) of pyroxene and plagioclase. Weathering of **Jd** produces characteristic orange-brown surfaces.	**Ancient Bedrock**—molten material that would become dikes was emplaced in fractured rock, which formed as Pangaea rifted apart. **Type Sections, Reference Locations, and Radiometric Ages**—**Jd** yielded an age of 200 million years ago.	**Slope Movements**—**Jd** weathers to produce boulders that may tumble downslope. **Bedrock Outcrop Management**—**Jd** weathers to produce staircases.	

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DEVONIAN and SILURIAN	Devonian and Silurian rocks, undivided (DSu)	Mahantango Formation: Unit consists of gray mudstone, sandstone, and shale that is locally fossiliferous. Needmore Shale: Unit contains greenish gray shale and calcareous (containing calcium carbonate) mudstone that are fossiliferous with a base of black shale. Tioga Ash Bed: Unit includes a distinctive brown-biotite bearing calcareous ash bed; gray shale and siltstone; and black, fissile (easily parted) shale. Marcellus Shale, undivided: Unit contains dark gray to black, fissile shale with some gray, silty limestone and calcareous shale beds interlayered. Ridgeley Sandstone: Unit is primarily calcareous and fossiliferous sandstone appearing light gray in outcrop with fine- to coarse-grained (locally conglomeratic) textures and cross-laminated sedimentary structures. Helderberg Group: An upper sandy portion of this unit grades downward into light gray, laminated to thick-bedded limestone with black nodular chert and white blocky chert. Keyser Limestone: Unit is mostly gray limestone, some of which is fossiliferous and some contains black, nodular chert and white blocky chert. Tonoloway Limestone: Unit is gray, laminated limestone with mudcracks as sedimentary features. Wills Creek Formation: Unit contains gray limestone with greenish gray siltstone and mudstone that is calcareous. Bloomsburg Formation: Distinctive unit of red mudstone interlayered with red, ferruginous (iron-bearing) sandstone and shale. McKenzie Formation: Unit consists of gray, calcareous shale.	**Ancient Bedrock**—these units contain mudcracks, cross laminations, and turbidite sedimentary structures. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of synclinorium. **Paleontological Resources**—some units contain fossils. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. **Connections with Park Stories**—although extraction was primarily focused north and west of the park in the northern Shenandoah Valley, chert nodules in these units may have provided tool and trade material for American Indians.	**Slope Movements**—dissolution of calcareous portions of these units may render them susceptible to mass wasting and undercutting. **Groundwater Quantity and Quality**—dissolution-enlarged conduits within the calcareous portions of this unit may more readily transmit groundwater than adjacent units. **Disturbed Lands**—American Indians extracted chert from **DSu**. Ferruginous (iron-bearing) rocks may have been targeted for iron mining. **Cave and Karst Hazards**—calcareous layers and limestones are prone to dissolution.	**Acadian–Neoacadian Orogeny**—influx of clastic sediment from Acadian Orogeny. Ash beds in the Tioga Ash Bed mark the eruption of island-arc volcanoes associated with the Acadian Orogeny, north of the park area, 390 to 374 million years ago. The Mahantango Formation is the youngest formation preserved in the core of the Massanutten synclinorium. It is exposed in Fort Valley.
SILURIAN	Massanutten Sandstone (Sm)	**Sm** consists of light gray sandstone. The unit is fine to coarse grained and in places considered conglomeratic. **Sm** exhibits cross lamination sedimentary structures. **Sm** crops out as ridges of Massanutten Mountain. Correlative with the Tuscarora Sandstone, named for exposures in Pennsylvania.	**Ancient Bedrock**—**Sm** contains cross-lamination sedimentary structures. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of synclinorium.	**Slope Movements**—where unit is exposed on slopes, it may be prone to rockfall.	None reported.
ORDOVICIAN (Upper and Middle)	Martinsburg Formation (Om)	**Om** contains light brown shale, calcareous shale, and siltstone. The upper portions of this unit contain layers of sandstone and metagraywacke, whereas the basal portions of the unit contain argillaceous (clay-rich) limestone. **Jpd** and **Jad** intrude this unit locally.	**Ancient Bedrock**—**Om** contains turbidite deposits with typical Bouma cycles and load casts. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—may contain bioturbated beds, algal bioherms, and algal limestone. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit.	**Slope Movements**—dissolution of calcareous portions of this unit may render certain layers susceptible to mass wasting and undercutting. **Groundwater Quantity and Quality**—dissolution-enlarged conduits within the calcareous portions of this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**— calcareous layers and limestones are prone to dissolution, but probably not enough limestone is present to cause significant issues.	**Taconic Orogeny**—siliciclastic rocks in **Om** records an inundation of the continental margin as sea level was rising—shallow-water carbonates were shifting towards deepwater clastic sediments.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
ORDOVICIAN (Middle)	Edinburg Formation, Lincolnshire Limestone, and New Market Limestone, undivided (Oeln)	**Oeln** consists of three components: (1) gray to black, fossiliferous limestone and black shale; (2) gray, fossiliferous, and cherty limestone; and (3) bluish gray, micritic (extremely fine-grained) limestone. **Oeln** is only exposed as a narrow band on limestone within the Great Valley section	**Ancient Bedrock**—the Edinburg Formation contains yellowish brown volcanic ash or bentonite beds. **Type Sections, Reference Locations, and Radiometric Ages**—similar volcanic ash beds elsewhere were dated at 470±1.4 and 451±4 million years ago. **Paleontological Resources**—some units contain fossils. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit. **Connections with Park Stories**—although extraction was primarily focused north and west of the park in the northern Shenandoah Valley, chert nodules in these units may have provided tool and trade material for American Indians.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within the limestone portions of this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**—limestones are prone to dissolution. **Disturbed Lands**—American Indians extracted chert from **Os**.	**Passive Margin**—**Ob** and **Oeln** are separated by an angular unconformity marking a shift from passive margin deposition to an active margin (convergent margin) as the Taconic Orogeny was beginning.
ORDOVICIAN (Lower and Middle)	Beekmantown Group, undivided (Ob)	**Ob** consists of light gray dolostone layered with thinly laminated dolostone that contains white and light gray chert nodules. Collapse breccia and paleokarst occur in the upper portions of the unit.	**Ancient Bedrock**—**Ob** features paleokarst features in the upper portions including collapse breccia. This indicates the unit was once exposed near the surface before being buried again during mountain building and re-exposed. Weathered joints in **Ob** render a "butcher-block" pattern on the surface. **Ob** contains a paleorecord of karst features and processes. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—may contain bioturbated beds, algal bioherms, and algal limestone. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Hosts Luray Caverns and Skyline Caverns. Sinkholes developed in this unit. **Connections with Park Stories**—although extraction was primarily focused north and west of the park in the northern Shenandoah Valley, chert nodules in this unit may have provided tool and trade material for American Indians. **Ob** was locally altered to yellow jasper beneath the Front Royal Fault. This was quarried by American Indians at the Flint Run Archeological District.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within the dolostone portions of this unit may more readily transmit groundwater than adjacent units. **Disturbed Lands**—American Indians extracted chert and jasper from **Ob**. **Cave and Karst Hazards**—calcareous dolostones are prone to dissolution though less soluble than limestone.	**Passive Margin**—**Ob** and **Oeln** are separated by an angular unconformity marking a shift from passive margin deposition to an active margin (convergent margin) as the Taconic Orogeny was beginning.
ORDOVICIAN (Lower)	Stonehenge Limestone (Os)	**Os** contains dark gray, fossiliferous limestone with fine- to medium-grained textures. Minor black chert occurs within the limestone as do interlayers of light gray, laminated, silty limestone; platy limestone; coarse-grained bioclastic (contains fragments of fossil organisms) limestone; gray fossiliferous limestone and crystalline dolostone with fine- to medium-grained textures; and dark gray chert nodules.	**Paleontological Resources**—**Os** includes algal bioherms, and bioclastic layers. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit. **Connections with Park Stories**—although extraction was primarily focused north and west of the park in the northern Shenandoah Valley, chert nodules in this unit may have provided tool and trade material for American Indians.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**—limestones and dolostones are prone to dissolution. **Disturbed Lands**—American Indians extracted chert from **Os**.	**Passive Margin**—**Os** contains a record of the abundant life flourishing along the passive margin prior to the onset of the Taconic Orogeny.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
ORDOVICIAN (Lower) and CAMBRIAN (Upper)	Conococheague Limestone (OCc)	**OCc** contains light gray, sandstone that ranges in composition from calcareous to dolomitic; gray, fine-grained limestone and intraformational, coarse-grained conglomerate; light gray, fine-grained dolostone with gray laminated algal limestone; dolomitic limestone; and light brown dolostone with calcareous sandstone.	**Ancient Bedrock**—bioturbated beds **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—**OCc** contains algal limestone and bioturbated beds. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within the calcareous, limestone, and dolostone portions of this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**—limestones and dolostones are prone to dissolution.	**Passive Margin**—**OCc** records the conditions locally present during the transition from Cambrian to Ordovician time as cyclic incursions of sandy sediment spread onto the carbonate platform.
CAMBRIAN (Upper and Middle)	Elbrook Limestone (Ce)	**Ce** consists of gray limestone with white marble interlayered throughout. Some light brown, laminated dolostone, and thin, calcareous shale and shaly dolostone are interlayered locally as well.	**Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—**Ce** elsewhere contains trilobite fossils. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within the calcareous, limestone, and dolostone portions of this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**—limestones and dolostones are prone to dissolution.	**Passive Margin**—marble in **Ce** records metamorphism affecting this unit.
CAMBRIAN (Lower)	Waynesboro Formation (Cwa)	**Cwa** includes three distinct subunits: (1) light olive-gray shale interbedded with light gray, fine-grained sandstone and darker gray, sandy, dolomitic limestone; (2) gray, bioturbated dolostone interlayered with dolomitic limestone, laminated limestone, and some scant sandy limestone beds in the middle portions of the subunit; and (3) dusky red shale, mudstone, and argillaceous (clay-rich) sandstone interlayered with light gray sandstone and light-brown, sandy, dolomitic limestone and dolostone.	**Paleozoic Sedimentary Rocks and Metamorphism**—contains bioturbated layers, and sedimentary features such as ripple marks, cross-beds, and mudcracks. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—may contain bioturbated beds, algal bioherms, and algal limestone. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit.	**Slope Movements**—dissolution of carbonate-rich portions of **Cwa** may render certain layers susceptible to mass wasting and undercutting particularly in cases where shales or sandstones are undercut on slopes. **Groundwater Quantity and Quality**—dissolution-enlarged conduits within the carbonate portions of this unit may more readily transmit groundwater than adjacent units. **Cave and Karst Hazards**—carbonate layers (limestones, dolostones, and calcareous portions) within **Cwa** are prone to dissolution.	**Passive Margin**—siliciclastic rocks in **Cwa** may record a pulse of continental sediment or a marine regression.
	Tomstown Formation (Ct)	In general, **Ct** contains gray limestone, dolostone, and marble. During mapping, four subunits were combined: (1) dark gray, fine-grained limestone exhibiting wispy dolomitic burrow traces that increase towards the top of the subunit, and some gray to white, mylonitic (highly deformed) marble; (2) dark gray, burrowed dolostone; (3) light gray, sugary (texture resembles sugar crystals) dolostone with cross-bedding sedimentary features; (4) dark gray, bioturbated dolostone with limestone underlying dark gray, bioturbated, oolitic (containing tiny pearl-like balls of sediment) dolostone interlayered with limestone and silty dolostone.	**Blue Ridge-South Mountain Anticlinorium and Regional Structures**—transported westward along thrust faults, exposed in Valley and Ridge province. **Paleontological Resources**—unit contains metamorphosed remnants of burrows and bioturbated (rummaged through by bottom feeders) sediments. **Cave and Karst Features**—karst topography is well-developed in the Great and Page valleys. Sinkholes developed in this unit.	**Groundwater Quantity and Quality**—dissolution-enlarged conduits within the carbonate portions of this unit may more readily transmit groundwater than adjacent units. **Disturbed Lands**—manganese deposits from **Ct** and its contact with **Cca** were mined on the western slope of the Blue Ridge. **Cave and Karst Hazards**—carbonate layers (limestones, dolostones, and calcareous portions) within **Ct** are prone to dissolution.	**Passive Margin**—**Ct** records the passive continental margin that existed along the eastern coast of the ancient continent Laurentia—a change from a shallow, carbonate shelf to a deepwater shelf, then to a carbonate bank.

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
CAMBRIAN (Lower)	Chilhowee Group	Antietam Formation (Cca)	**Cca** is locally olive gray, medium- to coarse-grained silty metasandstone and quartzite with very fine-grained, silty layers present. Some layers are ferruginous (iron-bearing) and micaceous (contain flashy, platy minerals).	**Ancient Bedrock**—**Cca** contains a coarsening-upward sequence, bioturbated beds, and cross-bedding sedimentary features. **Cch** contains upward-coarsening sequences and wavy lamination sedimentary features. **Ccw** contains upward-coarsening sequences, wavy laminations, and cross-bedding sedimentary features. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed on flanks of anticlinorium. **Bedrock Outcrop Habitats**—**Cca:** Central Appalachian acidic boulderfield. **Cch** and **Cchs**: Sweet-birch-chestnut oak talus woodland; Central Appalachian heath barren; Central Appalachian acidic boulderfield; Central Appalachian high-elevation boulderfield forest; and Central Appalachian xeric chestnut oak-Virginia pine woodland. **Paleontological Resources**—trace fossils, most prevalently the worm burrow, *Skolithos linearis*, occur in quartzite beds within **Cca**. Elsewhere **Cca** may contain other trace fossils and rare body fossils. trace fossils, most commonly the worm burrow, *Skolithos linearis*, occur in pure quartzite beds in the upper part of **Cch**. These are the oldest fossils in the park and the Mid-Atlantic Inventory and Monitoring Network. Metasiltstone and, locally, quartzite within **Ccw** is heavily bioturbated. **Cave and Karst Features**—Sinkholes developed in this unit. **Connections with Park Stories**—quartzite was used by American Indians for tools. Trace fossils are visible in some of the guardrails along Skyline Drive. Blocks of **Cca** were used in park infrastructure such as guardrails, retaining walls, building foundations, and fences. May have been used as flagstones in front of The Byrd's Nest. Dark quartzite at Blackrock is **Cch**. **Cch** is well-exposed along Big Run.	**Slope Movements**—erosion-resistant metasandstones and quartzites underlie local ridges and could be prone to rockfall and topple. **Bedrock Outcrop Management**—these units tend to form mixtures of isolated outcrops, ledges, and open talus fields. Examples of Rock Outcrop Management Project sites include Blackrock South District, Calvary Rocks-Chimney Rock, Rocky Mountain, Trayfoot Saddle boulderfields west, Trayfoot Saddle boulderfields east, and Brown Mountain. **Surface Water and Sediment Loading**—Chilhowee Group rocks with lesser pyroxene and feldspar minerals lack acid-neutralizing capabilities. Chilhowee Group (e.g., **Cchs** and **Ccw**) may locally contain high amounts of iron sulfide minerals that would increase the acidification of a stream or watershed, especially in areas that were disturbed by mining. **Disturbed Lands**—ferruginous (iron-bearing) rocks may have been targeted for iron mining. Manganese deposits from the contact between **Cca** and **Ct** were mined locally on the western slope of the Blue Ridge.	**Continued Opening of the Iapetus Ocean and Transition to a Passive Margin**—the Chilhowee Group is mostly restricted to the western slope of Blue Ridge, but locally occurs along Skyline Drive near the crest in the southern and northern parts of the park. It unconformably overlies the Catoctin Formation indicating a period of erosion following volcanism. The pure quartzite within **Cca** suggests a beach or bar depositional environment with occasional sea level fluctuations represented by silty layers. The trace fossils and sand- and silt-rich composition of these units suggest the depositional environment was a beach or nearshore marine setting. They reflect fluvial to shallow-marine transgressive and regressive environments as the tectonic setting shifted from rifting into a passive margin along the eastern side proto-North America (Laurentia) as the Iapetus Ocean basin continued to widen.
		Harpers Formation (Cch) Harpers Formation, ferruginous metasandstone (Cchs)	**Cch** is greenish to bluish gray phyllite and metasiltstone. The phyllite contains quartz, chlorite, and sericite as the definitive mineral constituents. Interlayered in the phyllite and metasiltstone are thin gray metasandstones, quartzite, and meta-arkose (a feldspar-rich sandstone). Locally, lower portions of **Cch** include green and brown metasiltstone and some metasandstones. In the northern areas of the park some coarse, pebbly metasandstones and metaconglomerate occur in the lower part beneath vitreous (glassy) quartzite and ferruginous, arkosic metasandstones. **Cchs** is maroon to dark blue to black, ferruginous (iron-bearing) metasandstones. It occurs only locally.			
		Weverton Formation (Ccw)	**Ccw** contains maroon and gray phyllite and discrete beds of pebbly quartzite interlayered with siltstone and metaconglomerate in the basal portions of the unit. In the southern part of the park, light tan to brown, pebbly and maroon, ferruginous metasandstones overlie the phyllite. In the northern part of the park, the metasiltstone is heavily bioturbated and blocky quartzite beds occur throughout beneath a cap of pebbly metasandstones and metaconglomerate. The coarse metasedimentary rocks exhibit cross-bedding sedimentary features.			

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<table>
<tr><th>Age</th><th colspan="2">Map Unit (Symbol)</th><th>Geologic Description</th><th>Geologic Features and Processes</th><th>Geologic Issues</th><th>Geologic History</th></tr>
<tr><td rowspan="5">NEOPROTEROZOIC ERA</td><td rowspan="4">Catoctin Formation</td><td>Metavolcanic phyllite (Zcp)</td><td>Phyllite is a metamorphic rock rich in flaky minerals—micas. Zcp is dark, multi-colored (gray, blue, reddish) phyllite exhibiting relict white to green elongated (deformed) vesicles and smeared blebs of sericite and chlorite. In outcrop the exposures appear mottled to lustrous.</td><td rowspan="4">Ancient Bedrock—the Catoctin Formation is an important widespread geologic unit in the area. It exhibits abundant relict igneous features including vesicles (bubbles), amygdules, flow patterns, ashfall, polygonal columnar cooling joints, and submarine pillows. Volcanic breccias mark the base of the individual flows. Where molten lava altered the surface of the basement rocks (contact metamorphism), the underlying rocks (sands and gneisses) were bleached and changed to unakite (containing pink potassium feldspar, quartz, and yellowish green epidote), which is the unofficial state stone of Virginia. Flows as much as 82 m (269 ft) thick locally flowed across the landscape filling valleys and covering adjacent hills.

Type Sections, Reference Locations, and Radiometric Ages—Zcr yielded an age of approximately 569 million years ago. The Catoctin Formation is well-exposed throughout the park with particular study locations at Stony Man, North and South Marshall, Compton Peak, roadcuts along U.S. Interstate Route 64, Big Meadows, and the Hawksbill-Spitler Hill area.

Blue Ridge-South Mountain Anticlinorium and Regional Structures—exposed on flanks of anticlinorium.

Bedrock Outcrop Habitats— Central Appalachian basic woodland; Central Appalachian acidic boulderfield; Central Appalachian mafic boulderfield; Central Appalachian circumneutral barren; sweet-birch-chestnut oak talus woodland; Central Appalachian high-elevation boulderfield forest; high-elevation outcrop barren; Central Appalachian mafic barren; high-elevation greenstone barren; and Central Appalachian xeric chestnut oak-Virginia pine woodland. Zcm caps some of the highest points of the park, including Hawksbill Mountain (peregrine falcon habitat). Weathering of the Catoctin Formation contributes to magnesium- and iron-rich soils. Chestnut oak and red oak are common on ridgetops and higher elevation locations underlain by Catoctin Formation greenstones. Greenstone typically forms cliffs and ledges with some open talus areas.

Connections with Park Stories—greenstone was used by American Indians for tools.</td><td rowspan="4">Slope Movements—the Catoctin Formation features prominently in the upland areas of the park and is prone to rockfall and topple.

Bedrock Outcrop Management—these units tend to form mixtures of outcrops of cliffs and ledges, and some open talus fields. Examples of Rock Outcrop Management Project sites include Bettys Rock, Big Devils Stairs, Blackrock Central District, Browntown Valley Overlook, Crescent Rock Overlook, Crescent Rock South, Dean Mountain Ridge, Dickey Hill, Dickey Ridge, Franklin Cliffs North, Franklin Cliffs South, Goat Ridge, Gooney Manor overlook, Halfmile Cliff, Hawksbill north slope outcrops, Hawksbill Summit, Hightop, Little Devils Stairs, Little Stony Man, Stony Man Summit, Loft Mountain Summit, North Marshall Summit, Overall Run Falls south, Overall Run Falls north, Pass Mountain, Sawlog Ridge, Stony Man north slope, South Marshall Cliff, Hawksbill North slope talus, Field Hollow Cliff, Bearfence Mountain, Rose River Cliffs, and Whiteoak Canyon.

Surface Water and Sediment Loading —carbonate rocks (limestones) and the pyroxene and feldspar-rich (greenstones or altered basalts) Catoctin Formation neutralize acid precipitation. Some sedimentary units in the Catoctin Formation may also contain significant amounts of sulfides and contribute to increased acidification.

Disturbed Lands—Ferruginous (iron-bearing) rocks may have been targeted for iron mining. Copper oxides, sulfides, and native copper occur sporadically in Zcm.</td><td rowspan="4">Rifting of Rodinia and Opening of the Iapetus Ocean—these units record an extensional, rifting event following the Neoproterozoic Grenville Orogeny that ultimately opened the Iapetus Ocean basin. It underlies most of the highlands of the Blue Ridge. Flows decrease in thickness and number toward the southwest, away from the feeder dikes.</td></tr>
<tr><td>Metasandstone and laminated phyllite (Zcs)</td><td>Zcs includes light greenish gray, medium- to coarse-grained metasandstones and multi-colored, laminated quartz-muscovite (mica mineral) phyllite. Zcs only occurs locally in the southwestern park area for about 17 km (10 mi) .</td></tr>
<tr><td>Metarhyolite (Zcr)</td><td>Metarhyolite is a metamorphosed extrusive igneous rock similar in composition to a granite (silica rich). Zcr contains light gray to pinkish white, very fine-grained metarhyolite and tuff. The tuff layers contain feldspar crystals (phenocrysts) and cm-wide clots of white quartz crystals and pale green epidote. Zcr occurs near the base of the Catoctin Formation in the northeastern park area for only 5 km (8 mi) in a 10 m (33 ft) thick layer.</td></tr>
<tr><td>Metabasalt (Zcm)</td><td>Metabasalt is a metamorphosed extrusive igneous rock that is relatively poor in silica and flows easily. Zcm consists of light green to dark greenish gray to bluish gray, fine-grained to aphanitic (no discernible grains) metabasalt. Outcrops may appear massive to platy (schistose). The metabasalt includes remnant amygdules (mineral-filled bubbles). Major mineral constituents include actinolite, chlorite, epidote, albite, and some quartz. Locally contains lenses and layers of light green, fine-grained epidosite (primarily epidote and quartz), phyllite, and metasandstones.</td></tr>
<tr><td colspan="2">Metadiabase dikes (Zmd)</td><td>Metadiabase is a metamorphosed intrusive igneous rock with a relatively low silica content whose original primary mineral constituents were labradorite and pyroxene. Zmd is dark greenish gray, fine- to medium-grained metadiabase that may appear massive or schistose in outcrop. The primary mineral constituents are chlorite, albite, epidote, and actinolite. Coarse-grained exposures have large (nearly 1 cm [0.5 in.]) actinolite crystals that formed as pseudomorphs after clinopyroxene. Relict plagioclase crystals occur within the finer grained (aphanitic) exposures. Dikes change in composition toward the northeastern part of the park becoming more amphibole rich and porphyritic (having large crystals in a finer-grained matrix). Similar in composition to Zcm.</td><td>Ancient Bedrock—Zmd were likely the feeder dikes for the Catoctin Formation.

Type Sections, Reference Locations, and Radiometric Ages—Zmd is aged dated at 567±4 and 555±4 million years ago. Zmd is well-exposed along Skyline Drive at northeast of Mount Marshall, north tunnel portal at Marys Rock, and north of Stony Man.</td><td>Bedrock Outcrop Management—dikes tend to form linear chutes (often used as trails, staircases) within older granites and gneisses.</td><td>Rifting of Rodinia and Opening of the Iapetus Ocean—these units record an extensional, rifting event following the Neoproterozoic Grenville Orogeny. Zmd intruded the Mesoproterozoic gneisses (Ybg through Ylg), Neoproterozoic Robertson River Igneous Suite (Zra through Zrr), and Zmr in the park area taking advantage of preexisting cracks and normal faults. Zmd was metamorphosed (foliated) during the Paleozoic.</td></tr>
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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
NEOPROTEROZOIC ERA	Swift Run Formation (Zsr)	**Zsr** is highly variable with pink to gray, very coarse- to medium-grained metasandstones and quartzite with cross-bedding sedimentary structures. Pebbles and cobbles within **Zsr** include quartz phyllite and sandstone. Some areas of **Zsr** contain brownish green metagraywacke and lustrous, silvery schist (mica-rich rock), whereas other areas include multi-colored phyllite and dark gray slate. The slate exhibits fining upward sequences.	**Ancient Bedrock**—Similar to **Zmr** as sedimentary rock deposited atop the Mesoproterozoic rocks prior to the emplacement of the Catoctin Formation, **Zsr** occurs on the west limb and at the nose of the Blue Ridge anticlinorium. **Bedrock Outcrop Habitats**—Central Appalachian heath barren; Central Appalachian acidic boulderfield; sweet-birch- chestnut oak talus woodland; Central Appalachian high-elevation boulderfield forest; and Central Appalachian xeric chestnut oak-Virginia pine woodland. **Type Sections, Reference Locations, and Radiometric Ages**—The age of **Zsr** is poorly constrained, but likely older than 555±4 million years ago. The type locality for **Zsr** are exposures on U.S. Highway 33, just east of Swift Run Gap and on the Skyline Drive just north of the gap. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed on flanks of anticlinorium. **Connections with Park Stories**—quartzite was used by American Indians for tools.	**Slope Movements**—erosion resistant quartzites and metasandstones underlie local ridges and could be prone to rockfall and topple. **Bedrock Outcrop Management**—this unit tends to form mixtures of isolated outcrops, ledges, and open talus fields. Examples of Rock Outcrop Management Project sites include Powell Gap Cliff.	**Rifting of Rodinia and Opening of the Iapetus Ocean**—rocks of **Zsr** are mostly fluvial (alluvial fan and floodplain) with minor lake (lacustrine) sediments. The uppermost sedimentary rocks of **Zsr** are largely interbedded with the volcanic rocks of the Catoctin Formation. Notable locations for this relationship occur: (1) northwest of Big Meadows; (2) along the West Branch of Naked Creek in Weaver Hollow; (3) East of Compton Gap; and (4) Sugar Hollow. **Zsr** was either deposited in isolated basins on a landscape of considerable topographic relief or the rocks experienced an erosional event prior to the deposition of the Catoctin Formation.
	Hornblende metagabbro dike and (or) sill (Zhg)	Dikes are igneous intrusions that cut across the fabric of the local bedrock whereas sills intruded parallel to preexisting bedrock fabrics. Metamorphosed gabbro is the result of heat and pressure changing a mafic (silica-poor), intrusive (extrusive equivalent is basalt) metaigneous rock. **Zhg** is greenish black, medium- to fine-grained, altered mafic (silica-poor) rock. The original mineral components include hornblende, plagioclase, epidote, and quartz. Locally, altered ultramafic rocks consisting of actinolite, epidote, chlorite, and magnetite occur beneath **Zhg** east of Graves Mill.	None reported.	None reported.	**Rifting of Rodinia and Opening of the Iapetus Ocean**—**Zhg** is likely older than **Zmd** and intrudes **Zmr**.
	Mechum River Formation (Zmr)	**Zmr** is subdivided into four distinctive units: (1) laminated metasiltstone, metamudstone, and minor arkosic (feldspar-rich) metawacke; (2) fine- to coarse-grained arkosic metasandstones and metawacke with minor metasiltstone and metaconglomerate interlayers; (3) arkosic metasandstones and metaconglomerate with relict cross-bedding sedimentary structures; and (4) laminated metasiltstone, metagraywacke, and arkosic metawacke also with cross-bedding.	**Ancient Bedrock**—**Zmr** contains graded and scoured beds representing subaqueous gravity-flow deposits (turbidites) as well as glaciomarine deposits in the form of boulder conglomerates. **Zmr** occurs in the middle part of the Blue Ridge anticlinorium. **Type Sections, Reference Locations, and Radiometric Ages**—**Zmr** is between 700 and 575 million years old. **Zmr** was named for exposures along the railroad cuts and banks of the Mechums River. The formation is a narrow band that extends for nearly 100 km (60 mi) northeast from near Batesville to near Ben Venue and U.S. Route 211. Metaconglomerates of **Zmr** are well-exposed on Bessie Bell Mountain.	**Slope Movements**—metasandstones and metaconglomerates may weather in blocks prone to falls and topples.	**Rifting of Rodinia and Opening of the Iapetus Ocean**—The boulders and cobbles of the conglomerates were derived mostly from Mesoproterozoic rocks with some from the Robertson River Igneous Suite. The boulder conglomerates are glaciomarine deposits from proglacial outwash fans. Much of the rest of the unit occurs from near Charlottesville to as far north as U.S. Route 33. The metawackes and arkosic rocks were deposited as submarine fans with some fluviodeltaic (nonmarine) input. **Zmr** was intruded by metadiabase dikes likely related to Catoctin Formation volcanism. **Zmr** may be part of a footwall syncline beneath a Paleozoic thrust fault that shoved older, Mesoproterozoic rocks above them.

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Age		Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
NEOPROTEROZOIC ERA	Robertson River Igneous Suite	Amissville Alkali Feldspar Granite (Zra)	Granite denotes a specific intrusive igneous rock composition characterized by relatively high silica contents, rich in quartz (10 to 50%) and alkali feldspars. **Zra** is gray, medium-grained alkali feldspar granite. The mineral components of **Zra** include mesoperthite (a feldspar), quartz, and larger, characteristic quartz crystals (phenocrysts).	**Ancient Bedrock**—small cavities within **Zra** contain protruding quartz crystals. Such “miarolitic” cavities may contain unusual minerals. **Type Sections, Reference Locations, and Radiometric Ages**—**Zra** yielded a uranium-lead radiometric age of 700 million years ago.	None reported.	**Failed Rifting**—the Robertson River Igneous Suite is a compound batholith that extends continuously for 110 km (66 mi) between Charlottesville and Markham. The entire suite intruded a fracture zone during crustal extension—analogous to a large dike. Rocks of the Robertson River Igneous Suite are similar to others in the Blue Ridge of southern Virginia and western North Carolina. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrbr** crops out near Battle Mountain; the cobbles of rhyolite, Mesoproterozoic granitoids, and sedimentary rocks are isolated from and not contiguous with those of **Zmr**. The presence of conglomerate within **Zrbr** records a history of igneous activity (volcanism) intermittent with mass wasting and weathering. These two units are roughly contemporaneous with igneous intrusions **Zra** and **Zrbd**. **Zrbd** intruded Mesoproterozoic gneisses as well as granites of the Robertson River Igneous Suite. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrqt** is the extrusive volcanic equivalent of **Zrc**. **Zrqt** occurs between older Mesoproterozoic rocks (**Yod** and **Yom**) and the Catoctin Formation. **Zrqt** is in turn intruded by metadiabase dikes associated with the Catoctin Formation.
		Battle Mountain Alkali Feldspar Granite (Zrb)	Similar to **Zra**, **Zrb** is gray, medium-grained alkali feldspar granite. Compositionally, **Zrb** is missing the distinctive quartz phenocrysts of **Zra**.	**Ancient Bedrock**—small cavities within **Zrb** contain protruding quartz crystals. Such “miarolitic” cavities may contain unusual minerals. **Type Sections, Reference Locations, and Radiometric Ages**—**Zrb** yielded a uranium-lead radiometric age of 705±2 million years ago.	None reported.	
		Rhyolite and metaconglomerate (Zrbr)	Rhyolite is an extrusive igneous rock similar in composition to a granite (silica rich). **Zrbr** consists of light gray, aphanitic (extremely fine-grained) felsic (silica-rich) metarhyolite formed during volcanic eruptions. Larger crystals (phenocrysts) within **Zrbr** include fluorite and feldspar. Interlayered with the metarhyolite are metaconglomerates including pebbles of metarhyolite and conglomerate of granite boulders.	**Type Sections, Reference Locations, and Radiometric Ages**—the rocks of the Robertson River Igneous Suite are well-exposed along the Robinson River and along Mill Run just south of Laurel Mills, Hitt Mountain, Battle Mountain, and the north side of U.S. Route 211 northwest of Amissville.	None reported.	
		Felsite (Zrbf)	Felsite is similar to rhyolite, almost entirely composed of quartz and feldspar (silica-rich). Similar to **Zrbr**, **Zrbf** consists of light gray, aphanitic (extremely fine-grained) (silica-rich) felsite formed during volcanic eruptions. Larger crystals (phenocrysts) within **Zrbf** include alkali feldspar (mesoperthite) and quartz.	**Ancient Bedrock**—small cavities within **Zrbf** contain protruding quartz crystals. Such “miarolitic” cavities may contain unusual minerals. **Zrbf** also contains lithophysae, which are hollow, bubble-like features exhibiting concentric shells of finely crystalline minerals. **Type Sections, Reference Locations, and Radiometric Ages**—**Zrbf** yielded a uranium-lead radiometric age of approximately 702 million years ago. **Zrbf** is well-exposed on the west side of Battle Mountain and along U.S. Route 522 near Boston.	None reported.	
		Felsic dikes (Zrbd)	Dikes are igneous intrusions that cut across the fabric of the local bedrock. **Zrbd** consists of light gray, aphanitic (very fine-grained), felsic dikes.	None reported.	None reported.	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
NEOPROTEROZOIC ERA	Robertson River Igneous Suite	Hitt Mountain Alkali Feldspar Syenite (Zrh)	Syenite is similar to granite (see **Zra**), but with less quartz and a variety of feldpsars—alkali feldspar and minor plagioclase. **Zrh** is gray, coarse-grained alkali feldspar syenite. Primarily the unit is equigranular (crystals are roughly the same size) composed of microcline (mesoperthite), quartz, plagioclase, hastingsite, and scant garnets. Locally, the unit is pegmatitic (very coarse-grained).	**Type Sections, Reference Locations, and Radiometric Ages**—**Zrh** yielded an age of 706±2 million years ago.	None reported.	**Failed Rifting**—the Robertson River Igneous Suite is a compound batholith that extends continuously for 110 km (66 mi) between Charlottesville and Markham. The entire suite intruded a fracture zone during crustal extension—analogous to a large dike. Rocks of the Robertson River Igneous Suite are similar to others in the Blue Ridge of southern Virginia and western North Carolina. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrbr** crops out near Battle Mountain; the cobbles of rhyolite, Mesoproterozoic granitoids, and sedimentary rocks are isolated from and not contiguous with those of **Zmr**. The presence of conglomerate within **Zrbr** records a history of igneous activity (volcanism) intermittent with mass wasting and weathering. These two units are roughly contemporaneous with igneous intrusions **Zra** and **Zrbd**. **Zrbd** intruded Mesoproterozoic gneisses as well as granites of the Robertson River Igneous Suite. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrqt** is the extrusive volcanic equivalent of **Zrc**. **Zrqt** occurs between older Mesoproterozoic rocks (**Yod** and **Yom**) and the Catoctin Formation. **Zrqt** is in turn intruded by metadiabase dikes associated with the Catoctin Formation.
		Quartz trachyte (Zrqt)	Trachyte is the extrusive volcanic equivalent of syenite (see **Zrh**) with alkali feldspar and some dark minerals (biotite, amphibole, or pyroxene) as the primary mineral constituents.**Zrqt** consists of dusky red to gray, aphanitic (extremely fine-grained) to fine-grained quartz trachyte. Mineral constituents include mesoperthite and quartz. Larger crystals (phenocrysts) of light gray mesoperthite occur. **Zrqt** only occurs southeast of Jenkins Gap in the park area.	**Type Sections, Reference Locations, and Radiometric Ages**—**Zrqt** was uranium-lead age dated at 719±6 to 714±5 million years ago.	None reported.	
		Cobbler Mountain Alkali Feldspar Quartz Syenite (Zrc)	**Zrc** is gray, medium-grained alkali feldspar quartz syenite. The unit has conspicuous stubby, 2 to 4 mm (0.1 to 0.2 in.) diameter, well-formed mesoperthite crystals intergrown with poorly formed quartz grains.	**Type Sections, Reference Locations, and Radiometric Ages**—**Zrc** yielded an age of 722±3 million years ago. **Zrc** crops out in the northeast part of the park area northeast of Cresthill and along Interstate Route 66 on Little Cobbler Mountain, east of the map area.	None reported.	
		White Oak Alkali Feldspar Granite (Zrw)	**Zrw** consists of gray, coarse-grained, alkali feldspar granite. The crystals are not the same size throughout the unit. The primary mineral constituents are mesoperthite (microcline, a feldspar), quartz, and hastingsite.	**Type Sections, Reference Locations, and Radiometric Ages**—**Zrw** yielded a uranium-lead radiometric age dated of 724±3 million years ago.	None reported.	
		Laurel Mills Granite (Zrl)	Similar to **Zrw**, **Zrl** contains gray, coarse-grained granite. The dominant mineral is alkali feldspar (microperthite, chiefly microcline). Other mineral constituents include characteristic pale blue quartz, hastingsite, biotite, magnetite, and titanite.	**Type Sections, Reference Locations, and Radiometric Ages**—**Zrl** yielded a uranium-lead radiometric age of 729±1 million years ago.	None reported.	

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Age	Map Unit (Symbol)		Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
NEOPROTEROZOIC ERA	Robertson River Igneous Suite	Arrington Mountain Alkali Feldspar Granite (Zram)	Similar to **Zrw** and **Zrl**, **Zram** consists of gray, medium-grained alkali feldspar granite. The texture of **Zram** is roughly equigranular; most of the visible crystals are of a similar size. Primary mineral components include mesoperthite, quartz, hastingsite, biotite, fluorite, and scant garnet and muscovite.	**Type Sections, Reference Locations, and Radiometric Ages**—**Zram** yielded a uranium-lead radiometric age of 730±4 million years ago.	None reported.	**Failed Rifting**—the Robertson River Igneous Suite is a compound batholith that extends continuously for 110 km (66 mi) between Charlottesville and Markham. The entire suite intruded a fracture zone during crustal extension—analogous to a large dike. Rocks of the Robertson River Igneous Suite are similar to others in the Blue Ridge of southern Virginia and western North Carolina. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrbr** crops out near Battle Mountain; the cobbles of rhyolite, Mesoproterozoic granitoids, and sedimentary rocks are isolated from and not contiguous with those of **Zmr**. The presence of conglomerate within **Zrbr** records a history of igneous activity (volcanism) intermittent with mass wasting and weathering. These two units are roughly contemporaneous with igneous intrusions **Zra** and **Zrbd**. **Zrbd** intruded Mesoproterozoic gneisses as well as granites of the Robertson River Igneous Suite. **Zra** and **Zrbd** are roughly contemporaneous with igneous volcanism of units **Zrbr** and **Zrbf**. **Zrqt** is the extrusive volcanic equivalent of **Zrc**. **Zrqt** occurs between older Mesoproterozoic rocks (**Yod** and **Yom**) and the Catoctin Formation. **Zrqt** is in turn intruded by metadiabase dikes associated with the Catoctin Formation.
		Rivanna Granite (Zrr)	**Zrr** is white, medium-grained granite with quartz, plagioclase, alkali feldspar (microcline), biotite, fluorite, and scant muscovite mineral constituents. The texture is largely equigranular.	**Ancient Bedrock**—small cavities within **Zrr** contain protruding quartz and pyrite crystals. Such "miarolitic" cavities may contain unusual minerals. **Type Sections, Reference Locations, and Radiometric Ages**—**Zrr** yielded an age of 735±4 million years ago.	None reported.	
	Garnet-graphite paragneiss (Zp)		The word gneiss refers to a metamorphic rock in which the minerals segregated into bands of alternating composition—commonly marked by bands of flaky or elongate minerals. The prefix para- refers to a metamorphic rock of sedimentary origin. **Zp** consists of rusty brown, medium- to fine-grained, graphite-garnet-biotite-plagioclase-quartz gneiss. The gneiss has a layered appearance due to compositionally different bands formed in the rock during metamorphism. Some bands are garnetiferous (contain abundant garnets), others are quartzofeldspathic (quartz and feldspar), and some contain only quartz. Coarse-grained pegmatites locally cut exposures of **Zp**. Some portions of **Zp** are changed (retrograde metamorphism) to chlorite schist.	**Ancient Bedrock**—**Zp** has almandine garnets as much as 1 cm (0.4 in.) in diameter occurring as aggregates whereas graphite occurs as disseminated flakes. **Type Sections, Reference Locations, and Radiometric Ages**—**Zp** yielded a uranium-lead radiometric age of less than 812 million years ago. **Zp** is well-exposed along Buck Mountain Creek, Lickinghole Creek, and Garth Run.	None reported.	**Neoproterozoic Era**—**Zp** displays conspicuous deformation fabrics (schistosity) that records conditions during Paleozoic mountain-building events. **Zp** occurs in isolated bodies surrounded by Mesoproterozoic rocks. Geochemistry suggests the parent material for **Zp** were impure sandstone or greywacke. **Zp** may represent the erosional remnants of the missing rock record between the emplacement of **Ybg** (1,028 million years ago) and the intrusion of the Robertson River Igneous Suite ("Zr" units) 730 million years ago.
MESOPROTEROZOIC ERA	Biotite monzogranite-quartz monzodiorite (Ybg)		Monzogranite is a variety of granite (see**Zra**) wherein the plagioclase and alkali feldspar contributions to composition are roughly equal. Monzodiorite is a dark rock that contains more alkali feldspar (sodic plagioclase) than diorite (an igneous rock with moderate silica content).**Ybg** is very dark gray, medium- to coarse-grained biotite monzogranite and quartz monzodiorite. The grain sizes of the various mineral constituents are not equal and the unit has very little if any planar or banded fabrics (foliation). Biotite content can reach 25%.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ybg** yielded a uranium-lead radiometric age of 1,040±9 to 1,028±9 million years ago. The reference locality is on the west side of a parsonage driveway along Virginia Route 670 in Criglersville.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—**Ybg** is the youngest rock mapped in the Mesoproterozoic Blue Ridge suite of Virginia.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
MESOPROTEROZOIC ERA	Orthopyroxene monzogranite-quartz monzodiorite (Yom)	**Yom** is dark green to black, medium- to coarse-grained orthopyroxene monzogranite and quartz monzodiorite. The monzogranite is rich in amphibole, orthopyroxene, and clinopyroxene minerals in unequal grain sizes. In outcrop, the unit appears massive without distinct banding (foliation).	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Bedrock Outcrop Habitats**—Central Appalachian basic woodland; Central Appalachian heath barren; sweet-birch-chestnut oak talus woodland; Central Appalachian high-elevation boulderfield forest; high-elevation outcrop barren; Central Appalachian mafic barren; and Central Appalachian xeric chestnut oak-Virginia pine woodland. **Type Sections, Reference Locations, and Radiometric Ages**—**Yom** yielded a uranium-lead radiometric age of 1,050±8 to 1,044±6 million years ago. The reference locality is on the east side of Bluff Mountain, approximately 3 km (2 mi) northwest of Graves Mill. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens. Examples of Rock Outcrop Management Project sites include Millers Head, Nakedtop, and Upper Devils Ditch.	**Grenville Orogeny and the Supercontinent Rodinia**—**Yom** occurs as both a massive pluton and discrete dikes in the Swift Run Gap area to north of Skyland. Intrusive relationships yield relative timing of geologic events.
	Megacrystic quartz monzonite (Ybp)	Monzonite contains even more alkali feldspar than monzodiorite (see **Ygb**).**Ybp** contains light to medium gray, medium-grained quartz monzonite. In places this unit has very large crystals and some weak banding texture (foliation). Characteristic of **Ybp**, are large crystals (porphyroblasts) of pink microcline (alkali feldspar).	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ybp** yielded an age of 1,049±6 million years ago. **Ybp** is well-exposed in the extreme northeast part of the map area.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—**Ybp** intruded **Yfh** and was in turn intruded by **Zrc** of the Robertson River Igneous Suite.
	Megacrystic biotite monzogranite (Ybm)	**Ybm** consists of light to medium gray, very coarse-grained, biotite monzogranite. Major mineral constituents include biotite and blue quartz. Outcrop exposures show weak to moderate banding textures (foliation). In places, dikes of pegmatite and biotite monzogranite intrude **Ybm**. Compositionally similar, those rocks are likely from the same magma source as **Ybm**.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ybm** yielded a uranium-lead radiometric age dated of 1,057±8 to 1,057±7 million years ago. **Ybm** underlies a broad area from Etlan north to Sperryville and is well-exposed along the Covington River west of Rock Mills. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	**Grenville Orogeny and the Supercontinent Rodinia**—**Ybm** forms part of the foundation of the Appalachian Mountains as an igneous intrusion.
	Crozet Granite (Ycg)	**Ycg** is light gray, very coarse-grained, biotite- and clinopyroxene-bearing monzogranite. Large megacrysts of euhedral (well-formed crystal faces) feldspar and anhedral (poorly-formed crystal faces) quartz may reach up to 10 cm (4 in.) in length. In places the unit appears massive, whereas elsewhere it may be nonfoliated to moderately foliated (banded). This type of texture formed during deformation. Undeformed pegmatite dikes intrude **Ycg**.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ycg** yielded a uranium-lead radiometric age of 1,0460±7 million years ago. The reference locality for **Ycg** is along the Moormans River downstream of the dam at the Charlottesville Reservoir in Sugar Hollow. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	**Grenville Orogeny and the Supercontinent Rodinia**—this unit records three geologic events: (1) major igneous intrusions; (2) deformation of the Crozet Granite; and (3) renewed igneous activity as pegmatite dikes intrude.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
MESOPROTEROZOIC ERA	Old Rag Granite (Yor)	A leucogranite is a granite (see **Zra**) generally lacking in dark, mafic (silica poor) minerals, whereas a syenogranite is a granite with more alkali feldspar than plagioclase in composition. **Yor** consists of white to light gray, medium- to coarse-grained leucogranite and syenogranite. The leucogranite contains some biotite, orthopyroxene, and garnet. The syenogranite also contains garnets. Both granites contain gray and blue quartz grains. Grain sizes are not equal. **Yor** appears massive in outcrop with some areas of weak foliation (banding) evident.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Bedrock Outcrop Habitats**—Central Appalachian basic woodland; Central Appalachian heath barren; sweet-birch-chestnut oak talus woodland; Central Appalachian high-elevation boulderfield forest; high-elevation outcrop barren; Central Appalachian mafic barren; and Central Appalachian xeric chestnut oak-Virginia pine woodland. **Type Sections, Reference Locations, and Radiometric Ages**—**Yor** yielded a uranium-lead radiometric age of 1,063±8 to 1,060±5 million years ago. **Yor** extends from Whiteoak Canyon north to near Front Royal. The reference locality is along the lower slope of Buck Mountain above the north bank of Gooney Run. Old Rag Mountain is another reference locality for the more leucogranitic component of this unit. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium. **Connections with Park Stories**—**Yor** was used in the construction of The Byrd's Nest.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens. Examples of Rock Outcrop Management Project sites include Old Rag southside, Old Rag summit east, Old Rag summit west, Oventop, and Whiteoak Canyon. **Disturbed Lands**—Copper mining prospects occur in **Yor**.	**Grenville Orogeny and the Supercontinent Rodinia**—Old Rag Granite and the Pedlar Formation were the two primary units previously recognized as the bulk of Mesoproterozoic rocks exposed within the park until more detailed mapping.
MESOPROTEROZOIC ERA	Porphyroclastic metagranitoid (Yml)	**Yml** is light gray, very coarse-grained, alkali-feldspar granite. **Yml** is strongly foliated (banded in outcrop) and contains abundant biotite that in part aligns to form the banded texture.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yml** yielded a uranium-lead radiometric age dated of 1,078±9 million years ago. Unit is well-exposed along the east bank of the Conway River, 1.5 km (0.9 mi) north of Fletcher.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—**Yml** occurs as a large xenolith within **Yom** indicating a relative timing of emplacement (**Yml** predates **Yom**).
MESOPROTEROZOIC ERA	Orthopyroxene granite-monzogranite (Yog)	**Yog** includes dark gray, medium- to coarse-grained, orthopyroxene granite-monzogranite. Major mineral constituents include orthopyroxene, biotite, and garnet. The grain sizes amongst the major minerals are similar. In outcrop the unit is weakly to strongly foliated.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium. **Type Sections, Reference Locations, and Radiometric Ages**—**Yog** yielded a uranium-lead radiometric age of 1,120±12 to 1,111±16 million years ago. **Yog** underlies rugged, northwest slopes of Stony Man and Skyland. The reference locality is on the east side of The Peak, northwest of the county road between Washington and Flint Hill.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	**Grenville Orogeny and the Supercontinent Rodinia**—xenoliths of **Yog** occur within **Yomg** indicating a relative timing of emplacement (**Yog** predates **Yomg**).

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
MESOPROTEROZOIC ERA	Flint Hill Gneiss (Yfh)	**Yfh** is dark to medium gray, medium-grained, quartzofeldspathic (contains quartz and feldspar) syenogranite to monzogranite forming compositional layers separated by biotite flakes. **Yfh** contains distinctive gray and blue quartz grains and veins of blue quartz.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yfh** yielded a uranium-lead radiometric age of dated at 1,444±8 million years ago. This unit also contains partially melted, in situ zones (migmatites) indicative of extreme heating during metamorphism. The reference locality for **Yfh** is a collection of roadcuts along U.S. Route 522, approximately 0.9 km (0.6 mi) south of Flint Hill.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—gneisses record deformation and metamorphic conditions during crustal compression as part of the construction of geologic foundation of the Appalachian Mountains.
	Lineated leucogranite gneiss (Yll)	**Yll** consists of light gray to tan, medium- to coarse-grained, leucogranite gneiss. In outcrop the unit is strongly banded (foliated) and lineated with lineations defined by aligned biotite flakes. This yields a distinctive stripped appearance.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yll** yielded a uranium-lead radiometric age of 1,150±23 million years ago. **Yll** is well-exposed on the south side of Roundtop, along Skyline Drive, about 0.5 km (0.3 mi) east of Powell Gap. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	
	Orthopyroxene monzogranite-quartz monzodiorte gneiss (Yomg)	**Yomg** contains greenish gray to black, orthopyroxene monzogranite and quartz monzodiorite gneiss. The monzogranite bears orthopyroxene, clinopyroxene, and biotite. Weathered outcrops of **Yomg** are rusty colored and show ribbed surfaces due to differential weathering of the compositional layering.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yomg** yielded a uranium-lead radiometric age of 1,158±13 million years ago. **Yomg** is a compound unit occurring in the southern part of the park with exposures along the south side of Virginia State Route 810 north of Nortonsville, or along Virginia State Route 674 north of the Moormans River.	None reported.	
	Megacrystic orthopyroxene syenogranite-monzogranite gneiss (Yos)	**Yos** consists of dark gray to dark greenish gray, very coarse–grained, megacrystic (large crystals) orthopyroxene syenogranite-monzogranite gneiss. **Yos** contains orthopyroxene, amphibole, and clinopyroxene. The unit appears strongly banded (foliated). Alkali feldspar crystals may reach up to 12 cm (5 in.) in length.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Bedrock Outcrop Habitats**—Central Appalachian basic woodland, Central Appalachian heath barren, sweet-birch-chestnut oak talus woodland, Central Appalachian high-elevation boulderfield forest, high-elevation outcrop barren, Central Appalachian mafic barren, Central Appalachian xeric chestnut oak-Virginia pine woodland. **Type Sections, Reference Locations, and Radiometric Ages**—**Yos** yielded a uranium-lead radiometric age of 1,166±14 to 1,159±14 million years ago. Reference localities include highland areas from near Stony Man north to near Pignut Mountain, on Slaughter Mountain, and the south portal of the tunnel at Marys Rock south of Thornton Gap. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens. Examples of Rock Outcrop Management Project sites include Hogback Mountain spur, Marys Rock, Pinnacles **Disturbed Lands**—copper mining prospects occur in **Yos**.	**Grenville Orogeny and the Supercontinent Rodinia**—**Yos** is a compound unit which occurs as xenoliths in **Ybm** and **Yor**. This indicates it is older than both of those units.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
MESOPROTEROZOIC ERA	Granodiorite gneiss (Ygd)	A granodiorite is an intrusive igneous rock with an intermediate composition between a quartz diorite (see **Ybg**) and a quartz monzonite (see **Ybp**).**Ygd** is light gray, granodiorite gneiss. The unit is strongly banded (foliated) with characteristic compositional layering. Lineations defined by aligned biotite flakes and clots of biotite are distinctive for this unit.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ygd** yielded a uranium-lead radiometric age of 1,161±9 million years ago. The reference locality for **Ygd** is on the southwest side of Turkey Mountain north of Fletcher Mill.	None reported.	None reported.
	Orthopyroxene quartz diorite gneiss (Yoq)	**Yoq** is greenish gray to black, medium-grained, quartz diorite-gneiss. Primary mineral constituents include orthopyroxene, biotite, garnet, and quartz. **Yoq** is strongly compositionally layered and banded (foliated) in outcrop.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yoq** yielded a uranium-lead radiometric age of 1,161±10 million years ago. The reference locality is along the east side of Virginia State Route 649, approximately 1.5 km (1 mi) north of Boyd's Mill.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—**Yoq** occurs as a large xenolith within **Yor** indicating it predates Old Rag Granite intrusive event. Geochemical tests suggest this unit originated from a melt with a significant island-arc component.
	Orthopyroxene syenogranite and monzogranite gneiss (Yon)	Similar to **Yos**, **Yon** consists of gray, medium- to coarse-grained, orthopyroxene syenogranite and monzogranite gneiss. Primary mineral constituents include orthopyroxene, biotite, garnet, and clinopyroxene. **Yon** displays compositional layering and strong foliation (banded appearance). Some layers are garnetiferous.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Yon** yielded a uranium-lead radiometric age of 1,164±8 million years ago. The reference locality for **Yon** is Skinners Ridge, opposite the Buck Hollow Overlook, just 2 km (1 mi) southeast of Thornton Gap. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	**Grenville Orogeny and the Supercontinent Rodinia**—gneisses record deformation and metamorphic conditions during crustal compression, often accompanied by igneous pluton intrusions as part of the construction of geologic foundation of the Appalachian Mountains
	Orthopyroxene granodiorte gneiss (Yod)	**Yod** is dark gray, medium- to coarse-grained, granodiorite gneiss. The unit is strongly foliated with compositional layering. Mineral constituents include amphibole and orthopyroxene. Some layers of leucocratic composition also present locally, transposed.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Bedrock Outcrop Habitats**—Central Appalachian basic woodland; Central Appalachian heath barren; sweet-birch-chestnut oak talus woodland; Central Appalachian high-elevation boulderfield forest; high-elevation outcrop barren; Central Appalachian mafic barren; and Central Appalachian xeric chestnut oak-Virginia pine woodland. **Type Sections, Reference Locations, and Radiometric Ages**—**Yod** yielded a uranium-lead radiometric age of 1,165±7 million years ago. **Yod** occurs only in the northern end of the park with diagnostic roadcut exposures along Skyline Drive on the south side of Carson Mountain between Lands Run Gap and Compton Gap. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens. Examples of Rock Outcrop Management Project sites include Gooney Manor Overlook.	

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Issues	Geologic History
MESOPROTEROZOIC ERA	Foliated, garnetiferous, porphyroblastic monzogranite (Ypg)	**Ypg** consists of medium gray, medium- to coarse-grained, monzogranite. The major mineral constituents are biotite, garnet, microcline, and blue quartz. The microcline frequently occurs in megacrysts or crystal aggregates as much as 3 cm (1 in.) in diameter and the quartz displays distinctive clots within the rock.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ypg** yielded an age of 1,172±8 million years ago. **Ypg** occurs in the eastern part of the park area, east of portions of the Robertson River Igneous Suite (**Zrr**) with a reference locality immediately east of the boundary between the Flint Hill and Jeffersonton 7.5-minute quadrangles.	None reported.	**Grenville Orogeny and the Supercontinent Rodinia**—gneisses record deformation and metamorphic conditions during crustal compression, often accompanied by igneous pluton intrusions as part of the construction of geologic foundation of the Appalachian Mountains
MESOPROTEROZOIC ERA	Leucogranite gneiss (Ylg)	**Ylg** is light gray, coarse-grained to megacrystic (with very large crystals), leucogranite gneiss. The foliated (banded) texture is weakly to strongly expressed in outcrop. The rock composition varies between alkali-feldspar granite, syenogranite, and monzogranite. Dikes of leucogranite cut the main body of **Ylg**. These dikes are medium gray, medium-grained, and contain biotite. Their mineral constituents have similar grain sizes and in outcrop, the dikes are folded. Leucocratic pegmatites in turn intrude the main body of **Ylg** and the aforementioned dikes.	**Ancient Bedrock**—these rocks are some of the oldest and most complex (structurally and lithologically) in eastern North America. **Type Sections, Reference Locations, and Radiometric Ages**—**Ylg** yielded a uranium-lead radiometric age of 1,183±11 to 1,171±22 million years ago. The reference locality for **Ylg** is in Deep Hollow, west of Virginia State Route 651. **Blue Ridge-South Mountain Anticlinorium and Regional Structures**—exposed in core of anticlinorium.	**Bedrock Outcrop Management**—this unit tends to form mixtures of flat or rounded outcrops and barrens.	**Grenville Orogeny and the Supercontinent Rodinia**—**Ylg** records several igneous and deformational events: (1) intrusion of the main body of **Ylg**; (2) foliation of **Ylg** formed through deformation; (3) intrusion of leucogranite dikes; (4) isoclinal folds in the dikes formed through deformation of the entire body; and (5) intrusion of leucocratic pegmatites during renewed igneous activity.