National Park Service
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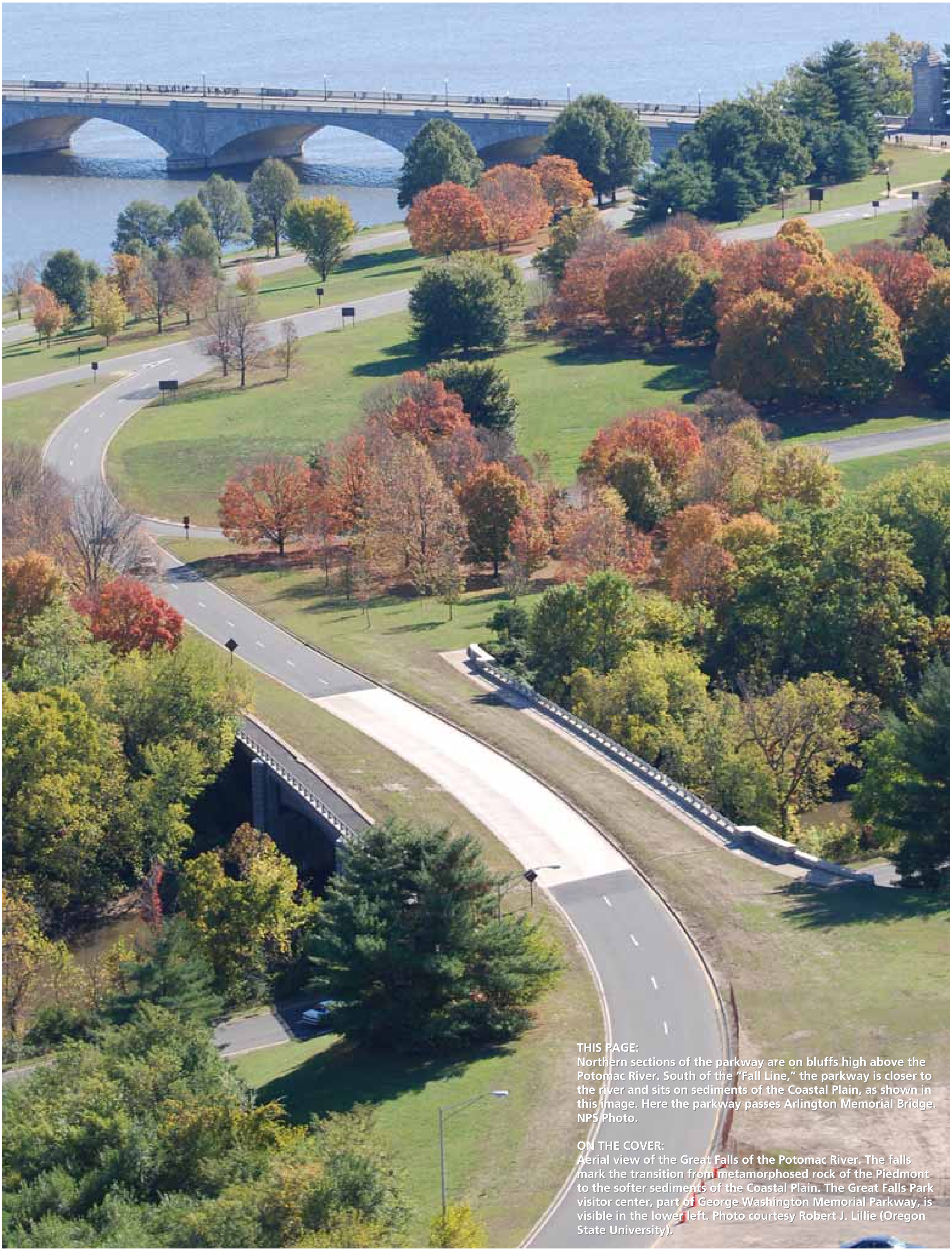
Natural Resource Program Center

George Washington Memorial Parkway
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/128



THIS PAGE:
Northern sections of the parkway are on bluffs high above the Potomac River. South of the "Fall Line," the parkway is closer to the river and sits on sediments of the Coastal Plain, as shown in this image. Here the parkway passes Arlington Memorial Bridge. NPS Photo.

ON THE COVER:
Aerial view of the Great Falls of the Potomac River. The falls mark the transition from metamorphosed rock of the Piedmont to the softer sediments of the Coastal Plain. The Great Falls Park visitor center, part of George Washington Memorial Parkway, is visible in the lower left. Photo courtesy Robert J. Lillie (Oregon State University).

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

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National Park Service
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Contents

Figures

Executive Summary

This report accompanies the digital geologic map for George Washington Memorial Parkway in Virginia, Maryland, and the District of Columbia, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

George Washington Memorial Parkway manages lands along the Potomac River in Virginia, Maryland and Washington, D.C. The parkway connects some of the most important historic, natural, and cultural sites from Mount Vernon to Great Falls Park, and provides a sanctuary for many rare and unique plant and animal species in the urbanized Washington, D.C. metropolitan area. The parkway area has a geologic history that spans from the ancient Precambrian through the formation of the Appalachian Mountains, the more recent Pleistocene ice ages and modern geologic events.

The rocks present along the Potomac River in the parkway reflect the tremendous tectonic forces responsible for the Appalachian Mountains. Precambrian–Cambrian schists, phyllites, and metamorphosed volcanic rocks underlie the Potomac River valley in the Piedmont Plateau. The entire region, compressed during three separate tectonic events—the Taconic, Acadian, and Alleghanian orogenies—resulted in a complex deformational history. Following uplift, thousands of meters of sediments were eroded from the mountains and deposited in a thick wedge toward the Atlantic Ocean. The Potomac River cuts through the sediments in the parkway as it flows toward the Chesapeake Bay. The significant geologic features along the river administered by the parkway include Great Falls and Mather Gorge, Theodore Roosevelt Island, and Dyke Marsh.

The park's landscape features are intimately connected with its long geologic history, which began hundreds of millions of years ago and established the framework for the current environment. The geologic processes that give rise to rock formations, hills, valleys, waterfalls, and wetlands played a prominent role in the history of the Potomac River valley and Washington, D.C. The resultant landscape both welcomes and discourages human use.

Humans have made significant modifications to the area, and the George Washington Memorial Parkway is the most obvious alteration in the modern landscape. The geologic framework is also dynamic, operating on a human timescale. Geological processes continue to alter the landscape, creating a challenge to both preservation and upkeep of the parkway. Thus, understanding the area's geologic history and resources is crucial to effective resource management, as well as to informed decision-making with regard to slope stability, urbanization, air and water quality, flood risk, wildlife populations and invasive species, future scientific research projects, and interpretive needs.

The following features, issues, and processes were identified as having the greatest geological importance and the highest level of significance to management of the parkway:

- Erosion, Slope Processes, and Stability.
  The relatively wet climate of the eastern U.S.—combined with severe storms, loose soils along slopes, and active streams along the parkway—creates a habitat susceptible to rockfall, slumping, slope creep, and streambank erosion. These processes threaten park infrastructure and features. An increase in runoff would dramatically alter the landscape, create new hazard areas, and clog streams with excess sediment that would affect hydrologic systems and aquatic life.

- Recreational Demands.
  George Washington Memorial Parkway is among the ten most visited units of the National Park System. The effects of this intense visitation to the parkway place increasing demands on its protected areas. Visitor use includes hiking, climbing, picnicking, and horseback riding. The landscape response to potential visitor overuse is a resource management concern and includes overall visitor safety, especially at the bottom of steep, rocky slopes.

- Water Issues.
  The Potomac River and its associated hydrogeologic system are primary resources at the parkway. The constantly increasing urban development in the Washington, D.C. metropolitan area affects the quality of the hydrogeologic system. Threats include: contamination by waste products and road salts; deforestation along the river edges, resulting in increased erosion and sediment load; and acidification from acid rain and snow. A working model of the hydrogeologic system along the parkway could help predict environmental responses to contaminants and remediate affected areas.

Additional critical management issues identified for George Washington Memorial Parkway include sea level rise and storm surge, sediment load and channel storage, and the need for general geological research. These are discussed in detail, along with suggestions for inventories, monitoring, and research. Interpretative needs related to land use planning and visitor use in the park also merit resource management attention.

A detailed geologic map, a road or trail log, and a guidebook could be used to relate George Washington Memorial Parkway's geologic context to the other parks in the National Capital Region thereby enhancing visitor appreciation. Such visitor aids would convey the geologic history, the dynamic processes that formed and continue to shape the natural landscape, and how they affected the history showcased along the parkway. Strategically placed wayside interpretive exhibits are another option to further communicate the area's geology to the visitor. The connection between geology and history of the parkway inspires wonder in visitors. Providing an emphasis on the geologic and historical resources will continue to enhance the visitor experience.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of George Washington Memorial Parkway.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRI team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRI products.

The goal of the GRI is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision-making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRI team is systematically conducting a scoping meeting for each of the identified 270 natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. This geologic report aids in the use of the map and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory Web site (http://www.nature.nps.gov/geology/inventory/).

Parkway Setting

One of a number of NPS units in the National Capital Region (fig. 1), George Washington Memorial Parkway runs along the western shore of the Potomac River through the District of Columbia and portions of northern Virginia. The parkway stretches 45 km (28 mi)—from Mt. Vernon (George Washington's home), past the nation's capital he founded in Washington, D.C., to the Great Falls of the Potomac (Mather) Gorge where George Washington demonstrated his skill as an engineer. As shown on the park map (fig. 2), many historic, natural, and cultural sites are accessible along the route, including (from north to south): Great Falls Park; Turkey Run Park; Claude Moore Colonial Farm; Fort Marcy; Theodore Roosevelt Island; United States Marine Corps War Memorial; Netherlands Carillon; Arlington Memorial Bridge and Memorial Avenue; Women in Military Service for America Memorial; Arlington House: The Robert E. Lee Memorial; Lady Bird Johnson Park; Lyndon Baines Johnson Memorial Grove-on-the-Potomac; Dyke Marsh Wildlife Preserve; and Fort Hunt Park. The Potomac Heritage National Scenic Trail and Mount Vernon Trail parallel much of the parkway on the Virginia side. A number of other small parks, natural areas, and marinas (operated by concessioners) are also administered by the parkway.

Originally intended to include a circular scenic highway along both sides of the Potomac River, the roadway only extends along the Virginia portion and ends at Interstate 495. Grouped with the parkway for NPS administration are Great Falls Park in Virginia, and the Clara Barton National Historic Site, Clara Barton Parkway, Glen Echo Park, and land along the Chesapeake and Ohio (C&O) Canal on the Maryland shore.

The first section of this historic highway was completed in 1932, to commemorate the bicentennial of George Washington's birth, and the boundaries of the park have changed several times since then. In 2008, the approximately 2,900 ha (7,200 acre) park hosted 7,009,630 visitors, making it the sixth most visited unit in the National Park System.

The Potomac River was a main corridor of settlement and exploration from early colonial times; thus, the parkway highlights the connection between the Potomac River and American history. In addition to its rich historical context, the park provides a sanctuary for many rare and unique plant and animal species in the highly urbanized Washington, D.C. metropolitan area, protecting a variety of cultural and natural resources.

Geologic Setting

The George Washington Memorial Parkway protects from development portions of the Piedmont and Atlantic Coastal Plain, two geologically significant physiographic provinces in the eastern United States. The landscape of the parkway consists of rolling hills, river terraces, riverside marshes, and inlets. The topography is complex due to varied hydrological influences. This complexity, along with seasonal flooding, supports a diversity of habitats. In the northern reaches of the parkway, the Potomac River has cut a relatively linear gorge along faults and fractures through the deformed metamorphic crystalline rocks of the Potomac terrane (section of the Piedmont). The river widens below the "Fall Line" as it cuts through the unconsolidated sediments of the Atlantic Coastal Plain.

The Potomac River—616 km (383 mi) long from its source near Fairfax Stone, West Virginia to its mouth at Point Lookout, Maryland—is the second largest tributary of the Chesapeake Bay. The Potomac watershed stretches across Maryland, Pennsylvania, Virginia, the District of Columbia, and West Virginia. The drainage includes 38,018 square km (14,679 square mi), and covers five physiographic provinces, expressing differences in underlying bedrock, surficial deposits, and resultant landscape. From west to east, these five provinces are: (1) Appalachian Plateau; (2) Valley and Ridge; (3) Blue Ridge; (4) Piedmont—including the Potomac terrane and the Westminster terrane; and (5) Atlantic Coastal Plain (fig. 1). The Piedmont and Atlantic Coastal Plain provinces are discussed below as they relate to George Washington Memorial Parkway.

Piedmont Province

Encompassing the "Fall Line," westward to the Blue Ridge Mountains, is the Piedmont physiographic province. The Fall Line (also known as the "Fall Zone") marks a transitional zone where harder, more resilient metamorphic rocks to the west intersect the softer, less consolidated sedimentary rocks of the Coastal Plain to the east, forming an area of ridges, waterfalls and rapids. This zone covers over 27 km (17 mi) of the Potomac River, from Theodore Roosevelt Island in Washington D.C. west to Seneca, Maryland. Examples of the rapids formed by Piedmont rocks are present in the Potomac Gorge of Great Falls Park and Chesapeake and Ohio Canal National Historical Park.

The rocks of the eastward-sloping Piedmont formed through a combination of folding, faulting, and metamorphism. The Piedmont is composed of hard, crystalline, igneous and metamorphic rocks such as schists, phyllites, slates, gneisses, and gabbros. Valley incision by streams, weathering, and slope erosion have resulted in an eastern landscape of gently rolling hills that start at an elevation of 60 m (200 ft) and become gradually steeper toward the western edge of the province to reach 300 m (1,000 ft) above sea level. Soils in the Piedmont are highly weathered and generally well drained.

Within the Piedmont (but west of the parkway) are a series of Triassic-age extensional basins. A depositional contact, best indicated by a topographic change from the rolling hills of the Piedmont to relatively flat ground within the basins, defines the boundary of the basins with the Piedmont. Each basin, formed by normal faults during crustal extension, is superposed on the rocks and structure of the Piedmont. The faults opened basins (grabens), and the basins rapidly filled with roughly horizontal layers of sediment. Examples include the Frederick Valley in Maryland and the Culpeper Valley of northern Virginia.

Atlantic Coastal Plain Province

Extending from New York to Georgia, the Atlantic Coastal Plain province consists of primarily flat terrain, with elevations ranging from sea level to about 100 m (300 ft) in northern Virginia. Sediments eroding from the Appalachian Highland areas to the west were intermittently deposited over the past 100 million years in a wedge-shaped sequence during periods of higher sea level. The deposits are more than 2,440 m (8,000 ft) thick at the Atlantic coast. These deposits were reworked by fluctuating sea levels, migrating rivers, and continual erosional and depositional action of waves and currents along the coastline. The province continues as the submerged Continental Shelf for another 121 km (75 mi) to the east.

On the Coastal Plain, from the Fall Line east to the Chesapeake Bay and Atlantic Ocean, soils are commonly sandy or sandy loams that are well drained. Large streams and rivers in the Coastal Plain province—including the James, York, and Potomac rivers—are often influenced by tidal fluctuations, and continue to transport sediment, interact with rising sea level, and modify shorelines.

Figure 1. Map showing the physiographic regions and selected NPS areas of the National Capital Region. George Washington Memorial Parkway follows the Potomac River between the black arrows. Note the Fall Line—the boundary between the Piedmont and Coastal Plain provinces. Modified from NPS Center for Urban Ecology Map, courtesy Giselle Mora-Bourgeois (NPS CUE).

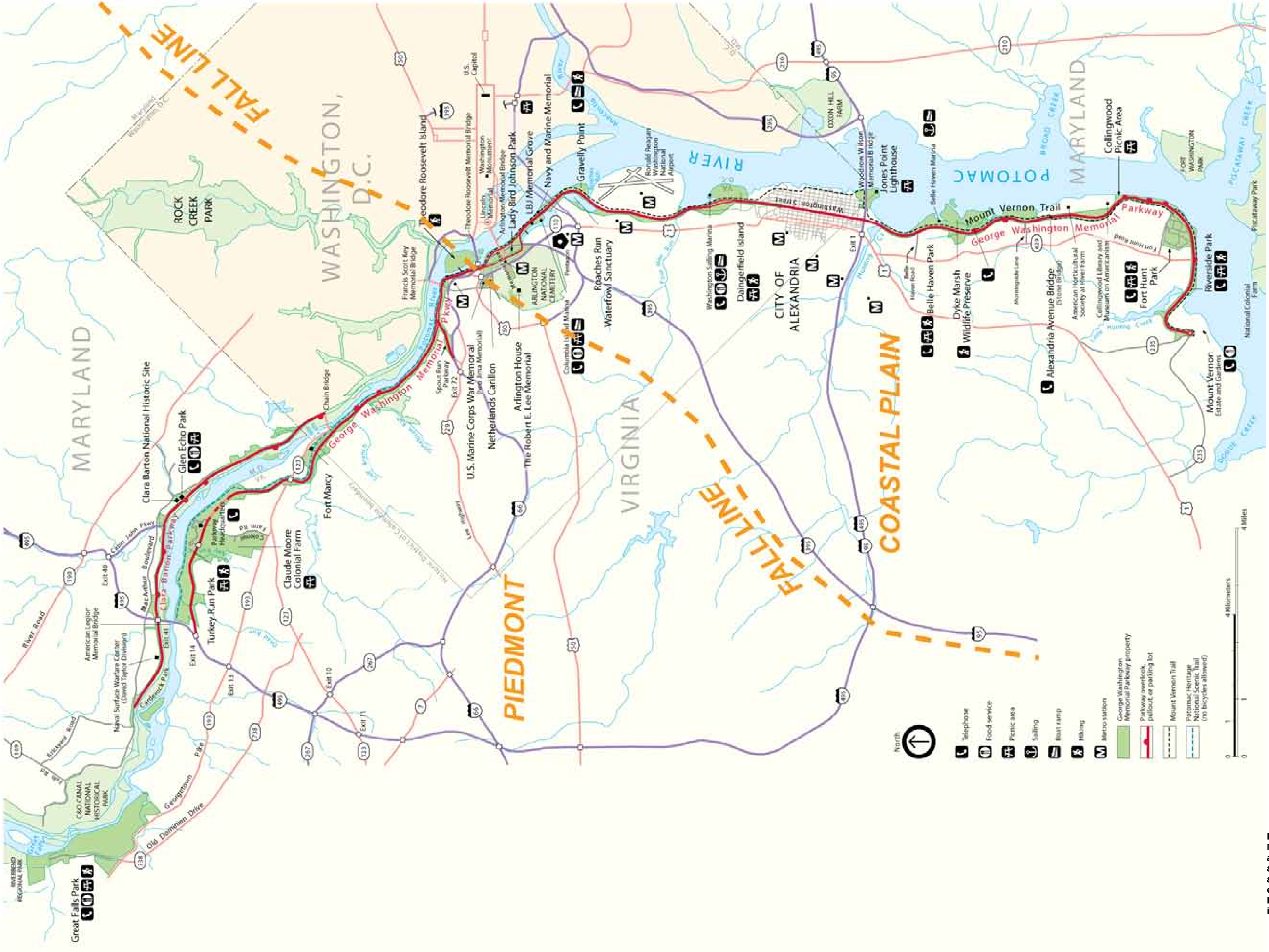

Figure 2. Map of George Washington Memorial Parkway. The parkway administers a number of diverse natural and historic features and recreational areas. The approximate trace of the Fall Line between the Piedmont and Coastal Plain provinces is indicated. Modified from NPS map.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for George Washington Memorial Parkway on April 30–May 2, 2001 to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. The following section synthesizes the scoping results, in particular those issues that may require attention from resource managers.

Potential research projects and topics of scientific interest are presented at the end of each section. Contact the Geologic Resources Division for technical assistance regarding the suggested projects.

Erosion, Slope Processes, and Stability

Large topographic differences occur along George Washington Memorial Parkway. The likelihood of landslides increases with precipitation and undercutting of slopes by roads, trails, and other development. Application of GIS technology showing steepness of slope, rock type, and precipitation would allow determination of landslide risk. The stunning Potomac River overlooks along Mather Gorge and Great Falls formed by intense erosion of the steep slopes. These same processes of mass wasting are the cause of important geological resource management issues. Heavy rainstorms, which are common in the eastern U.S., quickly saturate soils on valley slopes. Rock and soil may mobilize and slide downhill on slopes that lack stabilizing vegetation. The result is a potentially hazardous slump or debris flow.

The walls of many of the river and tributary valleys along the parkway are high slopes, which makes them hazardous because of the potential for rock falls, landslides, slumps, and slope creep. The danger is a major concern in the weaker, weathered rock units (e.g., saprolite) and in unconsolidated surficial deposits. Even the stronger metamorphic rocks are highly fractured and prone to fail, particularly where joints in the rocks intersect (M. Pavich, USGS, written communication, December 2008; Southworth and Denenny 2006). Rock slides near Windy Run (figs. 3 and 4) were first documented in September 2003 following Hurricane Isabel. Smaller rock slides and rock falls have also occurred since then (V. Santucci, NPS GWMP, written communication, August 2009).

The relatively high relief in the cemetery surrounding Arlington House has created immediate resource management issues, including stability and sliding problems along the slopes leading to the house as well as elsewhere in the cemetery. A geologic GIS layer would assist park management in dealing with these issues.

Inventory, Monitoring, and Research Suggestions for Erosion, Slope Processes, and Stability

- Perform a comprehensive study of the active erosion/weathering processes at the park. Account for differing rock formations, slope aspects, location, and slope stability.
- Evaluate aerial photographs for information regarding land use changes, historic slope failures and problem areas, shoreline changes, and stream morphology changes over time.
- Create a mass wasting susceptibility map using rock unit versus slope aspect in a GIS. Use the map in evaluating future developments and current resource management, including trails, buildings, and recreational use areas.
- Assess trails for stability, and determine which trails are most at risk and in need of further stabilization.
- Monitor steep slopes for rock movement and manage undercut areas appropriately, particularly those near park infrastructure.
- Use repeat light detection and ranging (LIDAR) measurements to document changes in shoreline location and elevation along the Potomac River and its tributaries. Document changes immediately after storms where impacts usually exceed processes operating in non-storm conditions.
- Monitor erosion rates by establishing key sites for repeat profile measurements to document rates of erosion or deposition, and, when possible, reoccupy shortly after major storm events. Repeat photography may be a useful tool.
- Form cooperative efforts with the U.S. Geological Survey or other agencies to inventory, map, and monitor slope changes in the park.
- Use shallow (25 cm [10-in]) and deeper core data to monitor the rates of sediment accumulation and erosion in local streams and springs.

Recreational Demands

The two primary goals of the National Park Service are to: (1) protect park resources; and (2) provide opportunities for visitors to enjoy and learn from those resources. George Washington Memorial Parkway provides numerous recreational opportunities along its entire length—e.g., hiking, bicycling, fishing, picnicking, rock climbing, horseback riding, and photography. The park promotes activities that do not damage the park’s resources or endanger other visitors.

As many as 7,009,630 people entered George Washington Memorial Parkway in 2008, and that figure does not include the number of daily commuters that utilize the parkway. The high number of visitors to the park each year increases demands on its resources.

Management concerns include trail erosion, water quality, wetland health, and riverbank erosion.

Trails wind through biological, historical, and geological environments at the park. Several of the trails are especially fragile, and off-trail hiking promotes their degradation. A particular example of ecosystem degradation is the delicate and threatened lichen community in the rocky part of the gorge. Human activity is causing the lichens, which have inherently slow recovery rates, to “wear down” (E. Zen, University of Maryland, written communication, November 2008).

Visitor safety is a primary resource management concern. Despite the warning signs, people drown at Great Falls Park every year. Park staff should monitor visitor access because of the extremely complex hydrodynamics of the river due to the underlying geology and geometry of the falls and gorge (E. Zen, University of Maryland, written communication, November 2008). The River Trail, a popular hiking area Great Falls Park, is often open to the cliffs that line Mather Gorge. The rocky terrain of the River Trail and Potomac Heritage National Scenic Trail makes them treacherous. Rock climbing, a popular activity at Great Falls Park, takes advantage of the cliffs within the park.

The unconsolidated soils and sediments along the parkway are often exposed on sparsely vegetated slopes, rendering them highly susceptible to erosion and degradation. The park attempts to concentrate the impacts of recreation using designated trails and picnic areas. Recreational use outside designated areas places delicate ecosystems at risk for contamination from waste.

The Potomac River forms the backdrop of the parkway. Overuse of fragile areas leads to degradation of the ecosystem and increased river-edge erosion. The park attempts to buttress certain reaches of the river where it approaches sensitive areas and visitor-use areas to lessen damage from erosion. These temporary supports are meant to reduce riverbank erosion.

Inventory, Monitoring, and Research Suggestions for Recreational Demands

- Develop resource management plans that include inventorying and monitoring to further identify human impacts to lichen communities, springs, seeps, wetlands, and marsh flora within the park.
- Design wayside exhibits to encourage responsible use of park resources.
- Determine hazards for climbers and restrict access where necessary.
- Plant stabilizing vegetation along slopes at risk of slumping and erosion.
- Plot recreational use on topographic/geologic maps of the park to determine areas at high risk for resource degradation.

Water Issues

Precipitation in Washington, D.C., averages 100 cm (39 in) per year, with most of the rain occurring in the summer months during storms of short duration. Although water seems to be refreshed in streams, rivers, runoff, springs, and groundwater wells in the moist eastern climate of Virginia/D.C./Maryland, water resources are constantly under threat of contamination and overuse because of the development of the surrounding areas.

Major threats to water quality in the Potomac River and its tributaries include: (1) acid drainage from coal mines in western Maryland and West Virginia; (2) sediment, nutrients, heavy metals, and organic chemicals in urban/agricultural runoff; (3) bacteria, nutrients, and heavy metals from sewage effluent discharges; and (4)organic chemicals, heavy metals, and high biochemical oxygen demand from industries and developed areas.

The integrity of the watershed is reflected in the water quality of the river. Differences in water quality stem from a variety of natural and non-natural sources. For instance, waters sampled from areas underlain by different rock units, often have natural geochemical differences. The process of hydrolysis controls the chemical composition of most natural waters (Bowser and Jones 2002). It is important to have well-characterized mineral compositions available for both the water and the surrounding rock units.

The hydrogeologic system changes in response to increased surface runoff. Surface runoff is increased by development of impervious surfaces, including parking lots, roads, and buildings. Sedimentation also increases due to land clearing for development. Water temperature increases because of the insulating nature of the impervious surfaces. Runoff from a parking lot on a hot July day is at a much higher temperature than runoff from a grassy slope.

Protecting the park’s watershed requires a knowledge of the chemicals used in regional agriculture and development, as well as an understanding of the hydrogeologic system, including groundwater flow patterns. The movement of nutrients and contaminants through the hydrogeologic system may be modeled by monitoring the composition of system inputs such as rainfall and outputs such as streamflow. Other required data include wind, surface runoff, groundwater transport, sewage outfalls, landfills, and fill dirt. Streams integrate the surface runoff and groundwater flow of their watersheds, providing a way to assess the watershed’s hydrologic system. Consistent measurement of the parameters mentioned above is crucial to establishing baselines for comparison.

Inventory, Monitoring, and Research Suggestions for Water Issues

- Establish working relationships with the NPS Water Resources Division, U.S. Geological Survey, Environmental Protection Agency, the Interstate Commission on the Potomac River Basin (ICPRB), the Northern Virginia Regional Park Authority (NVRPA), and the Maryland Geological Survey, as well as other conservation groups, to study and monitor the park’s watershed and the hydrology of the area. Compiled

data would be useful for applications in hydrogeology, soil creep, streambank erosion, and other geologic hazards.
- Apply a mass transfer and/or balance model with a forward modeling approach to the groundwater and surface water at the park to quantify lithologic controls on water chemistry (Bowser and Jones 2002).
- Research geologic controls on water pollution patterns and target remediation efforts accordingly.

Sea Level Rise and Storm Surge

The Potomac River experiences daily 1-m (3-ft) tidal fluctuations at Washington, D.C., which strongly influence the flow regime of the river and its subsequent channel morphology. Relative sea level rise and surges of water associated with hurricanes and storms affect the estuarine Potomac River, and thus the shoreline of George Washington Memorial Parkway (M. Pavich, USGS, written communication, December 2008). The local rate of sea level rise is 27.4 cm (10.8 in) per century (Froomer 1980). Several meters of shoreline can be eroded in a single storm event as evidenced further south along the Potomac River at George Washington Birthplace National Monument in Virginia (GRI, scoping notes, 2001). The Chesapeake-Potomac Hurricane in 1933 caused a 3.4-m (11-ft) storm surge and severe flooding in Alexandria, Virginia and other low-lying areas of the (then new) parkway (M. Pavich, USGS, written communication, December 2008).

More recently, severe flooding was associated with Hurricane Isabel in September of 2003 (figs. 5 and 6). Much of George Washington Memorial Parkway is composed of floodplain areas along the Potomac River. Floods have damaged foundations of bridges, walkways, buildings, and other facilities. As global sea levels continue to rise, these inundation issues will only become more prevalent at the parkway. Flooding along the Potomac River is also discussed under the "Terraces and Flooding of the Potomac River" heading of the "Geologic Features and Processes" section.

Inventory, Monitoring, and Research Suggestions for Sea Level Rise and Storm Surge

- Develop resource management plans that include inventorying and monitoring to further identify human impacts to yearly and seasonal floods.
- Design wayside exhibits to encourage responsible flood response.
- Use historical documents and Washington Metropolitan Area Transit Authority (Metro) records, as well as sediment coring, to determine the historical flood record to aid in future prediction and management.
- Prepare educational exhibits to describe the natural processes of floods, including the benefits to soil fertility.
- Use tree ring studies and other historical data to develop chronologies of past floods and their impacts. Document future changes to shoreline morphology and position, nature of the substrate, post-flood changes, and ecosystem recovery.
- Research and implement techniques to stabilize floodplain areas around cultural resources to protect them from damage.
- Investigate human- and sea-level-rise-driven shoreline changes, focusing on the tidal areas of the parkway.

Sediment Load and Channel Storage

Erosion of the landscape and increasing impervious surface area within the Potomac River tributary watersheds leads to increases in sediment carried by the park's rivers (M. Pavich, USGS, written communication, December 2008). Sediment loads and distribution affect aquatic and riparian ecosystems. Sediment loading may result in changes to channel morphology and increase the frequency of overbank flooding.

Suspended sediment load in tributary watersheds of the Potomac River along the parkway is a resource management concern. The sediments could contaminate drinking water sources. Bioturbation or mechanical mixing of old and new sediments during turbulence caused by severe storms could liberate toxic chemicals from river bottom sediments (E. Zen, University of Maryland, written communication, November 2008). However, fine-grained sediments are also vital in the overall fluvial transport of contaminants in a water system. Channel storage of fine sediment (and the contaminants contained therein) follows a seasonal cycle. This cycle is subject to hydrologic variability, with increased availability during the peak flows of spring and decreased availability during the low stands of autumn. Fine-grained sediments do not travel downstream in a single pulse, but they are often re-suspended bottom material (Miller et al. 1984). The intermittent transport of contaminants and fine-grained sediment increases the affected area.

Inventory, Monitoring, and Research Suggestions for Sediment Load and Channel Storage

- Measure and document changes in the hydrologic regime, focusing on impacted areas along the parkway. These include roadways, trails, and visitor and administrative facilities.
- Correlate tributary watershed disturbance with sediment load in streams and reductions in biological productivity.
- Use sediment coring to provide a historical perspective on sediment cycling throughout the history of the parkway region.
- Perform channel morphology studies in tributary watersheds in relation to intense seasonal runoff. Consult professional geomorphologists concerning erosional processes.
- Inventory current tributary channel morphological characteristics and monitor changes in channel morphology.

General Geology and Miscellaneous Action Items

As described in the sections above, potential uses of this GRI report and map could include: (1) identifying and describing critical habitats for rare and endangered plants; (2) assessing hazards for floods, rockfalls, slumps, etc.; (3) creating interpretive programs for illustrating, in layperson terms, the evolution of the landscape and earth history of the park; (4) identifying the source locations of aggregate and building stone for historical reconstruction; (5) determining environmental impacts for any new construction; (6) inventorying natural features such as springs, cliffs, marker beds, fossil localities, and caves; (7) characterizing land use; and (8) defining ecological zones and implementing conservation plans (Southworth and Denenny 2003).

At a meeting held in August 2002 to assess geological monitoring objectives for the National Capital Region Vital Signs Network (including George Washington Memorial Parkway), the following geologic resource components were identified: soils/bedrock; urban soil; groundwater; bare ground/exposed rock; karst, surface water; coastal areas; and riparian areas and wetlands. Useful geologic resource management tools will include these components and their roles in the ecosystem.

Threats to these components include: (1) nutrient and chemical contamination; (2) sediment erosion and deposition; (3) urban soils disturbance; (4) shoreline changes; and (5) geohazards. Monitoring of these stresses is a priority. Development, acid rain/atmospheric deposition, climate change, abandoned mines and wells, and visitor use are primary sources of concern with regard to the natural resources at George Washington Memorial Parkway.

Inventory, Monitoring, and Research Suggestions for General Geology

- Study invertebrates found at seeps along the parkway from Great Falls to Key Bridge. Determine the relationship between their distribution and the geology of the area.
- Integration of digital geologic data with the parkway soils database (projected for completion in late 2010) would allow for correlation between the geologic parent material.
- Document locations of swelling clays, and assess any influences they may have on park resources and infrastructure, including roadways, trails, and buildings.
- Investigate “created landscapes”(human-altered) and their connection to the underlying geology.
- Collect additional topographic information at higher resolutions. LIDAR and GPS can be used for fine-scale topographic measurements. Relate topographic aspect and digital elevation models to the geology.
- Monitor non-point source pollution in the parkway area.
- Develop interpretive materials to relate the current landscape, ecosystem, biology, and human history to the geologic history of the eastern United States. Examples of connections between the geology of the parkway and human history are given in the “Geologic Features and Processes” section.
- Develop an interpretive exhibit for the geology of Theodore Roosevelt Island, including seeps on the south parkway, springs (including historic James Smith spring), and the Fall Line.

Figure 3. The Windy Run rockslide in September 2003 covered a portion of the Potomac Heritage National Scenic Trail (steps in foreground) leaving behind a large debris field of broken boulders and toppled trees. NPS Photo courtesy Ben Helwig (NPS GWMP).

Figure 4. The source area and debris field ("talus apron") of a 2005 Windy Run rockslide are labeled in this 2008 photograph. Note the fractures (joints) in the Sykesville Formation bedrock. Photo courtesy Callan Bentley (Northern Virginia Community College).

Figure 5. Following Hurricane Isabel in September 2003, the Potomac River completely filled Mather Gorge along the northern stretches of the parkway. The narrow rocky river valley, typical of the Piedmont Province, facilitates rapid rises in water level during such events. NPS photo courtesy Ben Helwig (NPS GWMP).

Figure 6. Debris associated with the Hurricane Isabel storm surge at Gravelly Point covers a portion of the Mount Vernon Trail (paved path in foreground). In the southern portions of the parkway, below the Fall Line, the wide Potomac River valley is susceptible to flood hazards over a wide area. The Potomac River can be seen across the center of the photo. NPS photo courtesy Ben Helwig (NPS GWMP).

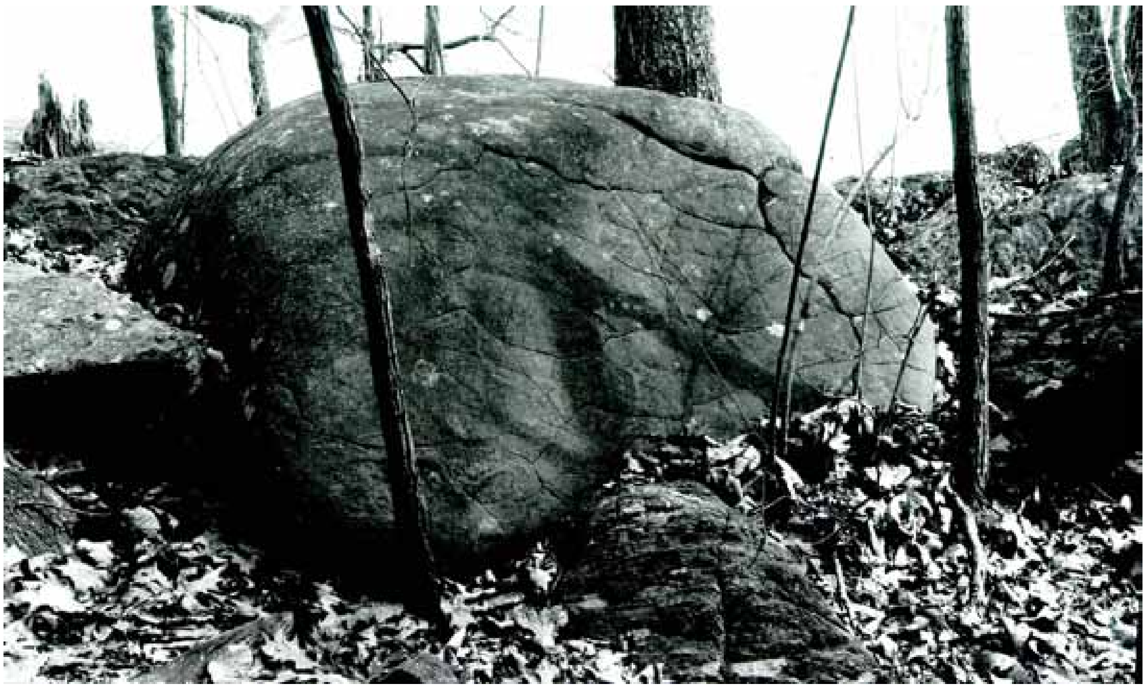

Figure 7. Large boulder deposited on the oldest recognizable terrace in the George Washington Memorial Parkway. The boulder is along the River Trail on Glade Hill in Great Falls Park. U.S. Geological Survey photo by Dave Usher.

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in George Washington Memorial Parkway.

Terraces and Flooding of the Potomac River

The deposition and erosion that defines the landscape of the Potomac River valley began millions of years ago. The distribution of ancient river terraces and flood plain deposits record the evolution of the drainage system. Most evidence indicates that the river has cut straight downward over the past five million years through bedrock using its earliest course with minimal lateral migration (Southworth et al. 2001). In the parkway area, 5.3-million-year-old Miocene–Pliocene fluvial deposits occur 101 m (330 ft) above the present river level, and more than 5 km (3 mi) away above Great Falls. Historically, the river's slope appears to have changed little, and geologists attribute the downcutting to global sea level changes or local uplift (Zen 1997a, 1997b; Reusser et al. 2004).

Terraces form when a river changes its rate of downcutting in response to a change in climate or tectonic conditions. A new channel erodes/cuts into the stream bottom, and the former riverbed remains behind as a remnant to be weathered and vegetated. As many as six different terrace levels exist along different stretches of the Potomac River (Southworth et al. 2001). The oldest Quaternary terrace deposits in the parkway area rest atop Glade Hill in Great Falls Park at 64 m (210 ft) above sea level. Along the River Trail, large boulders attest to the river's former elevation approximately 45 m (140 ft) above sea level (fig. 7). Correlation of these different levels is difficult on a regional scale because of weathering, different geologic substrates, and modern development.

The floodplain of the Potomac River is broad, often wider than 1 km (0.6 mi). A large portion of the river's edge along the parkway is part of the floodplain. In the 1800s, settlers and farmers cleared many of the buffering trees along the riverbank for agriculture. The park is encouraging the reestablishment of native plant life along the river to buffer erosion during floods and to absorb (in part) potentially harmful nutrients, waste, and sediments from nearby developments.

Although floods evoke thoughts of disasters in the form of lost property and resources, they are a natural process and are vital to soil formation in fertile floodplain areas. Sediments deposited on the eastern side of Theodore Roosevelt Island contributed to the development of natural wetland areas. Floodplains, by definition, are areas of land adjacent to rivers covered on a regular basis by water during high river flows.

The U.S. Geological Survey maintains gauges at several locations to measure the stream flow of the Potomac. Hydrographs are available at the following website: http://md.water.usgs.gov/surfacewater/streamflow/. The website details the location, drainage area, station type, peak streamflow, daily streamflow, and contact information for the gauges.

According to the National Oceanic and Atmospheric Administration, there were 85 floods above a flood stage of 3 m (10 ft) at Little Falls between 1930 and 2008 (http://www.erh.noaa.gov/marfc/Rivers/FloodClimo/Months/pot/). This averages more than one per year with the potential to cause serious damage to low-lying areas along the river's edge including long portions of the parkway. Seven major floods have occurred since 1930—on March 19, 1936; April 28, 1937; October 17, 1942; June 24, 1972; November 7, 1985; January 21, 1996; and September 9, 1996—demonstrating the non-seasonal variability in water flow. These floods were large enough to inundate Bear Island and Great Falls Park Visitor Center. Peak flow for all but the September 1996 flood exceeded 300,000 cubic feet per second (cfs) at the Little Falls gauge station. Flows of about 240,000 cfs are enough to turn the higher points on Bear Island into isolated islets and cause the national parks flanking the river to take emergency measures (E. Zen, University of Maryland, personal communication, 2008). When the islands are fully submerged, the river level near Great Falls is practically linearly dependent on the flow value recorded at Little Falls. This relationship exists because the valley walls above the level of the islands only gradually splay out (E. Zen, University of Maryland, written communication, November 2008).

The Fall Line and Great Falls Park

The Piedmont physiographic province, underlain by resistant metamorphic rocks, meets the unconsolidated sedimentary layers of the Atlantic Coastal Plain along a relatively narrow, topographically pronounced zone known as the Fall Line. Rivers crossing the Fall Line show a sudden change in morphology, but perhaps none more so than the Potomac. The bed of the river at the Fall Line consists of rock, with channels and depressions as deep as 24 m (80 ft) (Reed 1981). At this point, the Potomac River plunges from Olmstead Island over a series of steep, jagged rocks through Mather Gorge at Great Falls Park (see cover image and fig. 8) located at the northwestern terminus of the parkway. The roar of the river is audible at great distances as it drops 23 m (76 ft) in elevation.

During George Washington's time (mid 1700s), many people considered this feature a serious obstacle to trade rather than a natural wonder, and sought a route to link the eastern seaboard with new settlements in the Ohio River valley. Thus, George Washington and other national leaders formulated a plan to develop a system of canals along the Potomac to allow navigation to proceed for over 322 km (200 mi). The remains of the Patowmack

Canal (fig. 9) of the Great Falls stand as a testament to the engineering ambition of the first U.S. President. These and other attempts to navigate the treacherous Potomac River valley had profound effects on the history of the area.

In 1785, construction on the canal system was initiated by the Patowmack Company as the first in a series of canals intended to make the river navigable. Slaves, immigrants, and indentured servants completed construction on the system in 1802. In order to navigate around the falls, locks were required (fig. 9). In other locations, developers simply dredged the existing riverbed. The venture proved a failure as mounting costs, river floods, poor construction materials, sedimentation, and seasonal variations took their toll. The Chesapeake and Ohio Canal Company (which later operated a canal on the Maryland side of the river) purchased the existing Patowmack Canal sections in 1828 but abandoned the canal entirely in 1830.

Dyke Marsh and Biodiversity

Just south of Old Town Alexandria is Dyke Marsh, a remnant wetland along the Potomac River. This area, named Dyke Marsh Wildlife Preserve, is composed of 154 ha (380 acres) of tidal freshwater marsh, swamp forest, and river floodplain. It is one of the largest tidal marshes administered by the National Park Service. The marsh dates back to perhaps 1480 ± 40 years (M. Pavich, USGS, personal communication, September 2009) suggesting a more recent and rapid development of the marsh than earlier studies such as Myrick and Leopold (1963) who estimated an age of 5,000 to 7,000 years old. Its existence serves as a history lesson to the changes in attitude in environmental management. In the 1800s, the consensus was that wetlands were "improvable wastelands." Developers diked portions of the marsh in the 1800s to create "fast land"—i.e., land that would not be flooded by tides flowing up the Potomac River. This new land was used to graze livestock and for other agricultural purposes. Dredging of large portions of the marsh for sand and gravel during the 1950s and 1960s greatly disturbed the environment at Dyke Marsh. As emergent marsh land was removed, water depth deepened considerably. Note changes in amount of emergent land between the 1959 and 1996 photos in figure 10. Changing attitudes toward wetlands, aided by improvements in modern medicine related to treatment and prevention of malaria, saved the marsh that people now perceive as a crucial component of a healthy watershed.

Incredible biodiversity exists in the area of Dyke Marsh. Geology, climate, and biology interact to encourage this diversity. Small changes to wetland elevation due to flooding or development appear to have major impacts on the ecosystem. At least 54 species of plants and animals listed as rare, threatened, or endangered exist within the parkway boundaries. Many of these rare species are associated with specific plant communities of the Potomac River Gorge. Locations such as Bedrock Terrace Rim Xeric Forest and Bedrock Terrace Xeric Savanna are directly correlated with the underlying geology. Many rare forest types are located on the bedrock terraces (Coastal Plain/Piedmont basic seepage swamp, Riverside Bedrock Terrace Pine Woodland, Potomac River Bedrock Terrace Oak–Hickory Forest); exposed rocks (Central Appalachian/Piedmont riverside prairie, Potomac Gorge riverside outcrop barren); ridges; and flooded shorelines (Abrams and Copenheaver 1999; Fleming et al. 2006). Parkway scientists discovered a new crustacean species as recently as 1995 in a freshwater seep.

Theodore Roosevelt Island

The Potomac River widens as it passes through the Potomac Gorge from the Piedmont onto the Atlantic Coastal Plain. It meanders as a broad river from below Theodore Roosevelt Island to the Chesapeake Bay. Theodore Roosevelt Island is the last bedrock island along the river above its wide course to the bay. The island thus marks the Fall Line with bedrock exposures on the northern shoreline (Piedmont) and swamp and tidal marshes on the southern shoreline (Atlantic Coastal Plain).

Algonquin Indians, who named it Analostan Island, first inhabited the island and used it for hunting and fishing. Under the ownership of Lord Baltimore, it was referred to as "My Lord's Island." A summer estate owned by John Mason on the (then named) "Mason's Island" burned during the Civil War. The National Park Service acquired the island from the Theodore Roosevelt Memorial Association to serve as a living monument. After being entirely cleared for agriculture, the 36-ha (88-acre) island now contains upland forest, swamp, and tidal marshes, due to the efforts of the Civilian Conservation Corps in the mid 1930s as well as natural processes influenced by the Potomac River.

Potential Paleontological Resources

According to the NPS paleontological resource summary report prepared by Kenworthy and Santucci (2004), there is little potential for paleontological resources in the rocks underlying George Washington Memorial Parkway. Quaternary alluvial deposits may include clasts containing fossils or trace fossils eroded from elsewhere. Likewise, Pleistocene-age gravel, sand, silt, and clay deposits; terrace gravel deposits; and the Cretaceous-age Potomac Formation (well known in other parts of the National Capital Region for its leaf and stem impressions, as well as rare silicified tree trunks in a clay-dominated lithofacies) are found within and surrounding the parkway, and may contain paleontological resources (Kenworthy and Santucci 2004; Southworth and Denenny 2006).

Sediments within Dyke Marsh contain tree, shrub, and herb pollen in Pleistocene gravels (Myrick and Leopold 1963; Kenworthy and Santucci 2004). Recent collaborations with the U.S. Geological Survey resulted in sediment coring in areas of Dyke Marsh. Cores contain seeds and pollen that will be useful for radiocarbon dating and paleoclimate studies (V. Santucci, NPS GWMP; E. Oberg, NPS GWMP; and M. Pavich, USGS, written communication, December 2008).

Researchers at the U.S. Geological Survey and George Washington Memorial Parkway hope to obtain cores in other areas. Cores were obtained in Fort Hunt Park, in May 2009 (M. Pavich, USGS, personal communication, September 2009).

Geologic Influences on the History of George Washington Memorial Parkway

The geology of the area has historically attracted humans to the Potomac. The Potomac River valley is rich in archeological resources, documenting human habitation in the area for the past 10,000 years. Ancient peoples came to use unique stones (e.g., flint) and established base camps and processing sites in several locations. The river environment provided American Indians with an abundance of fish, game, and numerous plant species. The availability of wood, stone, shell, and bones fostered tool manufacture and trade. This connection with the past is a highlight of George Washington Memorial Parkway.

Geologic features and processes played a vital role in early European settlement. The area around the Potomac River provided fertile floodplains and necessary resources for local inhabitants, and also facilitated trade. The geology of the area created natural sites for river crossings and fords. Early railroads and roads often followed the patterns of natural geologic features.

However, the rapids and falls associated with the Fall Line were barriers to river navigation. Bypassing Great Falls, George Washington's Patowmack Canal (Virginia side) and the Chesapeake and Ohio Canal (Maryland side) supported commerce from 1802 to 1830 and 1830 to 1924, respectively. Destructive Potomac River floods contributed to the ultimate failure of these enterprises.

The geologic history of the area formed strategically important areas of high topography, critical to defense of Washington, D.C. Bluffs of metamorphic rock (Sykesville Formation) provided a vantage point for Fort Marcy, part of the Civil War Defenses of Washington, above Chain Bridge. During the Spanish-American War, Fort Hunt was constructed upon river terrace deposits to guard the river approach to the capital. George Washington built Mt. Vernon in this location in part for the view afforded by the topographically high terrace deposits (Southworth and Denenny 2006).

In addition to strategic topographic positions, rocks along the parkway provided raw material for building stones in the late 1800s. Rocks such as pyroxenite, serpentinite, talc schist, and soapstone (Georgetown Intrusive Suite) near parkway headquarters and Sykesville Formation gneiss below Chain Bridge were all quarried for building stone (Southworth and Denenny 2006). The same joints and fractures that facilitate rock falls aided quarrying (Southworth and Denenny 2006). Many of the steep "scarps" along the Potomac River near Chain Bridge and within Turkey Run Park may be high walls left over from quarrying operations (D. Steensen, NPS Geologic Resources Division, personal communication, September 2009). Precious metals, including gold, have also been mined in the area. Near Great Falls, the Maryland Mine and Ford Mine within C&O Canal National Historical Park on the Maryland side of the river are just two examples near the parkway. Gold may have also been discovered near Glen Echo Park (Kuff 1987).

Landscape Preservation

One of the major goals of the National Park Service is to preserve the historical context of the area; this includes preserving and restoring old buildings and the landscapes surrounding them. Maintaining this landscape often means resisting natural geologic changes, which presents management challenges. Geologic slope processes of landsliding, slumping, chemical weathering, and slope creeping are constantly changing the landscape at the park. Runoff erodes sediments from open areas and transports sediment particles down streams and gullies. Erosion naturally diminishes higher areas, fills in the lower areas, and distorts the historical context of the landscape.

Issues arise from opposing values between cultural and natural resource management. For example, a proposal for restoration of a historic building may consist of removing surrounding natural resources or planting exotic plant species. Streams and rivers in the parks are also sometimes changed to preserve fish habitat and to protect trails, buildings, and stream banks from being undercut. These efforts may entail alteration of natural geologic processes.

Figure 8. Photograph in autumn looking north to the Great Falls of the Potomac River. The falls presented a significant barrier to commerce. NPS Photo.

Figure 9. Lock 1 of the Patowmack Canal within Great Falls Park. With construction beginning in 1785, and spearheaded by George Washington, the Patowmack Canal was an early attempt to bypass the Great Falls and open trade to the west. NPS Photo.

Figure 10. Aerial photos illustrate the impact of human activity at Dyke Marsh. The natural extent of the marsh (visible in the 1937 and 1959 photos) was diked to dry land for grazing in the late 1800s through the early-mid 1900s. Dredging operations in the 1950s and 1960s removed approximately a third of the emergent marsh, those areas are now submerged under much deeper water (1996 and 2007 photos). The "thumb" of land visible to the south of Dyke Marsh in the 1937 photo was one of the first areas to be dredged, and does not appear in subsequent photos. Photographs span approximately 3.5 km (2.25 miles) north to south. Information from B. Steury (NPS, GWMP, personal communication, July 2009). Images from the parkway's GIS files; courtesy Ben Helwig (NPS GWMP).

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of George Washington Memorial Parkway. The accompanying table is highly generalized and is provided for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of the Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for George Washington Memorial Parkway informed the "Geologic History," "Geologic Features and Processes," and "Geologic Issues" sections of this report. Geologic maps are essentially two-dimensional representations of complex three-dimensional relationships. The various colors on geologic maps represent rocks and unconsolidated deposits. Bold lines that cross and separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a geographic information system (GIS) increases the utility of geologic maps and clarifies spatial relationships to other natural resources and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps do not show soil types and are not soil maps, but they do show parent material, a key factor in soil formation. Furthermore, resource managers have used geologic maps to make correlations between geology and biology; for instance, geologic maps have served as tools for locating threatened and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where future earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Geologic maps will not show where the next landslide, rockfall, or volcanic eruption will occur, but mapped deposits show areas that have been susceptible to such geologic hazards. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by various geomorphic features that are shown on geologic maps. For example, alluvial terraces may preserve artifacts, and inhabited alcoves may occur at the contact between two rock units.

The features and properties of the geologic units in the following table correspond to the accompanying digital geologic data. Map units are listed from youngest to oldest. Please refer to the geologic time scale (fig. 11) for the age associated with each time period. This table highlights characteristics of map units such as susceptibility to hazards; the occurrence of fossils, cultural resources, mineral resources, and caves; and the suitability as habitat or for recreational use.

GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes and graphics, and report. The following references are source data for the GRI digital geologic map for George Washington Memorial Parkway:

Southworth, S., and D. Denenny. 2006. *Geologic Map of the National Parks in the National Capital Region, Washington, D.C., Virginia, Maryland and West Virginia*. Scale 1:24,000. Open File Report OF 2005-1331. Reston, VA: U.S. Geological Survey.

Southworth, S., D.K. Brezinski, R.K. Orndorff, P.G. Chirico, and K. Lagueux. 2001. *Digital Geologic Map and Database of the Chesapeake and Ohio Canal National Historical Park, District of Columbia, Virginia, Maryland, and West Virginia*. Scale 1:24,000. Open File Report OF 2001-188A and 2001-188B. Reston, VA: U.S. Geological Survey.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall quality and utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase, shapefile, and coverage GIS formats, layer files with feature symbology, FGDC metadata, a Windows HelpFile that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Map Units within George Washington Memorial Parkway

The map units exposed along George Washington Memorial Parkway include those of the Potomac Terrane of the Piedmont physiographic province and the Atlantic Coastal Plain deposits. The sedimentary and igneous rock deposits of the Potomac Terrane were thrust along faults during deposition in a Neoproterozoic–Early Cambrian oceanic trench setting mixed with unconsolidated sediments to form a mélange (i.e., a mixture) of rocks. This mélange was then metamorphosed into deformed crystalline rocks that now comprise the map units found along the northern reaches of the parkway.

The quartz-rich schists, gneisses, migmatites, and metagraywackes of the Mather Gorge Formation thrust upon younger, mixed origin phyllonitic rocks (mélange) of the Sykesville Formation along the Plummers Island thrust fault. Closely resembling the Sykesville Formation is the Cambrian age Laurel Formation (Southworth et al. 2001). The variety of rock types in these formations includes migmatites, ultramafic rocks (talc, actinolite schist, serpentinite), amphibolite, vein quartz, and granitoid and schist cobbles (Drake and Morgan 1981).

The Cambrian Sykesville Formation and similar bedrock underlie the bluffs (Potomac Palisades) in Washington, D.C. and on Theodore Roosevelt Island. Several Ordovician mafic and felsic igneous intrusions penetrate the Sykesville and Mather Gorge formations. Rocks that intrude the Sykesville Formation in the parkway area include the Georgetown Intrusive Suite, pegmatite, vein quartz lamprophyre dikes, amphibolite sills, Clarendon Granite, Kensington Tonalite, Dalecarlia Intrusive Suite, and Bear Island Granodiorite (Southworth and Denenny 2006).

Cretaceous sands, dark gray silts and clays, and quartzose gravels of the Potomac Formation dominate the map units found southeast of the Fall Line, downstream from Theodore Roosevelt Island (Southworth and Denenny 2006). Overlying this unit are upland terrace deposits. Lower terraces containing sand, silt, gravel, estuarine deposits, and peat underlie much of the broad flood plain flanking the Potomac River at the parkway (Southworth and Denenny 2006).

Elsewhere, artificial fill and locally limonite-cemented alluvial clays, silts, sands, and lowermost colluvial gravels vary in age from the middle Miocene to modern alluvium (Maryland Geological Survey 1968; Southworth et al. 2001). Prominent among these later sediments are terrace deposits perched atop bedrock ledges carved by the Potomac River (Southworth et al. 2000b, 2001). The oldest of these boulder bed deposits is less than one million to about 10 thousand years old at Glade Hill (fig. 7; E. Zen, University of Maryland, written communication, November 2008).

Map Unit Properties Table

Map units that are shaded gray are not mapped within George Washington Memorial Parkway, but are present on the regional geologic map data set.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (RECENT)	Disturbed ground and artificial fill (Qdgf)	Mix of boulders, rip rap, unsorted fill, and other materials associated with disturbed lands used in road construction, urban development, water management facilities, and other purposes.	Low	Units are used for development. Avoid highly permeable and/or undercut areas.	Units may fail if present on a steep slope and/or water saturated.	None documented	May contain modern artifacts and information about historic development.	None	None	None documented	Suitable for most recreation unless present on a steep slope.	Older deposits may contain a record of historic human developments.
QUATERNARY (HOLOCENE)	Alluvium (Qa)	*Qa* contains broad deposits flanking active stream channels of sand, gravel, clay, and silt layers.	Very low	Avoid stream edge/riparian areas for heavy development, especially for wastewater treatment facilities, due to proximity to water and high permeability.	Associated with stream banks and riparian zone areas, and may be unstable if exposed on a slope or water saturated.	Modern remains	May contain artifacts and/or settlement sites along major waterways.	None	Sand, gravel, silt, clay	Riparian zones and burrow habitat.	Suitable for some trail development.	Contains a record of modern stream valley development throughout the Quaternary.
QUATERNARY (HOLOCENE & PLEISTOCENE)	Terrace deposits, low level (Qt) Colluvium (Qc) Debris (Qd) Landslide (Ql)	*Qt* deposits are concentrated near stream confluences and contain reworked alluvial sand, gravel, silt, and clay, as well as larger colluvium clasts. *Qc* often fills broad hollows in meadow areas and contains relatively unsorted fine-grained fragments in layers of variable thickness. *Qd* is a heterogeneous mix of fine and coarse fragments, often found filling hillslope depressions. *Ql* contains a jumbled mix of large rock fragments in an unsorted sand, gravel, clay, and silt matrix.	Very low	Avoid most terrace and colluvium deposits for heavy development due to instability of slopes and high permeability.	Units are associated with stream edge slopes and mass movements deposited by gravity, water, and debris flow processes.	May contain modern remains and plant fragments, pollen (from trees, shrubs, and herbs), and petrified logs.	May contain artifacts and/or settlement sites along major waterways.	None	Cobbles, gravel, sand	Forms upland areas supporting larger trees and bushes with more soil development along waterways.	Avoid areas near slopes due to likelihood of failure.	Terrace units record the evolution of local waterways and changes in channel morphology. Mass movement processes detail erosion and weathering of bedrock.
QUATERNARY (PLEISTOCENE)	Low-level fluvial and estuarine deposits (Qte) Upper-level fluvial and estuarine deposits (Qfe)	*Qte* contains sand, gravel, and peat interbedded with thin silt and clay beds with scattered pebbles and cobbles. This unit is incised into younger fluvial and estuarine deposits. *Qfe* contains modern swamp deposits overlying bedrock in Washington, D.C. area.	Low	Avoid for most development due to presence of modern swamp areas and high permeability, as well as proximity to water.	Heterogeneity of units may render them unstable on slopes, especially if undercut by local waterways.	Wood fragments, limonite-filled root zones, may contain silicified bald cypress logs and mammal fossils.	May contain artifacts.	None	Clay, sand, gravel, peat	Units underlie much of metro Washington, D.C. area.	Units should be avoided for heavy develop-ment due to the presence of modern swamp deposits.	Units may contain some record of the evolution of land use in the Washington D.C. area.
QUATERNARY (PLEISTOCENE) & TERTIARY	Terrace deposits, upper level (QTt)	Unit contains sand and gravel in beds as much as 15 m (50 ft) thick. Local incision into underlying Cretaceous units is possible.	Low	Avoid most terrace deposits for heavy development due to instability of slopes and high permeability.	Unit thickness and presence along upper valley areas may increase likelihood of slope instability and mass wasting.	Plant fragments and recent remains possible	May contain artifacts.	None	Sand, gravel	Upper deposits support hardwood forests.	Suitable for most recreation unless high slopes are present.	Unit records changes in climate and tectonic uplift with incision history.
TERTIARY	Terrace deposits (Tt) Highest level upland terrace deposits (Ttu)	Units have layered mixtures of gravel and sand, with sandy gravel and gravelly quartz sand layers containing large pebbles and cobbles of vein quartz and quartzite. Terraces occur at various elevations above sea level: at 94, 110, 113, and 122 m (310, 360, 370, and 400 ft).	Low	Suitable for light development. Avoid for waste water treatment facility develop-ment due to high permeability.	Heterogeneous nature of units may render them unstable on slopes. Units are prone to gullying, especially at higher levels. Layered nature of units may render sheet flow a possible hazard.	Plant fragments and recent remains possible.	May contain artifacts.	None	Sand, gravel, clay, pebbles, silt	Units support upland forest areas along waterways.	Suitable for light recreation unless highly gullied and/or undercut on a slope.	Units record the movement of waterways across the landscape throughout the Tertiary, and contain evidence of changing climatic and tectonics.

Map units that are shaded gray are not mapped within George Washington Memorial Parkway, but are present on the regional geologic map data set.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (PLIOCENE)	Yorktown Formation and Bacons Castle Formation, undivided (Tyb)	Unit contains quartz and feldspar sands and gravels in planar and crossbedded thin to thick, fine- to coarse-grained, poorly to well-sorted beds. Some clay and silt occurs as matrix material in yellowish to orangish gray outcrops.	Low	High permeability of unit may prove unsuitable for waste treatment facility development. Heterogeneity of layers may render them unstable along slopes, and especially if undercut by erosion.	Mass movements are likely for units when water saturated.	*Ophiomorpha nodosa* present in beds and estuarine remains.	Contains fossil shells used for early trade.	None	Gravel, sand, silt, clay, pebbles, cobbles	High level habitat. May provide burrowing habitat.	Good for most recreation unless undercut. Present as cliffs along waterways, or water saturated.	Unit records Pliocene depositional environments that are correlative throughout the region.
TERTIARY (MIDDLE MIOCENE)	Calvert Formation (Tc)	Unit is mostly fine to very fine quartzose sand with some variable silt and clay layers. Unit is thickly bedded with mappable sand-silt-clay sequences. In outcrop, unit appears grayish olive, light gray to white, pinkish gray, and pale yellowish orange.	Moderately low	Suitable for most development. Avoid pebbly layers for waste treatment facilities, and avoid expandable clay-rich layers for road and trail development.	Massive bedding may be prone to large block slides when unit is undercut along rivers and gulleys.	Diatoms (including *Rhaphoneis diamantella*); fish and shark teeth; scales; shell fragments; lignitized wood; marine vertebrate bones; silicoflagellates; dinocysts; and plant remains of oak, elm, holly, bean leaves, sumac, supplejack, blueberry, and fetterbrush species.	Kaolinite may have been used for painting and dyes.	None	Gravel, sand, kaolinitic clay (diatomaceous and expandable), pebbles, cobbles, phosphate pebbles; kaolinite, quartzite and crystalline etched pebbles	Units cap higher hills supporting ridgetop forests.	Good for most recreation unless clay-rich layers are primary sediment type present.	Unit records Miocene age marine depositional environments.
TERTIARY (EOCENE)	Nanjemoy Formation (Tn)	Unit contains yellowish brown (weathered) to dark olive gray, greenish gray, and olive black glauconitic quartz sand. Present in layers are fine to coarse, clayey and silty, micaceous and shelly interbeds of silty and sandy clay.	Low	Suitable for most forms of development	Glauconite cemented sand may slide off slopes in large blocks or sheets, especially if water saturated.	Unit is bioturbated. Contains shell fragments and mollusks, including: *Venericardia poapacoensis*, *V. ascia*, *Macrocallista sumimpressa*, *Corbula aldrichi*, *Lucina dartoni*, *Lunatia* sp., *Cadulus* sp., clam shells, pollen, dinoflagellates, foraminifers, and ostracodes.	Iron sulfide concretions may have provided fire making materials.	None	Sand, gravel, silt, clay, glauconite, iron sulfide nodules	None documented	Suitable for most forms of recreation unless very clay-rich layers are present.	Unit records Eocene marine depositional environments
TERTIARY (EOCENE & PALEOCENE)	Marlboro Clay (Tm)	Unit is a conspicuous layer of gray clay and yellow silt-rich clay with lenses of silt present locally. Unit thickness ranges from 0 to 12 m (0 to 40 ft), and is present over a wide area.	Low	Avoid for most development as unit is slippery on slopes and acts as an aquitard locally.	Unit may precipitate mass wasting on slopes when water saturated.	Lignitic coal remains, small mollusks, foraminifera, calcareous nannoplankton, and dinoflagellates.	Clay may have been used to make pots and paint.	None	Clay	None documented	Unit makes a slippery trail base. Avoid for most recreation development.	Unit is a widespread marker bed, conspicuous in the regional stratigraphic column.
TERTIARY (PALEOCENE)	Aquia Formation (Ta)	Unit is nearly massive micaceous glauconitic quartz sand. Thickly bedded, fine to medium sands are interlayered with some clay- and silt-rich beds, as well as lenses of sandy and shelly limestone. Fresh surfaces are dark olive gray and greenish black, whereas weathered exposures are yellowish gray to orange. Unit supports an important freshwater aquifer.	Low	Suitable for most forms of development unless highly permeable layers are present, or significant heterogeneity exists locally, which may cause unit to be unstable.	Glauconite cemented sand may slide off slopes in large blocks or sheets, especially if water saturated or undercut by poorly consolidated shelly layer.	Mollusks (*Cucullaea gigantea*, *Ostrea alepidota*, *Crassatellites* sp., and *Dosiniopsis* sp); *Ophiomorpha*-type burrows; gastropod *Turitella mortoni*; bivalves (*Ostrea sinuosa*, *Crassatellites alaeformis*, and *Cucullaea* sp.); foraminifera; dinocysts; nannofossils; pollen; burrows; molds and casts of pelecypods, and taeniodont molar fragment (see paleontological inventory for NCRN).	None documented	None	Sand, glauconite, silt, clay, ilmenite	Poor cementation may provide burrowing habitat.	Suitable for most forms of recreation unless very clay-rich layers are present.	Unit records marine to terrestrial depositional environment during the Cretaceous-Tertiary transition.

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Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (PALEOCENE) & CRETACEOUS	Brightseat Formation and Monmouth Formation, undivided (TKb)	Unit contains deposits of greenish gray clayey sand in the upper beds and dark gray, micaceous sand in the lower beds. At the base of the unit is a thin gravel layer.	Moderately low	Clay- and mica-rich layers render unit unstable locally. Avoid undercut slopes.	Unit is prone to slope processes, including slumping, creep, and sliding as semi-cohesive blocks.	Unit is fossiliferous.	None documented	None	Clay, sand, gravel	Poor cementation may provide burrowing habitat.	Suitable for most forms of recreation unless very clay-rich layers are present.	Unit records the transition between Cretaceous and Tertiary periods.
CRETACEOUS	Monmouth Formation (Km) Severn Formation (Ks)	*Km* contains basal gravels of vein-quartz pebbles below interlayered sand, clayey sand, and silty sand. *Ks* contains mixed marine deposits, including sands, silts, and clays.	Moderate	Variations in bedding, sediment type, and degree of cementation may render unit unstable on slopes.	Sand and gravel units undercut by clay-rich (less resistant) layers may pose mass wasting hazard along slopes and waterways.	Marine fossils; shell marl; 100 species of mollusks, including pelecypods bivalves; gastropods; cephalopods (nautiloid and ammonoid); ostracodes (at least 37 species); shark; ray; sawfish teeth; fish bones; otoliths; pliosaur and mosasaur; crocodile teeth; sea turtle; hadrosaur; and ornithomimid scraps (see paleontological inventory for NCRN).	None documented	Not enough carbonate present	Pebbles (some with vein quartz), pea gravel, sand, silt, clay	Poor cementation may provide burrowing habitat. Resistant units may form ledges on slopes attractive to birds.	Suitable for most forms of recreation unless very clay-rich layers are present or unit outcrops as bluffs along major waterways.	Unit records widespread Cretaceous basin with abundant life.
CRETACEOUS	Potomac Formation: undivided (Kp) Clay-dominated lithofacies (Kpc) Sand-dominated lithofacies (Kps)	Units contain alluvial and channel deposits of massive, mottled, silty clay with minor sand and thin beds of tan clayey sand. Some quartz and feldspar sand and pebbles locally grade into other layers. Local interbeds include unconsolidated coarse sand with feldspar and quartz grains, quartz gravel, montmorillonite and illite, clayey sand, and sandy silt with lignite.	Moderate, depending on degree of consolidation	Variations in bedding, sediment, and degree of cementation may render unit unstable on slopes. Generally suitable for most development.	Clay-rich massive bedded layers may spall in large blocks when unit is exposed on slope. Susceptible to slumps and slides.	Plant stems; leaf and stem impressions; silicified tree trunks; dinosaur fossils; pollen; "Mount Vernon flora" (collection of 40 species of ferns, conifers, and flowering plants); Menispermites; and fossil bones of "*Capitalsaurus*." Arundel clay contains theropod, sauropod, ornithopod, akylosaurian, and ceratosaurian dinosaur remains; fish; crocodiles; turtles; bird remains; and 25 species of angiosperm (see paleontological inventory for NCRN).	May preserve ancient campsites and relics.	None	Lignite, clays, sand, vein quartz, quartzite, and metamorphic rock pebbles and cobbles	Supports eastern hardwood forests throughout region.	Suitable for most forms of recreation unless present as bluffs along major waterways.	Very widespread unit records the Cretaceous environment along the Atlantic Coast. Dominant unit of coastal plain sediments, Early Cretaceous (Barremian?, Aptian, and Albian) age pollen and leaves dated. Some of the oldest angiosperm fossils in the world.
DEVONIAN	Lamprophyre dike (Dl)	Unit is present as linear igneous intrusions composed of lamprophyre, with dark mafic minerals present as clasts and matrix material.	Moderately high, depending on degree of alteration	Suitable for most development.	Unit may pose rockfall hazard if undercut or exposed on a slope.	None	None documented	None	Biotite, hornblende, pyroxene, and feldspar	Unit weathers to magnesium-, iron-, and calcium(?)-rich soils.	Unit is suitable for most recreation unless highly fractured.	Unit has an argon-biotite cooling age of approximately 360 million years.
ORDOVICIAN	Pegmatite (Op)	*Op* contains a non-foliated coarse-grained assemblage of muscovite, microcline, albite, and quartz.	High; may be moderately high in areas of high fracture density or alteration	Suitable for most development unless radioactive minerals are present. Avoid heavily fractured areas.	Unit is associated with steep slopes along waterways, and poses mass wasting hazard along trails and in undercut areas.	None	Large crystals may have provided trade material.	None	Muscovite, microperthitic microcline, albite, quartz crystals	Unit weathers to poor soils.	Unit is suitable for most recreation unless highly fractured.	Pegmatites may contain unusual minerals.
ORDOVICIAN	Clarendon Granite (Oc) Kensington Tonalite (Ok)	*Oc* is composed of leucocratic biotite-muscovite monzogranite that is well foliated. *Ok* consists of light gray granodiorite gneiss that is present in a well foliated 2.9-km (1.8-mile)-wide shear zone with augen and coarse porphyroblasts of microcline.	Moderately high to high depending on degree of alteration and brittle deformation	Avoid areas of intense preferential compositional weathering (along foliation). Suitable for most development unless highly weathered and/or fractured.	Units are associated with steep slopes along waterways and pose mass wasting hazard along trails and in undercut areas.	None	Interesting minerals may have provided trade material.	None	Attractive building stone material; muscovite, microcline augen, garnet, biotite, vein quartz	None documented	Suitable for most recreation unless highly weathered along foliation.	*Ok* has a Uranium-Lead radiometric age of 463 ± 8 million years old.

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Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
ORDOVICIAN	Dalecarlia Intrusive Suite: Biotite monzogranite and lesser granodiorite (Odm) Muscovite trondhjemite (Odt)	*Odm* contains biotite monzogranite. *Odt* contains muscovite trondhjemite that appears light gray to white in outcrop with a fine-grained sugary texture.	High	High mica content of some units may prove unstable for foundations.	Unit is associated with exposure on steep slopes near the parkway and may be susceptible to blockfall.	None	None documented	None	Attractive building stone material; sugary trondhjemite	Unit supports wide range of forest types.	Suitable for most recreation unless highly weathered.	*Odm* has a Uranium-Lead radiometric age of 478 ± 6 million years. *Odt* has a zircon Uranium-Lead radiometric age of 478 ± 6 million years.
ORDOVICIAN	Georgetown Intrusive Suite: Biotite-hornblende tonalite (Ogh) Quartz gabbro (Ogg) Biotite tonalite (Ogb) Garnetiferous biotite-hornblende tonalite (Ogr) Soapstone and talc schist (Qgus) Ultramafic rocks (Ogu) Pyroxenite (Ogp)	This intrusive suite contains various tonalites rich in biotite, garnet (locally), and hornblende, with ultramafic-mafic rocks, including quartz gabbro (rich in olivine and quartz), talc schists, and soapstone, and xenolith-rich areas containing ultramafic, mafic, and assorted metasedimentary rocks.	Moderate to moderately high depending on degree of alteration	Heterogeneous nature of unit, as well as heavily altered areas, may render the unit unsuitable for heavy development projects. Avoid highly fractured areas.	Unit outcrops locally as bluffs and are susceptible to mass wasting processes, including landslide and blockfall.	None	Interesting minerals may have provided trade material.	None	Units were quarried for dark greenish gray foliated pyroxenite, serpentinite, talc schist, soapstone, abrasives; garnets, quartz gabbro	Unit weathers to support an iron- and magnesium-rich soil.	Unit is suitable for most recreation unless highly altered, cleaved, and/or fractured.	*Ogh* has a zircon Uranium-Lead radiometric age of 472 ± 4 million years.
ORDOVICIAN	Bear Island Granodiorite (Ob) Granite (Ogl)	*Ob* contains a leucocratic muscovite-biotite granodiorite with coarse-grained pegmatitic textures locally in sheets, sills, and dikes of moderate size. *Ogl* is present in small dikes, sheets, and other irregular bodies, as well foliated, fine- to coarse-grained muscovite monzogranite and granodiorite. May be of the same age as *Og* and *Ok*.	High	Avoid areas of intense preferential compositional weathering (along foliation and between heterogeneous lenses). Suitable for most development unless highly weathered and/or fractured.	Unit may pose rockfall hazard if undercut or exposed on a slope.	None	None documented	None	May have been used as building stones; quartz, albite, and microcline in pegmatite, biotite, and hornblende	Unit supports wide range of forest types.	None documented	Units record wide range of tectonic conditions and intrusion events during the Ordovician.
CAMBRIAN	Sykesville Formation: Diamictite (Csd) Diamictite tectonite (Cst) Metagraywacke and schist (Csg) Chlorite-sericite phyllonite (Csp)	The Sykesville Formation is a conspicuous unit of sedimentary mélange, including diamictite, tectonite, metagraywacke, schist, and phyllonite. The unit is dominated by a gray matrix of quartz and feldspar containing distinctive round and tear-shaped cobbles of white and clear quartz. Other inclusions are large boulders of dark gray phyllonite, light gray migmatite and metagraywacke, greenish black mafic and ultramafic rocks, metagabbro, and light gray metafelsite and plagiogranite. The entire mélange was squeezed into a massive gneiss wedge.	Moderately high	Unit is fine for most development unless heavily altered and/or fractured.	Rockfall hazard when unit is exposed on slope, especially if slope and dominant cleavage direction are parallel.	Possible trace fossils	Widespread unit underlies Theodore Roosevelt island, Turkey Run Park, and American Legion Bridge.	None	Unusual and attractive building stone; lustrous phyllite, clear quartz cobbles	Unit supports wide range of forest types.	Unit is suitable for most recreation unless highly altered, cleaved, and/or fractured.	Unit records deformation conditions along the Rock Creek shear zone, and contains a record of a slope depositional setting within a collapsing basin.
CAMBRIAN	Laurel Formation (Cl)	*Cl* has a sedimentary mélange origin, and contains a matrix of quartz and feldspar that supports fragments, elongate cobbles, and bodies of meta-arenite and muscovite-biotite schist. Some local partial melting is recorded as migmatites and leucosomes.	Moderately high	Altered schist layers, as well as brittlely deformed layers, render these units locally unstable for heavy development.	Unit is susceptible to slope processes, including blockfall, landslides, slumping, and slope creep for altered, deformed, and fine-grained units.	Possible trace fossils	None documented	None	Migmatites	Unit supports wide range of urban habitat.	Altered and deformed areas of units should be avoided for most forms of recreation.	Unit records accretionary environment during Appalachian mountain-building events.
PALEOZOIC	Vein quartz bodies (PZq)	Unit is present as lenses, veins, and irregular bodies of massive white and clear vein quartz of various ages. Unit is jointed and locally foliated from tectonic stress. Unit is often present as resistant loose boulders.	Very high	Suitable for most development. Unit is very localized. Avoid highly fractured areas.	Unit is resistant to weathering and may pose a rockfall hazard if cobbles are large enough.	None	None documented	None	Massive white quartz for building stones	None documented	Suitable for most recreation.	Ubiquitous quartz-rich vein material may hold clues to tectonic history of area. Useful marker beds.

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Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
CAMBRIAN AND (OR) NEOPROTOEROZOIC	Diamictite (CZd) Mather Gorge Formation: Schist (CZms) Metagraywacke (CZmg) Migmatite (CZmm) Migmatitic metagraywacke (CZmmg) Migmatitic schist (CZmms) Migmatitic phyllonite (CZmmp) Sheared Migmatitic schist and Migmatitic phyllonite (CZmss)	*CZd* contains conglomerate in a mixed quartz and feldspar matrix. Pebbles include milky quartz and other clasts derived from phyllites, schists, etc. The Mather Gorge Formation contains a suite of metasedimentary rocks, including schist interbedded with thin metagraywacke and meta-arenite. These rocks originated as impure sandstones and shales. Original features include graded beds, soft-sediment slump folds, and clastic dikes. Muscovite-rich schist was intruded by thin quartz veins, and many layers have been metamorphosed to staurolite-kyanite grade with local migmatization in a narrow belt.	Moderately high	Heterogeneous nature of units may prove unstable for heavy foundations and development. High degree of foliation and cleavage also weakens the unit.	Metagraywackes are associated with the formation of waterfalls and rapids throughout the area and may pose rockfall hazards.	None	None documented	None	Attractive building stone; epidote, staurolite, kyanite, migmatite, and lustrous muscovite schist	Units support wide range of habitat types.	Units suitable for most recreation unless highly altered, cleaved, and/or fractured.	Units record the metamorphism and deformation associated with accretion onto the North American continent during early collision events.
CAMBRIAN AND NEOPROTEROZOIC	Metavolcanic and meta-igneous rocks of uncertain origin (CZmvmi): Ultramafic rocks (CZu) Amphibolite (CZa) Metagabbro and metapyroxenite (CZg) Soapstone, talc schist, and actinolite (CZt)	The metavolcanic and meta-igneous rocks of uncertain origin contain several differentiated units. All the units have been metamorphosed and occur as irregular bodies within the Laurel Formation (*Cl*). Ultramafic rocks include dark greenish black metagabbro and metapyroxenite. These have been altered to soapstone, talc schist, serpentinite, and dark green and black, medium- and coarse-grained amphibolite. Some actinolite schist is present locally as greenish gray and fine- to coarse-grained foliated layers.	Moderate to high depending on degree of alteration and/or deformation	High degree of alteration associated with some units may prove unstable for heavy development. Avoid fractured areas for septic systems and wastewater treatment areas.	Cobbles of soapstone and talc schist may be susceptible to rockfall locally.	None	Units underlie much of the Washington area, especially in the National Zoo.	None	Soapstone and talc schist locally quarried; pyroxene, hornblende, plagioclase, epidote, and actinolite	Unit develops into iron-, magnesium-, and calcium-rich soils that support a variety of hardwood forest types.	Unit is suitable for most recreation unless highly altered, cleaved, and/or fractured.	Rocks record extensive metamorphism and hydrothermal alteration associated with deep burial and tectonic collision events.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of George Washington Memorial Parkway, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

George Washington Memorial Parkway straddles the Fall Line, the zone between the Piedmont Plateau and Atlantic Coastal Plain physiographic provinces. As such, the parkway contains features intimately tied with the long geologic history of the Appalachian Mountains and the evolution of the eastern coast of the North American continent. The regional perspective presented here connects the landscape and geology of the park with its surroundings.

The recorded history of the Appalachian Mountains begins in the Proterozoic (fig. 11). In the mid Proterozoic during the Grenville Orogeny, a supercontinent formed, consisting of most of the continental crust in existence at that time, including North America and Africa. The sedimentation, deformation, plutonism (the intrusion of igneous rocks), and volcanism are preserved in the metamorphic gneiss in the core of the modern Blue Ridge Mountains west of Washington, D.C. (Harris et al. 1997). These rocks formed over a period of 100 million years, and are more than a billion years old, making them among the oldest rocks known in this region. They form a basement upon which all other rocks of the Appalachians were deposited (Southworth et al. 2001).

The late Proterozoic, roughly 800 to 600 million years ago, brought extensional rifting to the area. The crustal extension (pulling-apart) created fissures through which massive volumes of basaltic magma were extruded (fig. 12A). This volcanic extrusion lasted tens of millions of years and alternated between flood basalt flows and ash falls. The metamorphosed remnants of these igneous rocks are in the Catoctin greenstones of Shenandoah National Park and Catoctin Mountain Park, and in many outcrops immediately west of Thoroughfare Gap (west of Manassas National Battlefield Park).

Extensional tectonic forces caused the supercontinent to break up, forming a sea basin that eventually became the Iapetus Ocean. This basin collected many of the sediments that would eventually form the Appalachian Mountains (fig. 12B). Thick layers of sand, silt, and mud were deposited in the Iapetus Ocean, part of which became the Sykesville and Mather Gorge formations after regional deformation and metamorphism. These are the primary bedrock units within the parkway. A thick sequence of rocks, both contemporaneous and somewhat younger, caps the gneisses of the Blue Ridge Mountains and the Catoctin greenstone, and forms the substrate to the rocks of the Valley and Ridge Province west of the parkway (E. Zen, University of Maryland, written communication, November 2008). Large blocks of eroded fragments from highlands formed during the Grenville Orogeny mixed with these sediments (Southworth et al. 2000a).

Some of the sediments were deposited as alluvial fans, large submarine landslides, and turbidity flows, and the deposits today preserve the dramatic features of their emplacement. These early sediments are exposed on Catoctin Mountain, Short Hill-South Mountain, and Blue Ridge-Elk Ridge, and in areas to the west of the parkway as the Chilhowee Group (Loudoun, Weverton, Harpers, and Antietam formations) (Southworth et al. 2001).

Associated with the shallow marine setting along the eastern continental margin of the Iapetus Ocean were large deposits of sand, silt, and mud in near-shore, deltaic, barrier island, and tidal flat areas. Some of these are present west of the parkway in the Chilhowee Group in Central Maryland, including the Harpers and Antietam formations (Schwab 1970; Kauffman and Frey 1979; Simpson 1991).

In addition, huge masses of carbonate rocks, such as the Cambrian age Tomstown Dolomite and Frederick Limestone, as well as the Upper Cambrian to Lower Ordovician Grove Limestone, were deposited atop the Chilhowee Group. They represent a grand platform, thickening to the east, that persisted during the Cambrian and Ordovician periods (545 to 480 million years ago) and form the floors of Frederick and Hagerstown valleys west of the parkway (Means 1995).

Somewhat later—540, 470, and 360 million years ago—igneous granodiorite, pegmatite, and lamprophyre, respectively, intruded the sedimentary rocks, including those of the Mather Gorge Formation (Southworth et al. 2000b). During the Ordovician igneous rocks of the Georgetown and Dalecarlia intrusive suites, Clarendon Granite, Bear Island Granodiorite, as well as pegmatite and veins of quartz, intruded the Sykesville Formation within what is now the parkway (Southworth and Denenny 2006).

Several episodes of mountain building and continental collision that resulted in the Appalachian Mountains contributed to the heat and pressure that deformed and metamorphosed the entire sequence of sediments, intrusive rocks, and basalt into schist, gneiss, marble, slate, and migmatites (Southworth et al. 2000b; Southworth and Denenny 2006).

Taconic Orogeny

From Early Cambrian through Early Ordovician time, mountain building (orogenic) activity along the eastern margin of the continent began again. The Taconic Orogeny (approximately 440 to 420 million years ago in the central Appalachians) was a volcanic arc- continent convergence. Oceanic crust and the volcanic arc from the Iapetus basin were thrust onto the eastern edge of the North American continent. The Taconic Orogeny resulted in the closing of the ocean, subduction of oceanic crust during the creation of volcanic arcs within the disappearing basin, and the uplift of continental crust (Means 1995). The initial metamorphism of the igneous and sedimentary rocks of the Sykesville and Mather Gorge formations into schists, gneisses, migmatites, and phyllites occurred during this orogenic event.

In response to the overriding plate thrusting westward onto the continental margin of North America, the crust bowed downward to create a deep basin that filled with mud and sand eroded from the highlands to the east (fig. 12C) (Harris et al. 1997). This so-called Appalachian basin was centered on what is now West Virginia. These infilling sediments covered the grand carbonate platform, and are now represented by the shale of the Ordovician Martinsburg Formation west of the parkway (Southworth et al. 2001).

This shallow marine to fluvial sedimentation continued for a period of about 200 million years during the Ordovician through Permian periods, resulting in thick layers of sediments. Their source was the highlands that were rising to the east during the Taconic Orogeny (Ordovician) and Acadian Orogeny (Devonian).

Acadian Orogeny

The Acadian Orogeny (approximately 360 million years ago) continued the mountain building of the Taconic Orogeny as the African continent drifted toward North America (Harris et al. 1997). Similar to the preceding Taconic Orogeny, the Acadian event involved collision of landmasses, mountain building, and regional metamorphism (Means 1995). This event was focused farther north than the Washington, D.C. area.

Alleghanian Orogeny

Following the Acadian Orogeny, the proto-Atlantic Iapetus Ocean closed during the Late Paleozoic as the North American and African continents collided. This collision formed the Pangaea supercontinent and the Appalachian mountain belt that exists today. This mountain-building episode, termed the Alleghanian Orogeny (approximately 325 to 265 million years ago), is the last major orogeny that affected the Appalachians (fig. 12D) (Means 1995). The rocks were deformed by folds and faults to produce the Sugarloaf Mountain anticlinorium and the Frederick Valley synclinorium in the western Piedmont, the Blue Ridge- South Mountain anticlinorium (including the Catoctin Mountains), and the numerous folds of the Valley and Ridge province west of the parkway (Southworth et al. 2001).

During the Alleghanian Orogeny, rocks of the Great Valley, Blue Ridge, and Piedmont provinces were transported along the North Mountain fault as a massive block (Blue Ridge- Piedmont thrust sheet) westward onto younger rocks of the Valley and Ridge. The amount of crustal shortening was very large. Estimates of 20 to 50 percent shortening would amount to 125 to 350 km (80 to 220 mi) (Harris et al. 1997).

Deformed rocks in the eastern Piedmont were also folded and faulted, and existing thrust faults were reactivated as both strike-slip and thrust faults during the Alleghanian Orogeny (Southworth et al. 2001). Paleoelevations of the Alleghanian Mountains are estimated at approximately 6,000 m (20,000 ft), analogous to the modern-day Himalaya Range in Asia. These mountains have been beveled by erosion to elevations of less than 600 m (2,000 ft) west of George Washington Memorial Parkway (Means 1995).

Triassic Extension to the Present

Following the Alleghanian Orogeny, during the late Triassic, a period of rifting began as the deformed rocks of the joined continents began to break apart from about 230 to 200 million years ago. The supercontinent Pangaea was segmented into roughly the same continents that persist today. This episode of rifting, or crustal fracturing, initiated the formation of the current Atlantic Ocean and caused many block-fault basins to develop with accompanying volcanism (fig. 12E) (Harris et al. 1997; Southworth et al. 2001).

The Newark Basin system is a large component of this tectonic setting. Large streams carried debris shed from the uplifted Blue Ridge and Piedmont provinces creating alluvial fans at their mouths. They were deposited as non-marine mud and sand in fault-created troughs, such as the Frederick Valley in central Maryland and the Culpeper basin in the western Piedmont of central Virginia. Many of these rift openings became lacustrine basins and were filled with thick deposits of silt and sand. Such rift basin sediments are not found within the parkway, but are visible within Manassas National Battlefield Park.

Large faults formed the western boundaries of the basins and provided an escarpment that was quickly covered with eroded debris. Magma was intruded into the new sandstone and shale strata as sills (sub-horizontal sheets) and nearly vertical dikes that extend beyond the basins into adjacent rocks. After this magma was emplaced approximately 200 million years ago, the region underwent a period of slow uplift and erosion. The uplift was in response to isostatic adjustments within the crust, which forced the continental crust upward and exposed it to erosion.

Thick deposits of unconsolidated gravel, sand, and silt were shed from the eroded mountains. They were deposited at the base of the mountains as alluvial fans and spread eastward to be part of the Atlantic Coastal Plain (Duffy and Whittecar 1991; Whittecar and Duffy 2000; Southworth et al. 2001; Southworth and Denenny

2006). The Cretaceous Potomac Formation is a very thick unit of eroded material, and it is inferred that an immense amount of material was eroded from above the now-exposed metamorphic rocks. Many of the rocks exposed at the surface must have been at least 20 km (approximately 10 mi) below the surface prior to regional uplift and erosion. The erosion continues today with the Potomac, Rappahannock, Rapidan, Monocacy, and Shenandoah rivers, and tributaries stripping the Coastal Plain sediments, lowering the mountains, and depositing alluvial terraces along the rivers, creating the present landscape (fig. 12F). The parkway traverses Coastal Plain sediments southbound from Key Bridge and Theodore Roosevelt Island to the terminus at Mount Vernon (fig. 2 and inside front cover).

Since the breakup of Pangaea and the uplift of the Appalachian Mountains, the North American plate has continued to move toward the west. The isostatic adjustments that uplifted the continent after the Alleghanian Orogeny continued at a lesser rate throughout the Cenozoic Period (Harris et al. 1997).

The landscape and geomorphology of the greater Potomac River valley are the result of erosion and deposition from about the mid part of the Cenozoic Era to the present, or at least the past five million years. The Potomac, flowing southeast, cuts obliquely across north-trending geologic units. Following the trend of joints and other fractures, the river flows straight though Mather Gorge.

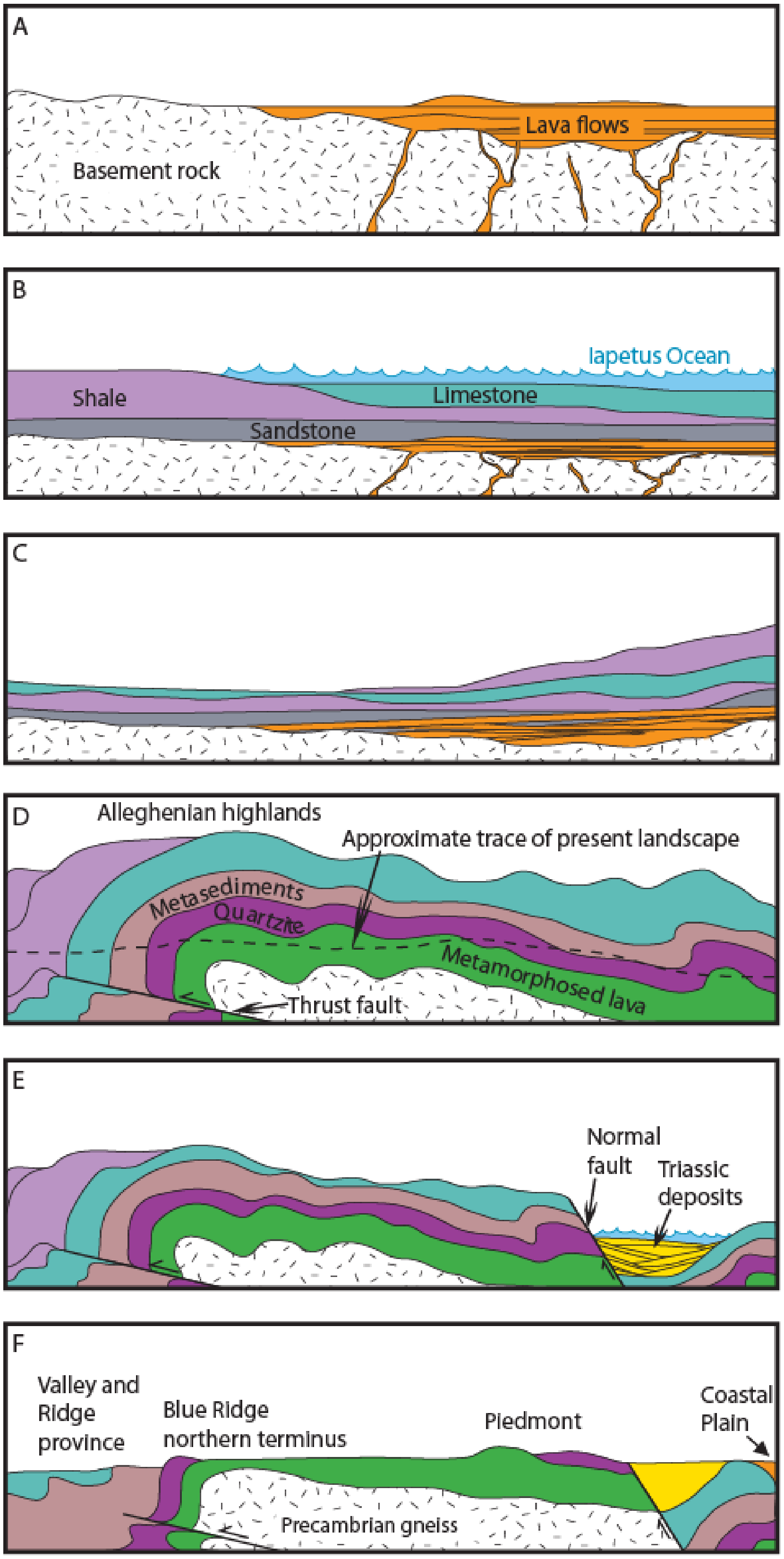
There is little to no evidence that the river migrated laterally across a broad, relatively flat region. It appears that the river cut downward through very old resistant rocks, overprinting its early course (Southworth et al. 2001).

The distribution of flood plain alluvium and ancient fluvial terraces of the regional rivers and adjacent tributaries record the historical development of both drainage systems. At this point, the river cut though bedrock and left deposits of large quartzite and diabase boulders (fig. 7). In creating these terraces, the erosional features left behind as islands, islets, pinnacles, oxbows, shoestring canals, potholes, and plungepools dot the landscape along the Potomac River today (Southworth et al. 2000b, 2001).

Although the masses of continent-scale ice sheets from the Pleistocene ice ages never reached the Washington, D.C. metropolitan area (the southern terminus was in northeastern Pennsylvania), the colder climates of the ice ages played a role in the formation of the landscape at George Washington Memorial Parkway. The periglacial conditions that must have existed at close proximity to the ice sheets intensified weathering and other erosional processes (Harris et al. 1997). The landforms and deposits are probably late Tertiary to Quaternary in age when a wetter climate, sparse vegetation, and frozen ground caused increased precipitation to run into the ancestral river channels, enhancing downcutting and erosion by waterways (Means 1995; Zen 1997a, 1997b).

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	2.6		Extinction of large mammals and birds	Worldwide glaciation
		Neogene	Pliocene	5.3		Large carnivores	Sierra Nevada Mountains (W)
			Miocene	23.0		Whales and apes	Linking of North and South America
		Paleogene	Oligocene	33.9			Basin-and-Range extension (W)
			Eocene	55.8		Early primates	Laramide Orogeny ends (W)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		199.6		First mammals	Elko Orogeny (W)
		Triassic		251		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant	Ancestral Rocky Mountains (W)
		Mississippian		359.2		Variety of insects First amphibians First reptiles	Antler Orogeny (W)
		Devonian		416	Fishes	**Mass extinction** First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of North America
Proterozoic		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust

Figure 11. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Isotopic ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy. http://www.stratigraphy.org/view.php?id=25. Note that this chart includes the August 2009 revision of the Pliocene-Pleistocene boundary to 2.59 Ma from 1.8 Ma.



800–600 Ma—Following the Grenville Orogeny and erosion, crustal extension leads to volcanism, producing flood basalt and ash flows.

650–450 Ma—Iapetus Ocean continues to widen and the basin subsides; deposits of sand, silt, and clay, shed from the nearby highlands, and marine limestone fill the basin atop the flood basalt.

450–350 Ma—Inland-sea deposition continues as the Taconic and Acadian highlands rise to the east, providing more sediment.

325–265 Ma—Alleghanian Orogeny leads to metamorphism of the rocks, which are fractured, folded, and overturned to form high mountains over the present landscape.

225–200 Ma—Following continental collision, the extensional environment creates fault-bounded basins along the eroding front of the mountain ranges, which provide sediment to the basins.

Present—Erosion bevels the mountains to the present topographic surface; deposition continues toward the eastern coast, and resistant rocks form local ridges.

Figure 12. Evolution of the landscape in the area of George Washington Memorial Parkway from the Precambrian through the present. George Washington Memorial Parkway spans the "Fall Line" between the Coastal Plain and the Piedmont. Triassic basins are not present within the parkway, but are present to the west at Manassas National Battlefield Park. Graphic adapted from Means (1995). Ma = millions of years. Drawings not to scale.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.

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

alluvium. Stream-deposited sediment.

anticline. A fold, generally convex upward, whose core contains the stratigraphically older rocks.

anticlinorium. A composite anticlinal structure of regional extent composed of lesser folds.

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

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

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

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

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

bedding. Depositional layering or stratification of sediments.

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

calcareous. Describes rock or sediment that contains calcium carbonate.

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

chemical weathering. The dissolution or chemical breakdown of minerals at the Earth's surface via reaction with water, air, or dissolved substances.

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

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

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

continental crust. The 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.

convergent boundary. An active boundary where two tectonic plates are colliding.

craton. The relatively old and geologically stable interior of a continent.

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions (e.g., direction and depth).

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

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

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

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

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

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

dike. A tabular, discordant igneous intrusion.

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

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

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

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

extrusion. The emission of relatively viscous lava onto the Earth's surface, as well as the rock so formed.

extrusive. Of or pertaining to the eruption of igneous material onto the Earth's surface.

facies (metamorphic). The pressure-temperature regime that results in a particular, distinctive metamorphic mineralogy (i.e., a suite of index minerals).

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

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

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

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

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

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

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

horst. Areas of relative up between grabens, representing the geologic surface left behind as grabens drop. The best example is the basin and range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition.

hydrogeologic. Refers to the geologic influences on groundwater and surface water composition, movement and distribution.

hydrolysis. A decomposition reaction involving water, frequently involving silicate minerals.

igneous. Describes a rock or mineral that originated from molten material. One of the three main classes of rocks—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.

isostasy. The process by which the crust "floats" at an elevation compatible with the density and thickness of the crustal rocks relative to underlying mantle.

joint. A semi-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.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

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

lava. Still-molten or solidified magma that has been extruded onto the Earth's surface though a volcano or fissure.

levees. Raised ridges lining the banks of a stream. May be natural or artificial.

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

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron.

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

mantle. The zone of the Earth's interior between crust and core.

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

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.

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

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

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

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during subaerial dehydration.

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

obduction. The process by which the crust is thickened by thrust faulting at a convergent margin.

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

orogeny. A mountain-building event.

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

overbank deposits. Alluvium deposited outside a stream channel during flooding.

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

parent (rock). The original rock from which a metamorphic rock was formed. Can also refer to the rock from which a soil was formed.

passive margin. A margin where 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. (also see "active margin").

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

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

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

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

plutonic. Describes igneous rock intruded and crystallized at some depth in the Earth.

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

radiometric age. An age in years determined from radioactive isotopes and their decay products.

recharge. Infiltration processes that replenish groundwater.

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

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

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

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

roundness. The relative amount of curvature of the "corners" of a sediment grain, especially with respect to the maximum radius of curvature of the particle.

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.

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

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

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

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

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.

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

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

soapstone. A soft metamorphic rock with fibrous or flakey texture and a soapy feel; composed primarily of talc with variable amounts of other minerals such as micas, chlorite, amphiboles, and pyroxenes. Frequently used as dimension or building stone.

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

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

strata. Tabular or sheetlike masses or distinct layers of rock.

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

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.

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 the Earth's surface.

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

synclinorium. A composite synclinal structure of regional extent composed of lesser folds.

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

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

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

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

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

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

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

trace fossils. Sedimentary structures, such as tracks, trails, or burrows, that preserve evidence of organisms' life activities, rather than the organisms themselves.

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

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

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

volcanic. Related to volcanoes. Igneous rock crystallized at or near the Earth's surface (e.g., lava).

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

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

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

References

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Abrams, M. L, and C. A. Copenheaver. 1999. Temporal variation in species recruitment and dendroecology of an old-growth white oak forest in the Virginia Piedmont, USA. *Forest Ecology and Management* 124: 275-284.

Bowser, C. J., and B. F. Jones. 2002. Mineralogic controls on the composition of natural waters dominated by silicate hydrolysis. *American Journal of Science* 302 (7): 582- 662.

Drake, A. A., Jr., and B. A. Morgan. 1981. The Piney Branch Complex – A metamorphosed fragment of the central Appalachian ophiolite in northern Virginia. *American Journal of Science* 281: 484-508.

Duffy, D. F., and G. R. Whittecar. 1991. Geomorphic development of segmented alluvial fans in the Shenandoah Valley, Stuarts Draft, Virginia. *Geological Society of America Abstracts with Programs* 23 (1): 24.

Fleming, G. P., P. P. Coulling, K. D. Patterson, and K. Taverna. 2006. *The natural communities of Virginia: classification of ecological community groups. Second approximation*. Version 2.2. Richmond, VA: Virginia Department of Conservation and Recreation, Division of Natural Heritage. http://www.dcr.virginia.gov/natural_heritage/ncintro.shtml (accessed November 2009).

Froomer, N. L. 1980. Sea level changes in the Chesapeake Bay during historic times. *Marine Geology* 35 (3-4): 289-305.

Harris, A. G., E. Tuttle, and S. D. Tuttle. 1997. *Geology of National Parks*. Dubuque, IA: Kendall/Hunt Publishing Company.

Kauffman, M. E., and E. P. Frey. 1979. Antietam sandstone ridges: exhumed barrier islands or fault-bounded blocks? *Geological Society of America Abstracts with Programs* 11 (1): 18.

Kenworthy, J. P., and V. L. Santucci. 2004. *Paleontological Resource Inventory and Monitoring, National Capital Region*. National Park Service TIC # D-289.

Kuff, K. R. 1987. Gold in Maryland. Pamphlet Series. Baltimore, MD: Maryland Geological Survey. http://www.mgs.md.gov/esic/brochures/gold.html (accessed November 2009).

Maryland Geological Survey. 1968. *Geologic Map of Maryland*. Scale 1:250,000. http://www.mgs.md.gov/esic/geo/index.html (accessed March 2005).

Means, J. 1995. *Maryland's Catoctin Mountain parks: an interpretive guide to Catoctin Mountain Park and Cunningham Falls State Park*. Blacksburg, VA: McDonald & Woodward Publishing Company.

Miller, A. J., J. A. Smith, and L. L. Shoemaker. 1984. Channel storage of fine-grained sediment in the Monocacy River basin. *Eos, Transactions, American Geophysical Union* 65 (45): 888.

Myrick, R. M. and L. B. Leopold. 1963. *Hydraulic geometry of a small tidal estuary*. Professional Paper 422-B: B1-B18. Reston, VA: U.S. Geological Survey.

Reed, J. C., Jr. 1981. Disequilibrium profile of the Potomac River near Washington, D.C. – a result of lowered base level or Quaternary tectonics along the Fall Line? *Geology* 9: 445-450.

Reusser, L. J., P. R. Bierman, M. J. Pavich, E. Zen, J. Larsen, and R. Finkel. 2004. Rapid late Pleistocene incision of Atlantic passive-margin river gorges. *Science* 305: 499-502.

Schwab, F. L. 1970. Origin of the Antietam Formation (late Precambrian?, lower Cambrian), central Virginia. *Journal of Sedimentary Petrology* 40 (1): 354- 366.

Simpson, E. L. 1991. An exhumed Lower Cambrian tidal-flat: the Antietam Formation, central Virginia, U.S.A. In *Clastic tidal sedimentology*. eds. D. G. Smith, B. A. Zaitlin, G. E. Reinson, and R. A. Rahmani. Canadian Society of Petroleum Geologists Memoir 16:123- 133.

Southworth, S., D. K. Brezinski, R. C. Orndorff, K. M. Lagueux, and P. G. Chirico. 2000a. *Digital geologic map of the Harpers Ferry National Historical Park*. Open-File Report OF 00-0297. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr00297 (accessed March 2005).

Southworth, S., D. K. Brezinski, R. C. Orndorff, P. G. Chirico, and K. M Lagueux. 2001. *Geology of the Chesapeake and Ohio Canal National Historical Park and Potomac River Corridor, District of Columbia, Maryland, West Virginia, and Virginia*. (Disc 1: A, geologic map and GIS files; Disc 2: B, geologic report and figures). Open-File Report OF 01-0188. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr01188 (accessed March 2005).

Southworth, S., P. Chirico, D. Denenny, and J. Triplett. 2002. Geology and GIS in the parks of the National Capital Region. *Geological Society of America Abstracts with Programs* 34 (6): 456.

Southworth, S., and D. Denenny. 2003. Geologic Maps Support Land Resource Management in the National Parks in the Eastern U. S. *Geological Society of America Abstracts with Programs* 35 (6): 331.

Southworth, S., and D. Denenny. 2006. *Geologic Map of the National Parks in the National Capital Region, Washington, D.C., Virginia, Maryland and West Virginia*. Scale 1:24,000. Open File Report OF 2005-1331. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr20051331 (accessed December 2008).

Southworth, S., C. Fingeret, and T. Weik. 2000b. *Geologic Map of the Potomac River Gorge: Great Falls Park, Virginia, and Part of the C & O Canal National Historical Park, Maryland.* Open-File Report OF 00-0264. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr00264 (accessed March 2005).

Whittecar, G. R., and D. F. Duffy. 2000. Geomorphology and stratigraphy of late Cenozoic alluvial fans, Augusta County, Virginia, U.S.A. In *Regolith in the Central and Southern Appalachians,* eds. G. M. Clark, H. H. Mills, and J. S. Kite. *Southeastern Geology* 39 (3- 4): 259- 279.

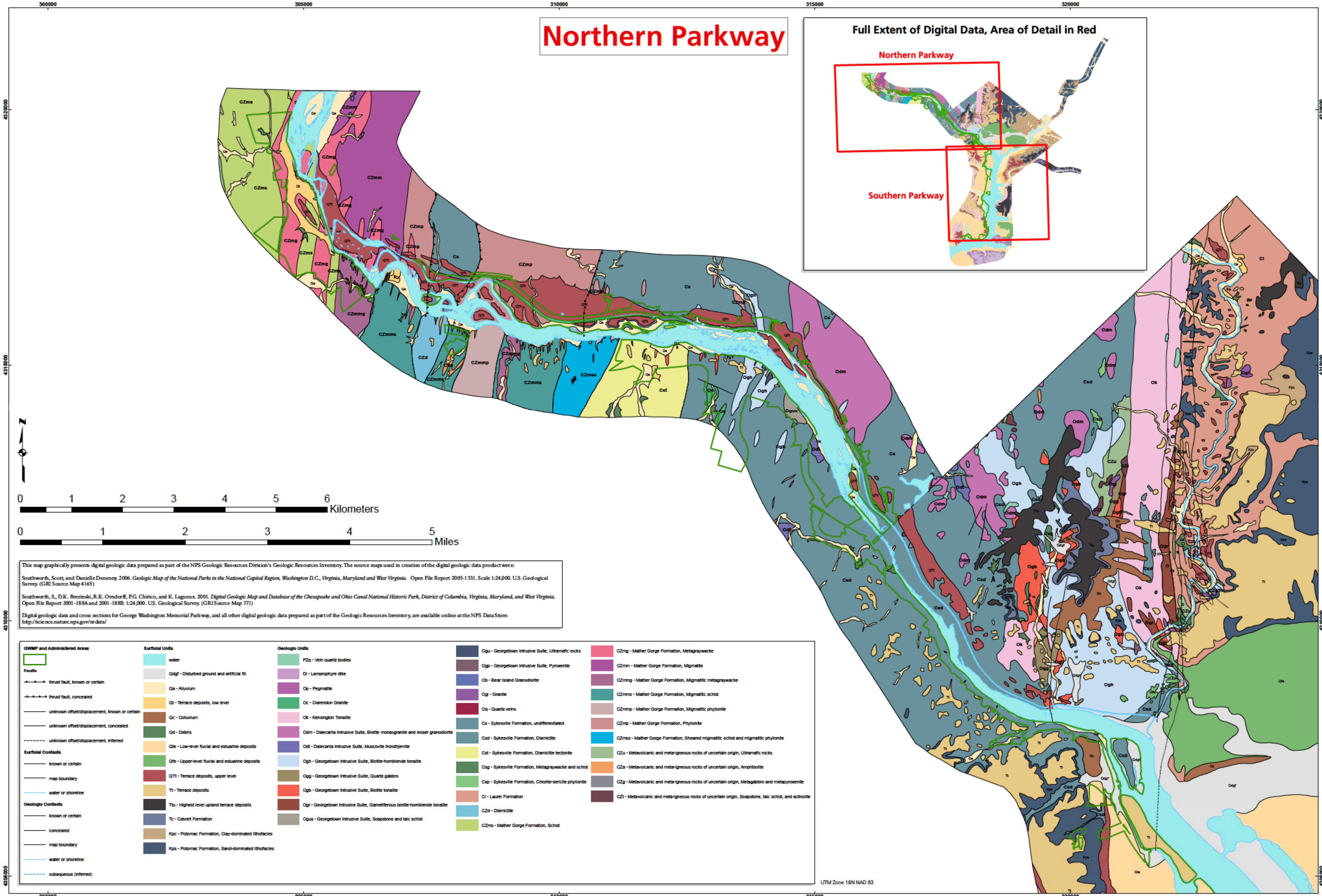
Zen, E-an. 1997a. *The seven-storey river: Geomorphology of the Potomac River channel between Blockhouse Point, Maryland, and Georgetown, District of Columbia, with emphasis on The Gorge complex below Great Falls.* Open-File Report OF 97-0060. Reston: VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr9760 (accessed March 2005).

Zen, E-an. 1997b. *Channel geometry and strath levels of the Potomac River between Great Falls, Maryland, and Hampshire, West Virginia.* Open-File Report OF 97-0480. Reston, VA: U.S. Geological Survey. http://pubs.er.usgs.gov/usgspubs/ofr/ofr97480 (accessed March 2005).

Appendix A: Geologic Map Graphic

The following page is a snapshot of the geologic map for George Washington Memorial Parkway. For a poster-size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resources Inventory publications Web page (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

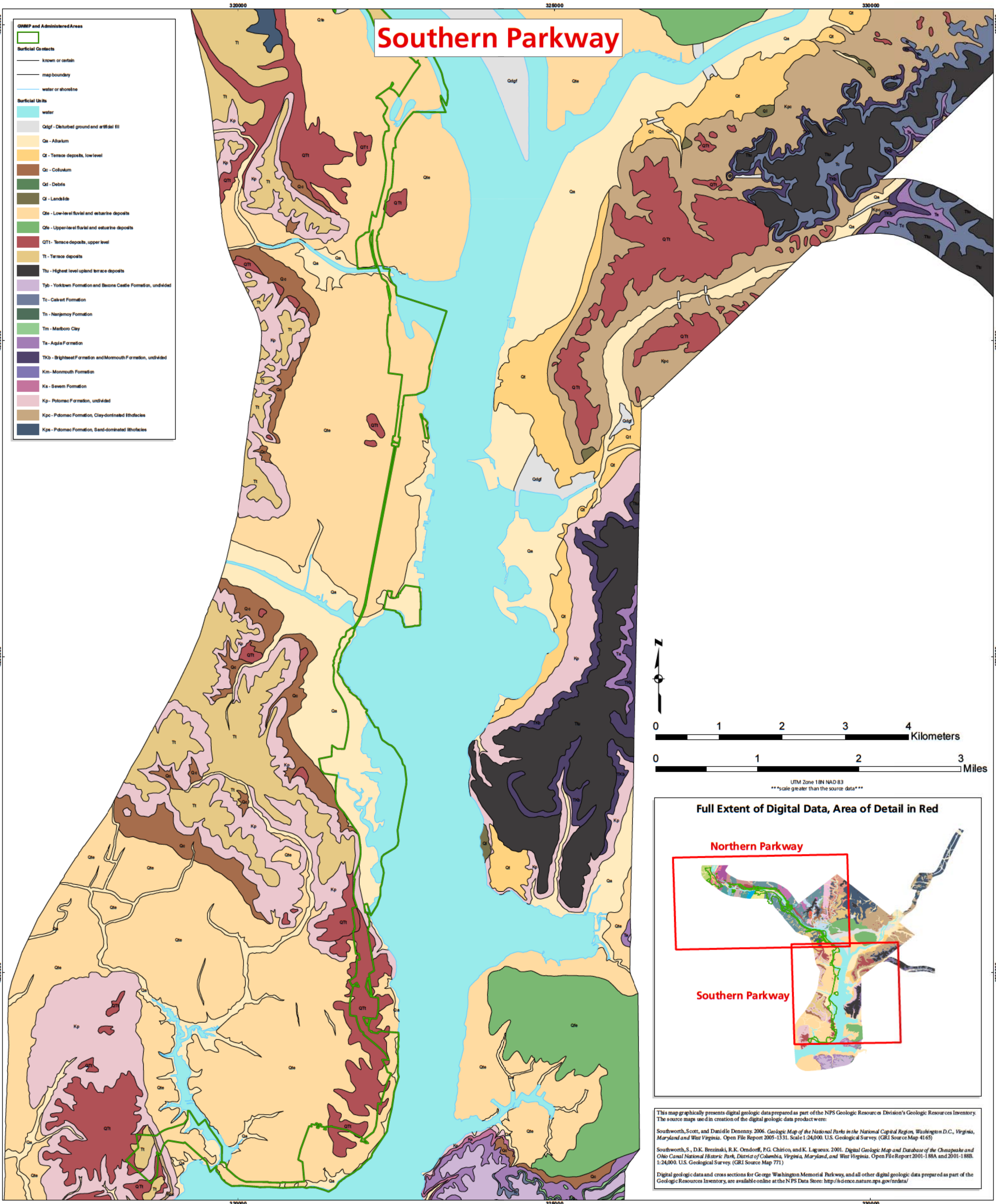
Geologic Map of George Washington Memorial Parkway



Produced by the Geologic Resources Inventory

December 2009

Geologic Map of George Washington Memorial Parkway



This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Southworth, Scott, and Danielle Denenny. 2006. *Geologic Map of the National Parks in the National Capital Region, Washington D.C., Virginia, Maryland and West Virginia.* Open File Report 2005-1331. Scale 1:24,000. U.S. Geological Survey. (GRI Source Map 4165)

Southworth, S., D.K. Brezinski, R.K. Orndorff, P.G. Chirico, and K. Lagueux. 2001. *Digital Geologic Map and Database of the Chesapeake and Ohio Canal National Historic Park, District of Columbia, Virginia, Maryland, and West Virginia.* Open File Report 2001-188A and 2001-188B. 1:24,000. U.S. Geological Survey. (GRI Source Map 771)

Digital geologic data and cross sections for George Washington Memorial Parkway, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

Appendix B: Scoping Summary

The following excerpts are from the GRI scoping summary for George Washington Memorial Parkway. The scoping meeting occurred on April 30 – May 2, 2001; therefore, the contact information and Web addresses referred to herein may be outdated. Please contact the Geologic Resources Division for current information.

Executive Summary

Geologic Resources Inventory (GRE) workshops were held for National Park Service (NPS) Units in the National Capital Region (NCR) over April 30-May 2, 2001. The purpose was to view and discuss the park's geologic resources, to address the status of geologic mapping for compiling both paper and digital maps, and to assess resource management issues and needs. Cooperators from the NPS Geologic Resources Division (GRD), Natural Resources Information Division (NRID), individual NPS units in the region, and the United States Geological Survey (USGS) were present for the workshop.

This involved half-day field trips to view the geology of Catoctin Mountain Park, Harpers Ferry NHP, Prince William Forest Park and Great Falls Park, as well as another full-day scoping session to present overviews of the NPS Inventory and Monitoring (I&M) program, the GRD, and the on-going GRE. Round table discussions involving geologic issues for all parks in the National Capital Region included the status of geologic mapping efforts, interpretation, paleontologic resources, sources of available data, and action items generated from this meeting.

Overview of Geologic Resources Inventory

It is stressed that the emphasis of the inventory is not to routinely initiate new geologic mapping projects, but to aggregate existing "baseline" information and identify where serious geologic data needs and issues exist in the National Park System. In cases where map coverage is nearly complete (ex. 4 of 5 quadrangles for Park "X") or maps simply do not exist, then funding may be available for geologic mapping.

After introductions by the participants, Tim Connors presented overviews of the Geologic Resources Division, the NPS I&M Program, the status of the natural resource inventories, and the GRI in particular.

He also presented a demonstration of some of the main features of the digital geologic database for the Black Canyon of the Gunnison NP and Curecanti NRA in Colorado. This has become the prototype for the NPS digital geologic map model as it reproduces all aspects of a paper map (i.e. it incorporates the map notes, cross sections, legend etc.) with the added benefit of being geospatially referenced. It is displayed in ESRI ArcView shape files and features a built-in Microsoft Windows help file system to identify the map units. It can also display scanned JPG or GIF images of the geologic cross sections supplied with the map. Geologic cross section lines (ex. A-A') are subsequently digitized as a line coverage and are hyperlinked to the scanned images.

Joe Gregson further demonstrated the developing NPS Theme Manager for adding GIS coverage's into projects "on-the-fly". With this functional browser, numerous NPS themes can be added to an ArcView project with relative ease. Such themes might include geology, paleontology, hypsography (topographic contours), vegetation, soils, etc.

Pete Chirico (USGS-Reston, VA) demonstrated the digital geology of Harpers Ferry and also showed the group potential uses of a digital geologic coverage with his examples for Anacostia and Cumberland Island. The USGS also showed various digital products that they've developed already for Chesapeake and Ohio Canal NHP and Great Falls.

Geologic Mapping

Existing Geologic Maps and Publications

After the bibliographies were assembled, a separate search was made for any existing surficial and bedrock geologic maps for the National Capital Region parks. The bounding coordinates for each map were noted and entered into a GIS to assemble an index geologic map. Separate coverage's were developed based on scales (*1:24,000, 1:100,000*, etc.) available for the specific park. Numerous geologic maps at varying scales and vintages cover the area. Index maps were distributed to each workshop participant during the scoping session.

Status

The index of published geologic maps are a useful reference for the NCR. However, some of these maps are dated and are in need of refinement and in other places, there is no existing large-scale coverage available. The USGS began a project to map the Baltimore-Washington DC area at 1:100,000 scale and as a result it was brought to their attention that modern, large-scale geologic mapping for the NCR NPS areas would be beneficial to NPS resource management.

Because of this, the USGS developed a proposal to re-map the NCR at large scale (1:24,000 or greater) and to supply digital geologic databases to accompany this mapping. Scott Southworth (USGS-Reston, VA) is the project leader and main contact. The original PMIS (Project Management Information Systems) statement is available in Appendix C and on the NPS intranet (PMIS number 60900); of note is that portions of it need to be changed to reflect that the source of funding will be Inventory and Monitoring funds and NOT NRPP.

Desired Enhancements in the geologic maps for NCR parks

To better facilitate the geologic mapping, Scott Southworth would like to obtain better topographic coverage for each of the NCR units. Tammy Stidham knows that some of these coverages are already available and will supply them to Scott and the USGS. In general, anything in Washington DC proper has 1 meter topographic coverage and Prince George's county has 1:24,000 coverage.

Notes on George Washington Memorial Parkway (Arlington House)

Arlington House has immediate resource management issues pertaining to the geology of the cemetery, as there are problems with stability and sliding at the site, and the sooner a geology GIS is created, the more beneficial it is likely to be to the park. The park hopes that Scott Southworth and USGS scientists will be able to assist on this issue.

Melissa Kangas and Ann Brazinksi gave us comments during our site visit. There are seep issues from Great Falls to Key Bridge. Invertebrates are found in these seeps and need studied for relationship to geology. Other geologic interpretive possibilities include the Historic Quarries of soapstone near Key Bridge and the geology of Theodore Roosevelt Island. Man-driven shoreline changes are also of interest to the park in the tidal area. Geologic hazards exist along trails for climbers. There is likely a good interpretive story of Theodore Roosevelt Island in the seeps on the south parkway in coastal plain, some springs, and the James Smith spring is of historic interest. They incorporate the fall line into the Theodore Roosevelt Island story. The website for the digital geology of Great Falls is available at:
http://geology.er.usgs.gov/eespteam/Greatfalls/INDEX.HTML

Digital Geologic Map Coverage

The USGS will supply digital geology in ArcInfo format for all of the NCR parks. GRI staff will take this data and add the Windows help file and NPS theme manager capability to the digital geology and will supply to the region to distribute to each park in NCR.

Other Desired Data Sets for NCR

Soils

Pete Biggam (GRD Soil Scientist) supplied the following information in reference to soils for parks:

National Capitol Parks - Central is covered by the "District of Columbia" Soil Survey (State Soil Survey Area ID MD099). It has been mapped, and is currently being refined to match new imagery. An interim digital product is available to us via NRCS, but the "final certified" dataset most likely will not be available until FY03.

National Capitol Parks - Eastern is covered by portions of 3 soil survey areas; "District of Columbia" (MD099), "Charles County, Maryland" (MD017), and "Prince George's County, Maryland" (MD033). Both Charles County and Prince George's County are currently being updated, with Charles County scheduled to be available sometime in calendar year 2002, and Prince George's County sometime within calendar year 2003.

Paleontology

Greg McDonald (GRD Paleontologist) would like to see an encompassing, systematic Paleontological inventory for the NCR describing the known resources in all parks with suggestions on how to best manage these resources. In addition to the parks containing paleo resources in NACE, according to his current database, the following are considered "paleo parks" in the NCR:

- Chesapeake & Ohio Canal NHP
- George Washington Memorial Parkway
- Manassas NBP
- Prince William Forest Park
- Harpers Ferry NHP

Geologic Report

A "stand-alone" encompassing report on each park’s geology is a major focus of the GRE. As part of the USGS proposal to map the NCR, they will be summarizing the major geologic features of each park in a report to accompany their database. It was suggested hoped that after the individual reports are finished that a regional physiographic report will be completed for the entire NCR.

List of Attendees for NPS National Capital Region Workshop

NAME	AFFILIATION	PHONE	E-MAIL
Joe Gregson	NPS, Natural Resources Information Division	(970) 225-3559	Joe_Gregson@nps.gov
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Lindsay McClelland	NPS, Geologic Resources Division	202-208-4958	Lindsay_mcclelland@nps.gov
Scott Southworth	USGS	(703) 648-6385	Ssouthwo@usgs.gov
Pete Chirico	USGS	703-648-6950	Pchirico@usgs.gov
Pat Toops	NPS, NCR	202-342-1443, ext. 212	Pat_toops@nps.gov
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Ellen Gray	NPS, NCR	202-342-1443, ext. 223	Ellen_gray@nps.gov
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Suzy Alberts	NPS, CHOH	301-714-2211	Susan_alberts@nps.gov
Dianne Ingram	NPS, CHOH	301-714-2225	Dianne_ingram@nps.gov
Bill Spinrad	NPS, CHOH	301-714-2221	William_spinrad@nps.gov
Debbie Cohen	NPS, ANTI	301-432-2243	Debbie_cohen@nps.gov
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Chris Jones	NPS-WOTR	703-255-1822	Christopher_Jones@nps.gov
Doug Curtis	NPS-NCR-NRS	202-342-1443, ext.228	Doug_Curtis@nps.gov
Brent Steury	NPS-NACE	202-690-5167	Brent_Steury@nps.gov
Dave Russ	USGS	703-648-6660	Druss@usgs.gov
Tammy Stidham	NPS-RTSC	202-619-7474	Tammy_stidham@nps.gov
Dan Sealy	NPS-GWMP	703-289-2531	Dan_Sealy@nps.gov
Sue Salmons	NPS-ROCR	202-426-6834, ext. 33	Sue_salmons@nps.gov

Appendix C: Report of the National Park Service Monitoring Workshop: Planning for the Future in the National Capital Network pp. 29-43

The following excerpts are from the National Capital Network monitoring workshop held on July 9-11, 2002, in Shepherdstown, West Virginia. Pages 29-44 are included in this appendix as they have direct relevancy to the geologic resources inventory of George Washington Memorial Parkway

B. Geology Workgroup

Purpose:
Continue the development of vital signs indicators for geologic resources in the National Capital Region of the National Park Service to provide essential information needed to preserve and enhance the region's most important geologic resources.

Outcomes:
1) Complete the geology table from previous meetings, allowing time to clarify items already in the table and identify additional information gaps.

2) Prioritize items in the geology table for future monitoring efforts.

3) Develop monitoring objectives for high priority threats in the geology table.

4) Develop a list of potential protocols that would meet the above monitoring objectives from the geology table.

Overview
This breakout session began by reviewing the conceptual model describing the geologic resources developed by the geology workgroup of the SAC including (1) resource components, (2) stressors to those resources, (3) sources of stressors, (4) ecological effects, and (5) potential vital signs monitoring indicators. Terminology was clarified, existing information was edited, and new information was added. The results of this discussion are captured in Table 4 below.

One point that was not captured in Table 4 (but which should be noted) is that the geology workgroup examined soil from an agricultural perspective, rather than from an engineering perspective. In addition, several people in the group commented that geology is an integrative, long-term perspective for monitoring, although there are both short- and long-term indicators that may be used to examine threats to the geological resources in the NCN.

Other topics of discussion during the morning session were urban soils and "engineered or created landscapes". Urban soils are generally horticultural in context, some of which may be "engineered" but, by far, most urban soils are not. Urban soils tend to be non-agricultural or non-forest situations where man has, to one degree or another, manipulated the landscape such that the natural soil regime no longer exists. In most cases, soil structure has been lost or redeveloped. In many cases, urban soils were composed from subsurface soils and, therefore, nothing resembling an "A" horizon exists.

Urban soils are often compacted, resulting in high bulk densities, and, as a result, have reduced oxygen content (e.g. trails, campsites, etc.). In addition, these soils are poorly drained, low in organic matter, retain little moisture, may be disconnected from the water table or capillary water, could be contaminated or have considerable "artifacts" (ash, glass, etc.), and are often depauperate in microfauna (bacteria, fungi) and macrofauna such as worms (even if most worms are non-native). Thus, many of the highly important landscape areas of National Capital Region, including the National Mall, battlefield cemeteries, visitor centers, picnic areas, trails, tow paths, etc., are places where manipulated soils need to be understood from their creation, through use and then management.

In addition, created landscapes were identified as one of the more unique, geological components of the National Capital Network (and especially, Washington DC), and for which the group felt that very little information currently was available. On one hand, these changed environments could lead to increased diversity - due to the potentially more-complex mosaic of soils and resulting vegetation communities. On the other hand, these landscapes are commonly affected by human manipulation, horticultural and agricultural practices, and urban landscaping efforts, all of which tend to lower biodiversity and lead to an increased occurrence of exotic species.

Several potential research topics were also discussed: historical records of floods, sedimentation, and land use in the region. Historical records of floods should be relatively easy to find for the National Capital Region. For example, Metro records and historical documents may provide an indication of historic structures affected by flooding on a sequential basis. In addition, Jim Patterson (NPS - retired) may have a lot of background information on NCR parks.
Sediment coring may also be used to provide a historical perspective on sediment "cycling" throughout the history of this region. The use of aerial photos, as available, may provide the necessary data to examine

land use change over time, changes in stream morphology over time, and shoreline change over time. Finally, through the use of newer technologies such as LIDAR and GPS, it is possible to examine changes in topography and geomorphology, at a fine scale, which is especially important in the Piedmont and Coastal Plain areas of the National Capital Region that have little or no topographic relief (e.g. Dyke Marsh).

In the afternoon session, the workgroup focused upon ways to condense the list of 30 threats to geological resources into a more manageable size (Table 5). This proved to be a difficult task due to the varied nature of some of the components in Table 4. The first two categories, (1) nutrients and contaminants and (2) erosion and sedimentation, were natural groupings of many of the entries in Table 4. The remaining components of Table 4 were more difficult to categorize because they did not fit nicely into a single group heading. However, the workgroup was finally able to group the components into the following subject headings: nutrient and contaminant cycling, sediment cycling, engineered lands and urban soils, shoreline change, geo-hazards, human influences within the park boundary, and human influences outside the park boundary. The group next began to prioritize these subject areas, but decided that some of these categories were too contrived, or overlapped too much, to be separated out in this way.

The final geology working group session was held on Thursday morning. The group decided to continue through the prioritization process by beginning with the categories that they were satisfied with - nutrient and contaminant cycling, and sediment cycling. For these two groupings, the group suggested established protocols for monitoring, wrote monitoring goals and objectives and identified potential collaborators. Once this analysis was completed for nutrient/contaminant and sediment cycling, the discussion continued for engineered lands and urban soils, shoreline change and geo-hazards.

The categories of human influences within the park boundary and human influences outside the park boundary were decided to be too broad and thus were eliminated from Table 4.
Categories were then ranked by considering the significance of the threat to the parks in the NCN, which included the following factors: amount of area affected by the threat, intensity of the threat to the resource, urgency of the threat to the resource, monitoring feasibility, and cost of monitoring.

By the end of the morning session, the group had decided upon the following categories, in priority order: nutrient and contaminant cycling, sedimentation and erosion, lack of understanding of engineered lands, shoreline change and geo-hazards. The workgroup then went back through Table 4 to assign all 30 elements to one (or more) of these specific groupings.

In addition to the work above, the workgroup noted information needs and studies of interest throughout the discussion. These are summarized below.

Information Needs:

A more recent and complete soils map for the region is needed.

Inventory information regarding land changes and the creation of lands for baseline data as well as how these lands change towards equilibrium is needed.

Are locations of air quality monitoring stations that also capture atmospheric deposition known? They need to be checked at the National Atmospheric Deposition Program (http://nadp.sws.uiuc.edu) or discussed with the air workgroup.

What about non-point source pollution monitoring in the region?

Is anyone considering the effects of acid rain on monuments in the region? There was, at one time, a long-term monitoring project regarding this process (in DC)?

Has anyone examined the flood and floodplain history of this area?

Previous studies of interest in NCR:

There were studies at 4-Mile Run beginning in the 1950's (pre-urbanization) to look at or capture the effects of urbanization.

Jeff Houser (Oak Ridge) has looked at the effects of sedimentation on streams and stream biota.

Personnel Involved:

Facilitator: Christina Wright, NPS – NCN I & M Program: and Dale Nisbet, NPS – HAFE
Participants: Joe Calzarette, Michelle Clements, Sid Covington, Dick Hammerschlag, Bob Higgins, Wright Horton, Lindsay McClelland, Wayne Newell, Scott Southworth, L. K. Thomas, and Ed Wenschhof.

Table 4. Revised conceptual model for geological resources in the NCN.

Resource Component	Stressor	Sources	Ecological Effects	Priority of Threat to Resource	Grouping used in priority table	Indicator/ Vital Sign	Protocol	Monitoring Goal	Potential contacts or collaborators
Soil	Pesticide loading	Agricultural, residential, and commercial use	Accumulation of pesticides that adhere to soil particles, causing changes to or the elimination of non-target soil fauna populations	High	1	Test soils and sediment for suite of pesticides commonly used in local area	Lithogeochemical studies (USGS), mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Soil/Bedrock	Nutrient loading	Agricultural, residential and commercial use	Acidification of the soil, reduction of soil organic matter, change in soil fertility status	High	1	Soil pH, soil N and P status, soil organic matter levels	Lithogeochemical studies (USGS), mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Soil/Bedrock	Change in pH, loss of buffering capacity	Acid rain, atmospheric deposition	Change in vegetation types, mycorrhiza and other soil flora, fauna	Unknown	1	Soil pH, acid neutralizing capacity (ANC)	Lithogeochemical studies (USGS), mass balance or input/output approach. Mass flow/hydrologic modeling.	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Soil	Temperature Change	Climate change	Changes in soil micro-climate	Unknown, locally high		Soil temperature/moisture regime, changes in soil flora, fauna and mycorrhiza suite	Soil temperature and moisture monitoring. Soil organism analysis.		
Soil/Surficial Factors	Clearing of land	Soil surface exposure, development, agriculture, zoning laws (local and county governments)	Loss of soil surface cover, increased soil surface and groundwater temperatures	High	2 and 3	Soil and groundwater temperature/moisture regime. Change in vegetation community. Land use change.	Measurement of soil surface and groundwater temperature, monitoring of bare soils in region. Land use change analysis, vegetation community analysis.	Use survey and analysis methods to evaluate changes in topography, sediment loading and water flow rates.	Rebecca Beavers (NPS - GRD), Wayne Newell, Nancy Simon, Pete Chirico (USGS - Reston), EPA - Office of Water and ORD, USGS - NAWQA, Loren Setlaw (?), Doug Curtis (NPS - CUE), Don Weeks (NPS - Denver)

Resource Component	**Stressor**	**Sources**	**Ecological Effects**	**Priority of Threat to Resource**	**Grouping used in priority table**	**Indicator/ Vital Sign**	**Protocol**	**Monitoring Goal**	**Potential contacts or collaborators**
Soil	Erosion	Developmen t, land clearing, increasing impervious surface	Increased siltation, reduced productivity/healt h/abundance of soil, plants, and aquatic organisms	High	2 and 4	Sediment loading, increased sedimentation and changes in sedimentation patterns, land use change, change in topography, shoreline change, change in wetland extent and condition.	Shoreline change/Wetland extent - aerial photo analysis. Change in topography - LIDAR, GPS. Changes in sedimentation - bedload analysis, storm water event sampling, total suspended solids, light penetration in water column. Condition of wetland - changes in wetland plant species, multiband aerial photography.	Use survey and analysis methods to evaluate changes in topography, sediment loading and water flow rates.	Rebecca Beavers (NPS - GRD), Wayne Newell, Nancy Simon, Pete Chirico (USGS - Reston), EPA - Office of Water and ORD, USGS - NAWQA, Loren Setlaw (?), Doug Curtis (NPS - CUE), Don Weeks (NPS - Denver)
Soil/Surficial Factors	Erosion	Developmen t	Change in "normal" sedimentation sequence and composition	Unknown, low	2 and 4	Increased deposition, change in scouring and deposition patterns, change in hydrologic flow regimes.	See above protocols. Also, analysis of sediment cores, including an analysis of historical sediment records.	Use survey and analysis methods to evaluate changes in topography, sediment loading and water flow rates.	Rebecca Beavers (NPS - GRD), Wayne Newell, Nancy Simon, Pete Chirico (USGS - Reston), EPA - Office of Water and ORD, USGS - NAWQA, Loren Setlaw (?), Doug Curtis (NPS - CUE), Don Weeks (NPS - Denver)
Soil	Change in vegetation /exotics	Developmen t, nursery use of exotics	Change in soil organic matter composition, changes in soil flora and fauna, pH, nitrification rates	Unknown		Exotic species monitoring and control measures, soil chemistry, soil organic matter levels, soil pH, soil nitrification rates			
Soil, creation of new soils	Fill dirt: complete changes in soil physical and chemical compositi on resulting from filling in land areas with soil from another location (esp. DC)	Landfills, abandoned mines, land engineering	Changed, destroyed, or new soil profile, change in chemical composition of soil, introduction of toxics, introduction of impervious structures into soil profile, compaction. Resultant changes to biodiversity and vegetation communities. Changes to hydrologic cycle.	High - esp. urban	1 and 3	Assessment and description of soil profile, change in subsurface temperatures, change in land surface elevation profile, movement of physical debris from land, soil compaction, change in biodiversity of flora and fauna	Assessment and description of soil profile, surface and ground water monitoring (lithogeochemical studies), bulk density, porosity or other soil compaction measures.	To understand the functioning and components of engineered landscapes (components - landfills, engineered soils, etc.)	USDA - NRCS, Dick Hammerschlag (USGS - Patauxent), Wright Horton (USGS - Reston). Also see contacts for nutrient and sediment cycling.
Soil	Compacti on	Visitor Use	Changes in vegetation survival, changes in soil physical properties, creation of soil crusts (an impervious surface).	Urban, locally - high	1 and 3	Monitor soil compaction, bulk density, porosity, or other soil compaction measures. Formation of soil crusts.	Soil coring, bulk density, porosity or other soil compaction measures.	To understand the effects of visitor use upon the soil profile - includes social and official trails.	

Resource Component	**Stressor**	**Sources**	**Ecological Effects**	**Priority of Threat to Resource**	**Grouping used in priority table**	**Indicator/ Vital Sign**	**Protocol**	**Monitoring Goal**	**Potential contacts or collaborators**
Soil	Impervious surfaces	Paving, walls, armored banks	Scouring, cutting/changing shoreline, flooding,	High	1 and 3	Increased velocity of storm water flow, land use change	Storm water event sampling, aerial photos to examine land use change.	To understand the effects of increasing impervious surfaces in the watershed upon hydrology.	Pat Bradley - EPA, USGS - NAWQA, EPA - Office of Water
Unique soils: calcareous and serpentine soils	Lack of information for these soils and soil in general	Lack of information for these soils and soil in general	Potential for damage to unknown/unmapped resource	unknown	1	Soils inventory work necessary.	Complete, up-to-date, high resolution soil maps	N/A	Pete Biggam - NPS, USDA - NRCS
Groundwater	Consumption of groundwater in excess of replenishment	Human, agricultural, residential, commercial use and domestic animal use	Reduced groundwater quantity, and quality. Loss of springs and seeps, wetland loss, changed of soil saturation zones. Change in drinking water quality and quantity.	High	1 and 2	Changes in groundwater table, Changes or loss of springs and seeps, change in extent of wetlands, changes in soil moisture profile.	Survey of groundwater table and groundwater chemistry. Groundwater flow monitoring wells		
Groundwater	Introduction of toxics, acid drainage (natural and mining)	Landfills, abandoned mines, land engineering, bedrock.	Reduced groundwater quality	high	1	Change in groundwater quality, quantity, and temperature. Increased toxics in groundwater.	Groundwater monitoring wells in conjunction with lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Groundwater	Physical Failure	Landfills, abandoned mines, land engineering	Change in subsurface water flow patterns, change in subsurface temperatures, introduction of contaminants	High	5	Groundwater monitoring wells (flow and mapping), subsurface temperature changes	Aerial photo mapping of areas with potential physical failures. Park staff observations of potential geo-hazard sites. Expert analysis of geo-hazard sites on a periodic basis.	To use observation and assessment to provide an early warning of physical failure in order to protect the resource, visitors, and park infrastructure.	John Pallister, Bula Gori, Gerry Wieczoff - USGS
Groundwater	Water bypasses the soil profile	Old - abandoned wells (farms)	Increased groundwater contamination with nutrients, pesticides and other chemicals	Unknown	1	Change in groundwater quality, increased toxics in groundwater.	Groundwater monitoring and monitoring of abandoned wells in conjunction with lithogeochemical studies (USGS), Mass balance or input/output approach. Abandoned wells need to be found and sealed to minimize contamination.	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA

Resource Component	Stressor	Sources	Ecological Effects	Priority of Threat to Resource	Grouping used in priority table	Indicator/ Vital Sign	Protocol	Monitoring Goal	Potential contacts or collaborators
Groundwater	Impervious Surfaces	Roads, buildings, infrastructure	Reduced water infiltration leading to reduced groundwater recharge, movement of water between watersheds	Medium	1 and 2	Map and monitor groundwater recharge areas, monitor groundwater table levels and chemistry, subsurface temperature monitoring.			
Exposed rock	Cutting the toe of slopes, over-steepened slopes, dipslopes	Development, roads, structures, trails, flooding, vegetation death (hemlock etc.), logging	Reduced slope stability	Low	5	Slope failure, reduced slope stability, movement of materials downslope, erosion, gully formation	Aerial photo mapping of areas with potential physical failures. Park staff observations of potential geo-hazard sites. Expert analysis of geo-hazard sites on a periodic basis. Monitoring for gulley formation or increasing erosion.	To use observation and assessment to provide an early warning of physical failure in order to protect the resource, visitors, and park infrastructure.	John Pallister, Bula Gori, Gerry Wieczoff - USGS. Also see personnel under erosion categories.
Karst	Toxics: pesticides, dumping, spills	Agriculture, septic systems, sewage, dumping, industry, spills	Rapid movement of contaminants to ground water, change in ground water chemistry and resulting in change in biology	High – locally	1	Subterranean invertebrates, ground water chemistry/ quality	Analysis of subterranean invertebrates. Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Smithsonian Institute Invertebrate specialists. Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Karst	Nutrient loading	Agriculture, septic systems, sewage, dumping, industry, spills	Rapid movement of nutrients to ground water resulting in change to ground water quality and change in biology	High – locally	1	Subterranean invertebrates, ground water nutrient content	Analysis of subterranean invertebrates. Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Smithsonian Institute Invertebrate specialists. Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Karst	Structural collapse, sinkholes	Inappropriate construction practices, dissolution in karst areas	Change in biology due to changes in air flow and temperature, volume and flow of water increased in areas dissolution of bedrock	High – locally	5	Change in sinkhole size, aerial photos to capture surface changes, subsurface temperature monitoring	Aerial photo mapping of areas with sinkholes. Park staff observations of potential geo-hazard sites. Expert analysis of geo-hazard sites on a periodic basis.	To use observation and assessment to provide an early warning of physical failure in order to protect the resource, visitors, and park infrastructure.	John Pallister, Bula Gori, Gerry Wieczoff - USGS

Resource Component	Stressor	Sources	Ecological Effects	Priority of Threat to Resource	Grouping used in priority table	Indicator/ Vital Sign	Protocol	Monitoring Goal	Potential contacts or collaborators
Surface water	Impervious surfaces	Infrastructure, development, residential and agricultural use, rip rap, armoring etc.	Increased storm water flow, increased erosion, changes in sedimentation, changes in stream morphology, increased exposure to nutrients/pesticides, change in hydrologic cycle effecting floodplains, and floodplain/riparian buffer capacity, change in base flow	High	1 and 2	Stream storm water flow, flood frequency, sedimentation load, stream morphology. Photo points. Storm event sampling, Mass flow/hydrologic modeling	Lithogeochemical studies (mass balance approach).Shoreline change/Wetland extent - aerial photo analysis. Change in topography - LIDAR, GPS. Changes in sedimentation - bedload analysis, storm water event sampling, total suspended solids, light penetration in water column. Condition of wetland - changes in wetland plant species, multiband aerial photography.	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem. Use survey and analysis methods to evaluate changes in topography, sediment loading and flow rates.	Rebecca Beavers (NPS - GRD), Owen Bricker, Nancy Simon, Wayne Newell, Pete Chirico, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA - Office of Water, USGS - NAWQA
Surface water	Pesticide loading	Agricultural, residential, and commercial use	Reduced water quality, fishery health, and aquatic invertebrate communities and populations	High	1	Test for suite of pesticides commonly used in local area.	Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Surface water	Nutrient loading	Agricultural, residential and commercial use	Reduced water quality, fishery health, and aquatic invertebrate communities and populations. Algal blooms, eutrophication	High	1	Soil water and stream levels of N and P. High algal growth, low light penetration	Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Coastal areas	Impervious surfaces	rip rap, armoring, coastal walls, dredging	Changes in water flow rates, unnatural erosion and deposition, changes in natural shoreline, changes in sedimentation, wetland flooding, changes in wetland extent.	High – locally	1 and 2	Sedimentation coring (deep cores - research, shallow cores - monitoring), mapping of shoreline change, use of Pope's Creek as a reference area	Using aerial photos or survey methods to map shoreline and shoreline change over time.	Use mapping or survey methods to track changes in shoreline and depositional patterns, over time.	NOAA (?)
Lakes, ponds, seeps, vernal pools	Nutrient loading	Agriculture, residential lawn care, vegetation change	Eutrophication, change in fauna (esp. herps), effect upon T&E species	Unknown	1	Size/volume, chemistry, and temperature of surface water component	Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA

Resource Component	Stressor	Sources	Ecological Effects	Priority of Threat to Resource	Grouping used in priority table	Indicator/ Vital Sign	Protocol	Monitoring Goal	Potential contacts or collaborators
Lakes, ponds, seeps, vernal pools	Pesticide loading	Agriculture, residential, and commercial use	Addition of herbicides and pesticides to surface water, change in fauna, effect upon T&E species	Unknown	1	Pesticide, herbicide content of surface water component	Lithogeochemical studies (USGS), Mass balance or input/output approach	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	Owen Bricker, Nancy Simon, Wayne Newell, Wright Horton, David Russ (USGS - Reston), Mark Nellis (USGS - Denver), USDA, EPA, USGS - NAWQA
Riparian areas, Wetlands	Change in soil surface elevation and horizontal dimension s	Land engineering resulting in changes to deposition and erosion, dredging, dumping, creation of impoundme nts and dams	Disruption to the wetland/riparian ecosystems, change in storm water flow rates, vegetation change, wildlife change, change in stream bed characteristics	High	4	High resolution riparian/ wetland elevation monitoring, vegetation monitoring, sediment budget, changes in size of wetland area	Changes in wetland extent - aerial photo analysis. Change in topography - LIDAR, GPS. Changes in sedimentation - bedload analysis, storm water event sampling, total suspended solids, light penetration in water column. Condition of wetland - changes in wetland plant species, multiband aerial photography.	Use survey and analysis methods to evaluate changes in topography, sediment loading and water flow rates.	Rebecca Beavers (NPS - GRD), Wayne Newell, Nancy Simon, Pete Chirico (USGS - Reston), Richard Lowrance (USDA/ARS), EPA - Office of Water and ORD, USGS - NAWQA, Loren Setlaw (?), Doug Curtis (NPS - CUE), Don Weeks (NPS - Denver)

Table 1. Priority threats, vital signs, and monitoring goals and objectives for geological resources in the NCN.

Threats (in priority order)	Vital Sign	Monitoring Goal	Monitoring Objectives
Nutrient and chemical contamination	Changes in soil and ground water chemistry.	Use an input/output approach to understand nutrient and contaminant cycling in the ecosystem.	(1) Measuring nutrient inputs from sources pertinent to each park unit. (2) Measuring contaminant inputs from sources pertinant to each park unit. (3) Tie information from numbers 1 and 2 to the hydrologic cycle, flood history, flood effects, and flood impacts.
Erosion and sedimentation	Changes in topography, sediment loading and deposition, shoreline change, wetland extent and condition.	Use survey and analysis methods to evaluate changes in topography, sediment loading, and flow rates.	(1) Measure loss of soil, growth of gulleys, changes in streambanks…. (2) Track sedimentation history, effects, and impacts (including streams and ponds, hillslopes and gulleys).
Lack of understanding of urban soils and engineered lands	Compaction, runoff, chemical composition, soil profile and structure, biodiversity.	To understand the functioning and components of urban soils engineered landscapes and their effects upon resident biota. Components include: highly impacted soil (compaction in and around trails, visitor centers), landfills, engineered soil, etc.	(1) Measure changes to physical components of urban soils and engineered lands and correlate with changes in resident biota (and exotic species). (2) Measure contaminant outflow from landfills, abandoned mines, etc.
Shoreline change	Inundation of wetlands, erosion and sedimentation processes.	Use mapping or survey methods to track shoreline change and depositional patterns.	(1) Measure shoreline change using aerial photos, LIDAR and survey methodologies and correlate changes to development, when possible. (2) Use sediment coring and historical data to understand long-term flood histories.
Geo-hazard	Physical failure, rock falls, landslides, sinkhole collapse.	Use observation and assessment to provide an early warning of physical failure to protect the resource, visitors, and park infrastructure.	(1) Monitor areas of potential hazard due to unstable slopes, rockfalls, etc. (2) Monitor for changes in unstable engineered sites or areas that are geologically active (e.g. Potomac Gorge). (3) Document and monitor areas underlain by swelling clays.

George Washington Memorial Parkway
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/128

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Natural Resource Program Center
The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring, and Evaluation, and Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross-cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the National Park System.

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