National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Colonial National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2016/1237

ON THE COVER: The Yorktown Victory Monument was completed in January 1885 and, at nearly 30 m (100 ft) tall, overlooks the wide harbor of the York River. Architecturally it was planned and constructed in three parts, with a base, a sculptured podium (in the form of a drum), and a column. The whole "is intended to convey, in architectural language, the idea, set forth in the dedicatory inscription, that, by the victory at Yorktown, the independence of the United States of America was achieved, or brought to final accomplishment." National Park Service photograph courtesy of Dorothy Geyer (Colonial National Historical Park).

THIS PAGE: Local fossils are historically significant to paleontological history. Many species were discovered, described, and named from locations in the park. The bivalve (mollusk) *Chesapecten jeffersonius* was likely the first fossil to be described in North America. It was included in Martin Lister's Historiae Conchyliorum in the late 1600s. National Park Service photograph courtesy of Melanie Peters (Geologic Resources Division) taken in August 2005.

Colonial National Historical Park

Geologic Resources Inventory Report

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June 2016

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

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

The Natural Resource Report Series is used to disseminate comprehensive information and analysis about natural resources and related topics concerning lands managed by the National Park Service. The series supports the advancement of science, informed decision-making, and the achievement of the National Park Service mission. The series also provides a forum for presenting more lengthy results that may not be accepted by publications with page limitations.

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

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

Thornberry-Ehrlich, T. L. 2016. Colonial National Historical Park: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1237. National Park Service, Fort Collins, Colorado.

NPS 333/133343, June 2016

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Colonial National Historical Park (Virginia) on 1 May 2005 and a follow-up conference call on 12 November 2014. Scoping participants identified geologic resources of significance and geologic resource management issues and needs, as well as the status of geologic mapping. This report is a companion document to previously completed GRI GIS data.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Sections of the report discuss distinctive geologic features and processes within Colonial National Historical Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data. A poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit. A glossary defines many of the geologic terms used in this text.

Colonial National Historical Park commemorates the origins of America across seven historic units:

- historic Jamestowne, the site of America's first permanent English settlement in 1607 and Virginia's capital until 1699;
- Yorktown Battlefield, the scene of the 1781 culminating battle of the American Revolutionary War;
- the 37-km (23-mile) Colonial Parkway;
- Green Spring Plantation;
- Cape Henry Memorial, marking the first landing of the colonists in 1607;
- Tyndall's Point in Gloucester; and
- Swanns Point.

Cape Henry is within the legislative boundary, but not the administrative boundary of the park; it is not part of the GRI GIS data coverage and is not on the poster.

The park spans the James-York peninsula between the James and York rivers—two major tributaries of the Chesapeake Bay watershed. In addition to its historic resources and stories, the park encompasses significant natural resources, including tidal and nontidal wetlands, upland forests, bluffs, open fields, streams, and the James and York rivers' shorelines. These features and their geologic foundations strongly influenced the history of the area from the prehistoric American Indian inhabitants to the European settlements and American struggles for independence and unity.

Colonial National Historical Park is in the Coastal Plain physiographic province, a province which stretches from Cape Cod to the Mexican border in Texas. The coastal plain formed at the same time the Atlantic Ocean was forming, more than 180 million years ago. Sediments eroded from the Appalachian Mountains to build the plain seaward as a thick wedge of sediments. In Virginia, the coastal plain is dominated by a series of step-wise, riverine terraces. A sloping scarp and relatively flat tread compose each terrace, the series of which locally decrease in elevation in a step-wise manner toward the Chesapeake Bay. During fluctuations in sea level more than 20,000 years ago, shoreline erosion along major streams and bays created the scarps that subsequent slope movements, deep incision by stream valleys, and overlapping features have obscured, producing a rolling and dissected terrain.

Geologic features and processes include the following:

- **Fluvial Features and Processes.** The James and York rivers and their tributaries are among the major natural resources at Colonial National Historical Park. Jamestown Island was chosen as a settlement because of its defendable position nearly surrounded by water. Former traces of the meandering river are visible as the swales and ridges along the island. The well-drained ridges were the first areas that the colonists settled. The shorelines within the park are estuarine and the James and York rivers are affected by tides of nearly 1 m (3 ft). Many areas of the park are nearly at sea level. Recent mapping of bottom sediments in the James River revealed how the currents and waves are moving deposits within the river system.

- **Coastal Plain Sediments**. The sedimentary units mapped in the park fall into two broad categories. The first are older, marine, fossiliferous layers. The second are younger, fluvial-estuarine sediments with a wide range in composition and spatial distribution. The composition and spatial continuity of both types of sediments are complex and the subject of much study. Yorktown lends its name to the Yorktown Formation. It was the excellent exposures near the Moore House that caused them to become the official type locality of the Moore House Member of the Yorktown Formation. This member is rich in shell hash and sand.
- **Slope Features and Processes**. Slope movements—the downslope transfer of earth materials—occur primarily as small scale slumps and slope creep on the park's steep bluffs and ravines. Human activities that disturb earth can exacerbate slope movement issues.
- **Paleontological Resources**. Fossil resources within Colonial National Historical Park are historically and scientifically significant. The bivalve (mollusk) *Chesapecten jeffersonius* was likely the first fossil to be described from North America. It was described by Martin Lister in the late 1600s and is now the state fossil of Virginia. The Yorktown Formation is particularly fossiliferous and yields a wealth of information about past climates and ecosystems. New fossil discoveries occur regularly in the region.
- **Karst Topography and Cornwallis "Cave"**. The only cave in the park is Cornwallis "cave"—a quarried cavity in the shell hash layers of the Moore House Member of the Yorktown Formation. Soluble, buried shell hash layers locally dissolve, causing subsidence sinkholes to form. Some of these sinkholes are large enough to hold water, for example Grafton pond and Brackens pond.
- **Subsurface Geologic Features and the Chesapeake Bay Impact Crater.** About 35 million years ago, a meteor or comet collided with Earth in a location which is now centered beneath Cape Charles on the Eastern Shore, adjacent to the Chesapeake Bay; today's Eastern Shore did not exist at that time. The resulting crater was a depositional center for millions of years afterwards. The disturbance to the surrounding sedimentary units included the formation of a ring of fractures and faults, which are still capable of movement. The impact affected the sedimentary history of the area, causing juxtapositions of units of differing age and composition. Other deep-seated geologic structures defy the classic model of the thick, undisturbed wedge of sediments of the Coastal Plain. New research is revealing the presence of faults in the subsurface of the park region. These structures have implications for the hydrogeologic system and geomorphology of the park.
- **Hydrogeologic System at Yorktown Battlefield**. The importance of the hydrogeologic system at Colonial National Historical Park continues to be the subject of much study, particularly in light of the increase in surrounding development. The park is underlain by a complex series of aquifers and confining layers with widely varying spatial distribution.

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

- **Sea Level Rise, Flooding, and Coastal Vulnerability**. Many of the low-lying areas in the park contain significant natural and cultural resources. Storms occasionally flood vast areas of the park. Climate models project that relative sea level will continue to rise at Colonial National Historical Park. Park resource managers are currently seeking a coastal vulnerability index study to measure the shoreline's vulnerability to the effects of sea level rise.
- **Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures**. Where the James and York rivers are tidal, such as in the park, fluvial processes and sea level rise are intimately connected. Rising sea level is causing wetland habitats to migrate and exacerbating shoreline loss. Loss is most pronounced at Jamestown Island. A historic sea wall protects the original settlement, but several other places exhibit loss, including College Creek, shorelines adjacent to riprap, and near bridge crossings. Much of the York River corridor is armored with riprap and other shoreline engineering structures. Resource managers have been active in shoreline management strategies for decades.

- **Stormwater Management along Colonial Parkway and Upland Erosion.** The decades-old stormwater structures along the Colonial Parkway are inadequate to handle peak flows and increased surface runoff associated with adjacent urban development. Erosion and undercutting threaten reaches of the parkway. Impervious-surfaces are a measured indicator of habitat condition whose threshold is exceeded along the parkway. Resource managers seek to develop a plan to manage runoff, erosion, and stormwater along the parkway. In uplands, increased erosion is threatening cultural sites.
- **Paleontological Resource Inventory, Monitoring, and Protection**. Fossils from Colonial National Historical Park are historically significant. All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation. A field-based, park-specific paleontological resource survey could provide site-specific information for resource managers.
- **Geologic Hazards and Risks: Slope Movements**. Many of the slope issues in the park follow erosive storms that also blow over trees releasing sediments and removing stabilizing roots on park slopes. Informal trails also cause erosion and degradation of historic earthworks. Slope wash is particularly problematic at College Creek. Resource managers are seeking to complete a slope monitoring plan.
- **Geologic Hazards and Risks: Earthquakes and Fault Locations**. Colonial National Historical Park is not near a seismic zone; however, the potential for large earthquakes exist. The probability of a magnitude-5.0 or greater earthquake within 100 years is 1–2%. This calculation, however, was made prior to the 2011 earthquake in central Virginia, which was felt at the park. New faults were revealed by recent mapping and the park is on a subsiding side of a fault block associated with the Chesapeake Bay impact structure. However unlikely, a moderate earthquake has the potential to damage park infrastructure, cause liquefaction in the marshy places, and/or trigger slope movements.
- **Geologic Hazards and Risks: Radon.** Radon is a heavier-than-air, colorless, odorless, radioactive gas produced by the decay of naturally occurring uranium and thorium in the sediments beneath the park. It tends to settle in basements and crawl spaces. Sediments at the base of the Yorktown Formation (where it overlies the Eastover Formation) commonly contain marine mammal bone enriched in phosphate and uranium. High levels of radon have been found in dwellings built within or just above this contact. Buildings and adjacent ground in James City County, near Williamsburg located on the Bacons Castle Formation, Shirley Alloformation, and Yorktown Formation, had elevated radon levels approaching the EPA recommended maximum level. Remediation of the threat requires monitoring and ventilation.
- **Groundwater Quantity and Quality**. Groundwater depletion and brackish water incursion has been a historic problem in the park. Groundwater from the area's shallow aquifer system can contribute more than half of the flow in the park area's streams and a large portion of the water in the wetlands. Pulses of groundwater help to flush out the stagnant water in marshes and pore water. Factors affecting fluctuations of the water table are complex and include variations in rainfall and evapotranspiration, hydrogeologic setting, tidal fluctuations, sea level rise, and human activity. A groundwater monitoring and management plan could be prepared for Colonial National Historical Park.
- **Karst Landscape Management**. Many subsidence sinkholes occur at the Yorktown Battlefield unit of the park and the potential exists that more will develop.
- **Yorktown Formation Shrink-and-Swell Clays**. The weathered sediments of the Moore House and Morgarts Beach members of the Yorktown Formation contain clay and silt that act as an aquitard to percolating groundwater and have high shrink-and-swell potential. The change in volume associated with wet clay expanding and then drying can damage roads, trails, building foundations, and other infrastructure.
- **Abandoned Mineral and Disturbed Lands**. Cornwallis cave is the only abandoned mineral and disturbed lands feature that occurs in the NPS database for this park. Other small features are within park boundaries. Park staff are requesting a condition assessment of Cornwallis "cave" (quarry) particularly the roof as large fragments of rock fall to the floor. Superfund sites and abandoned borrow pits near the park may impact resources within the park.

Products and Acknowledgments

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

GRI Products

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

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

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

The GRI team thanks Rick Berquist and the rest of the staff at the Virginia Division of Geology and Mineral Resources.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Colonial National Historical Park and summarizes connections among geologic resources, other park resources, and park stories.

Park Setting

Colonial National Historical Park was originally authorized as a national monument on June 3, 1930. It became a national historical park on June 5, 1936 and now receives about three million visitors per year. The park includes more than 3,500 ha (8,600 ac) of natural and cultural space spread across seven units along and including the 37-km (23-mi) -long and 150-m (500-ft) -wide Colonial Parkway in James City and York counties (plate 1). Elevations within the park range from sea level to 38 m (120 ft) above sea level (Lookingbill et al. 2012). The park straddles the peninsula between the James and York rivers, spans two subwatersheds, and is within the southern part of the Chesapeake Bay watershed (fig. 1). The park encompasses significant natural resources, including about 810 ha (2,000 ac) of tidal and nontidal wetlands, 405 ha (1,000 ac) of open fields, and 65 km (40 mi) of shorelines along streams and the James and York rivers (Rafkind 1990).

Figure 1. Map of the Chesapeake Bay watershed. Colonial National Historical Park (green) straddles the boundaries between two subwatersheds on the James-York Peninsula. Graphic is adapted from figure 2.3 in Lookingbill et al. (2012) by Trista L. Thornberry-Ehrlich (Colorado State University). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 18 September 2014).

The Historic Jamestowne unit, the site of America's first permanent English settlement in 1607 and Virginia's capital until 1699, anchors the western end of the Colonial Parkway unit. Yorktown Battlefield, the scene of the 1781 culminating battle of the American Revolutionary War, is at the eastern terminus (plate 1). The Colonial Parkway passes through Williamsburg, capital of Virginia from 1699 to 1776. The Green Spring Plantation unit, site of a battle that occurred prior to the military engagement at Yorktown, is 3 km (2 mi) northwest of Jamestown. This was the home of an influential 17th century governor of Virginia,

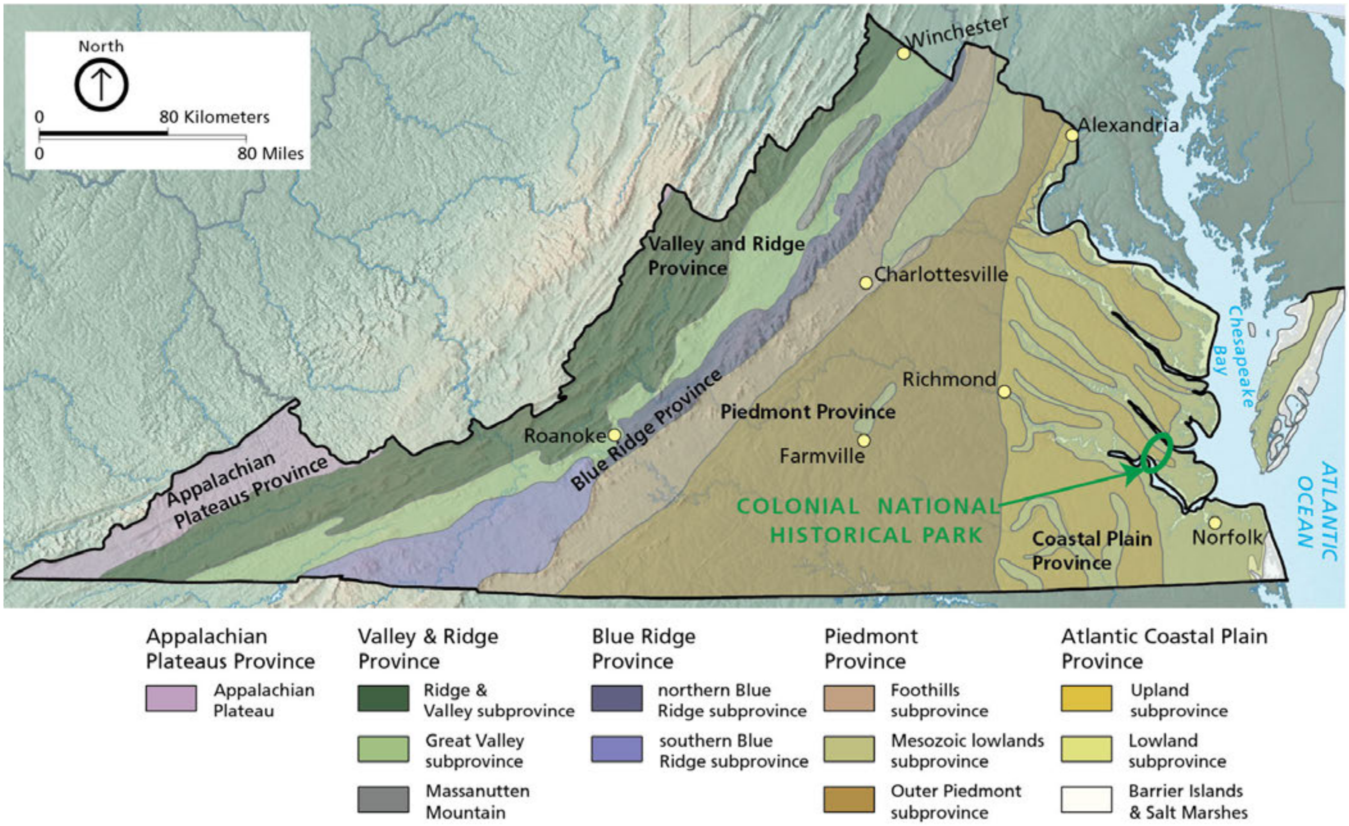


Figure 2. Map of the physiographic provinces and subprovinces of Virginia. Colonial National Historical Park (green oval) is within the Coastal Plain province, straddling the Upland and Lowland subprovinces on the James-York Peninsula. Graphic is adapted from Bailey (1999) by Trista L. Thornberry-Ehrlich (Colorado State University). Basemap by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html (accessed 18 September 2014).

Sir William Berkeley (US Army Corps of Engineers 2002). The Cape Henry Memorial unit in Virginia Beach marks the approximate site of the first landing of Jamestown colonists in 1607. The military fortifications of the Tyndall's Point unit are across the York River in Gloucester County. Another unit, at Swanns Point, lies in Surry County across the James River from Jamestown Island. The park also features Civil War era history; Yorktown and Williamsburg were sites of battles during the Peninsula Campaign. Yorktown National Cemetery was established for Civil War interments.

Geologic Setting

Five distinct physiographic provinces encompass Virginia, from west to east: Appalachian Plateaus, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain provinces (fig. 2). Colonial National Historical Park is in the Coastal Plain physiographic province—a relatively flat landscape underlain by a wedge-shaped sequence of more than 2,400 m (8,000 ft) of soft, mostly unconsolidated sediments (fig. 3) that were eroded from the bedrock highlands to the west (Bailey 1999). Large streams and rivers in the Coastal Plain province, including the James, Rappahannock, and Potomac rivers, continue to transport sediment and build the coastal plain eastward onto the submerged Continental Shelf province which extends another 120 km (75 miles) into the Atlantic Ocean. The boundary between the Piedmont and Coastal Plain provinces is called the "fall line". It is a low, east-facing escarpment that parallels the Atlantic coastline from New Jersey to the Carolinas. An escarpment is a long, steep slope that faces one direction breaking the continuity of the land by separating two adjacent surfaces and is commonly produced by erosion or faulting. This erosional scarp, 80 km (50 mi) northwest of Colonial National Historical Park, formed where the hard, resistant metamorphic rocks of the Piedmont and the unconsolidated sediments of the Atlantic Coastal Plain, approximately 120 to 140 km (75 to 90 mi) inland from the coast, were

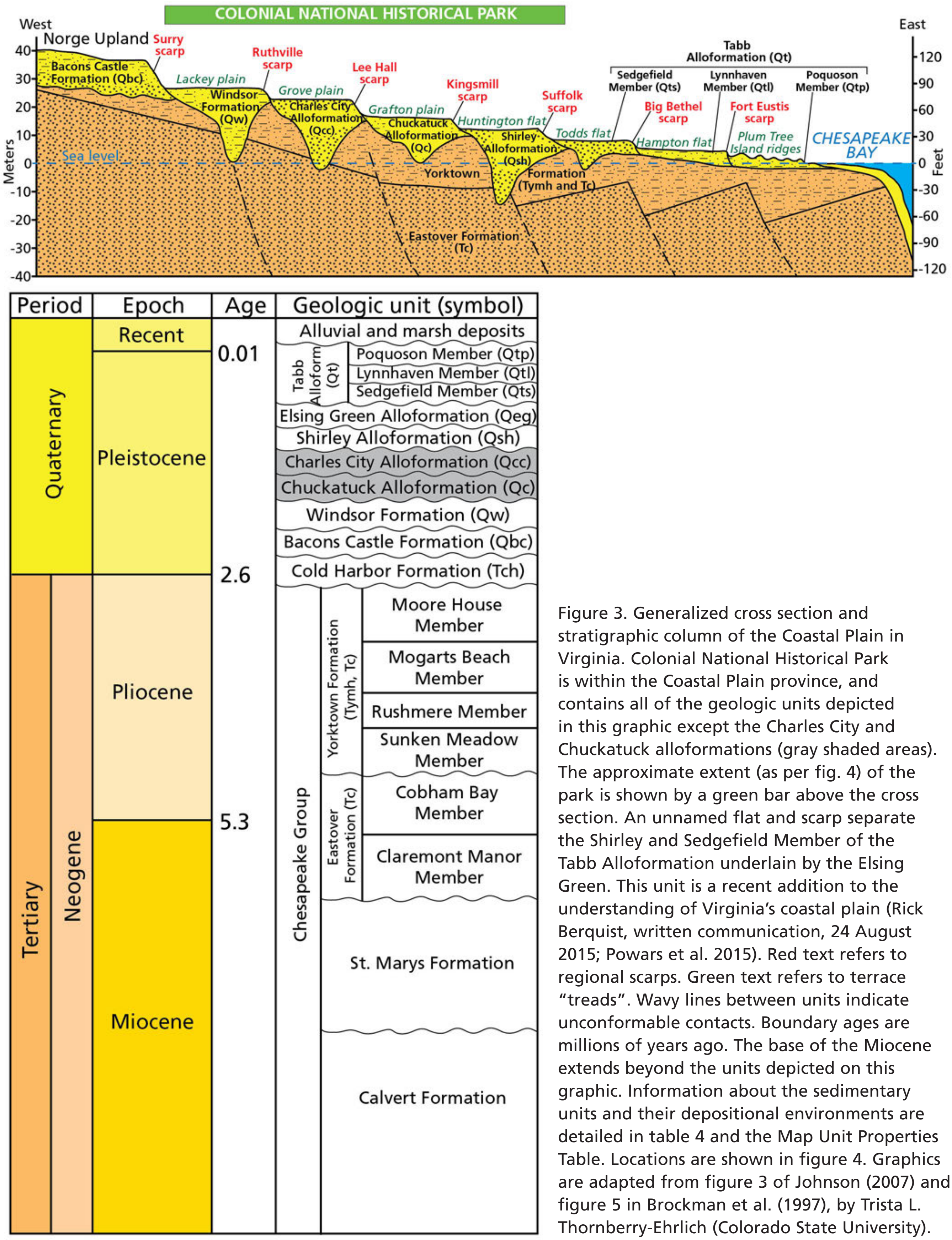


Figure 3. Generalized cross section and stratigraphic column of the Coastal Plain in Virginia. Colonial National Historical Park is within the Coastal Plain province, and contains all of the geologic units depicted in this graphic except the Charles City and Chuckatuck alloformations (gray shaded areas). The approximate extent (as per fig. 4) of the park is shown by a green bar above the cross section. An unnamed flat and scarp separate the Shirley and Sedgefield Member of the Tabb Alloformation underlain by the Elsing Green. This unit is a recent addition to the understanding of Virginia's coastal plain (Rick Berquist, written communication, 24 August 2015; Powars et al. 2015). Red text refers to regional scarps. Green text refers to terrace "treads". Wavy lines between units indicate unconformable contacts. Boundary ages are millions of years ago. The base of the Miocene extends beyond the units depicted on this graphic. Information about the sedimentary units and their depositional environments are detailed in table 4 and the Map Unit Properties Table. Locations are shown in figure 4. Graphics are adapted from figure 3 of Johnson (2007) and figure 5 in Brockman et al. (1997), by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 4. Map of terraces on the James-York Peninsula. Colonial National Historical Park (pink area) spans several treads or flat areas among erosional scarps. The elevations of the base of the scarps are as follows: Surry scarp is 29m (95 ft); Ruthville scarp is 24 m (79 ft); Lee Hall scarp is 19 m (62 ft); Kingsmill scarp is 14 m (46 ft); Suffolk scarp is 8 m (26 ft); unnamed scarp is 12 m (38 ft); Big Bethel scarp is 5.5 m (18 ft); and Fort Eustis scarp is 3.5 m (11 ft). Yellow lines and text refers to regional scarps. Green text in black boxes refers to terrace "treads". Graphic is adapted from figure 2 of Johnson (2007) by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap, (accessed 7 October 2014) and information from Powars et al. (2015) and Rick Berquist (written communication, 24 August 2015).

juxtaposed. The fall line is the site of many waterfalls that yielded flume- and waterwheel-powered industries in colonial times and thus became the location of major cities such as Philadelphia, Baltimore, Washington DC, and Richmond (US Geological Survey 2000). The park includes areas of the Upland and Lowland subprovinces of the Coastal Plain province. Elevations in these subprovinces range from 20 to 80 m (60 to 250 ft) and 0 to 20 m (0 to 60 ft), respectively (Bailey 1999).

A succession of riverine, erosional terraces composes the landscape of Virginia's coastal plain. Each terrace, composed of a gently sloping scarp and relatively flat "tread" or level area referred to as flats or plains, decreases in elevation in a step-wise manner toward the Chesapeake Bay (figs. 3 and 4). The local succession from west to east are the Norge upland, Surry scarp, Lackey plain, Ruthville scarp, Grove plain, Lee Hall scarp, Grafton plain, Kingsmill scarp, Huntington flat, Suffolk scarp, unnamed flat and scarp (Elsing Green), Todds (Hornsbyville) flat, Big Bethel scarp, Hampton flat, Fort Eustis scarp, and the Plum Tree Island ridges (Johnson 2007; Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, written communication, 24 August 2015; Powars et al. 2105). Park areas or the parkway are located on most of these features (figs. 3 and 4). The Surry scarp is one of the most extensive landforms on the coastal plain extending along the Atlantic coast (Johnson et al. 2001a). During the past 2.6 million years or more (late Pliocene and Pleistocene epochs; see fig. 5), shoreline erosion along major streams and bays created the scarps, which vary in height from less than 2 m (6 ft) to more than 20 m (66 ft). Slope movements, deep incision by stream valleys, and overlapping features have obscured the terraces and produced a rolling and dissected terrain (Johnson 2007).

The park is 8 km (5 mi) northwest of the open Chesapeake Bay on the estuarine York River and 24 km (15 mi) upstream of the bay on the James River. The landscape ranges from tidally influenced marshy lowlands and wetlands of Jamestown Island, to eroded rolling hills of the interior of the James-York Peninsula, to deeply scoured bluffs above the York River at Yorktown.

Geologic Significance and Connections

The geologic framework of Colonial National Historical Park has strongly affected the history and natural features of the region. In 1607, English settlers established a colony on a defensible upland site on the otherwise low-lying Jamestown Island. At that time, the region was in the midst of a prolonged drought (Stahle 2005). The colonists were also challenged with brackish water, prolific insects, starvation, and sometimes-hostile relations with American Indians. However, despite these issues, the colony persisted and today is considered a fundamental piece of American history. The story of the colony stretched through the American Revolutionary and Civil wars when the area was a strategic target. The region's fossils played a role in the history of North American paleontology. Today, the geology contributes to the development of soils and together with landforms supports a series of natural habitats and ecosystems in an otherwise urban landscape, and continues to shape the human and natural stories at Colonial National Historical Park.

Prehistory and European Colonization

Humans lived in coastal Virginia for thousands of years prior to the arrival of the European colonists, as evidenced by myriad archeological sites, including a hearth at Black Point (Thornberry-Ehrlich 2005). When humans first migrated to southeastern Virginia at least 10,000 years ago, sea level was approximately 70 m (230 ft) lower than at present, meaning that what is now Jamestown Island was part of the mainland and perched more than 30 m (100 ft) above the James River (Johnson et al. 1995; Johnson 2007; Vanasse Hangen Brustlin, Inc. 2009). A series of ridges separated by freshwater streams emerged from the western side of the island (Johnson et al. 1995). At this time, the James River was not tidally influenced; it was completely freshwater and flowed through a deeply entrenched valley. Sea level began to rise after the end of the last major glaciation, approximately 12,000 years ago. By about 5,000 years ago, local sea level was only about 10 m (33 ft) below its present level and the lower James River began to be affected by tides. As brackish marshes replaced the lowest-lying lands, human occupation moved further upslope (fig. 6) (Johnson et al. 1995). Throughout this time of sea level rise, James River tributaries were a source of freshwater for local inhabitants, including the Powhatan Indians around Jamestown Island (US Army Corps of Engineers 2002; Johnson 2007). Abundant middens suggest that human settlements concentrated in places underlain by sand and gravel, rather than wetland muck (GRI conference call participants, 12 November 2014).

Thousands of years later, after landing at Cape Henry at the mouth of Chesapeake Bay, English colonists sailed three ships into the bay, searching for suitable sites for a settlement. On 13 March 1607, they landed at Jamestown Island and the "settlement era", which would last until 1745, began (Vanasse Hangen Brustlin, Inc. 2009). Colonists also took advantage of uplands underlain by the Lynnhaven Member of the Tabb Alloformation (geologic map unit **Qtl**) such as the western end of Church Point ridge (fig. 7) where they built James Fort and Jamestowne (Johnson 2007). At this time, Jamestown island was connected to the mainland by a narrow isthmus near Back River, but was otherwise

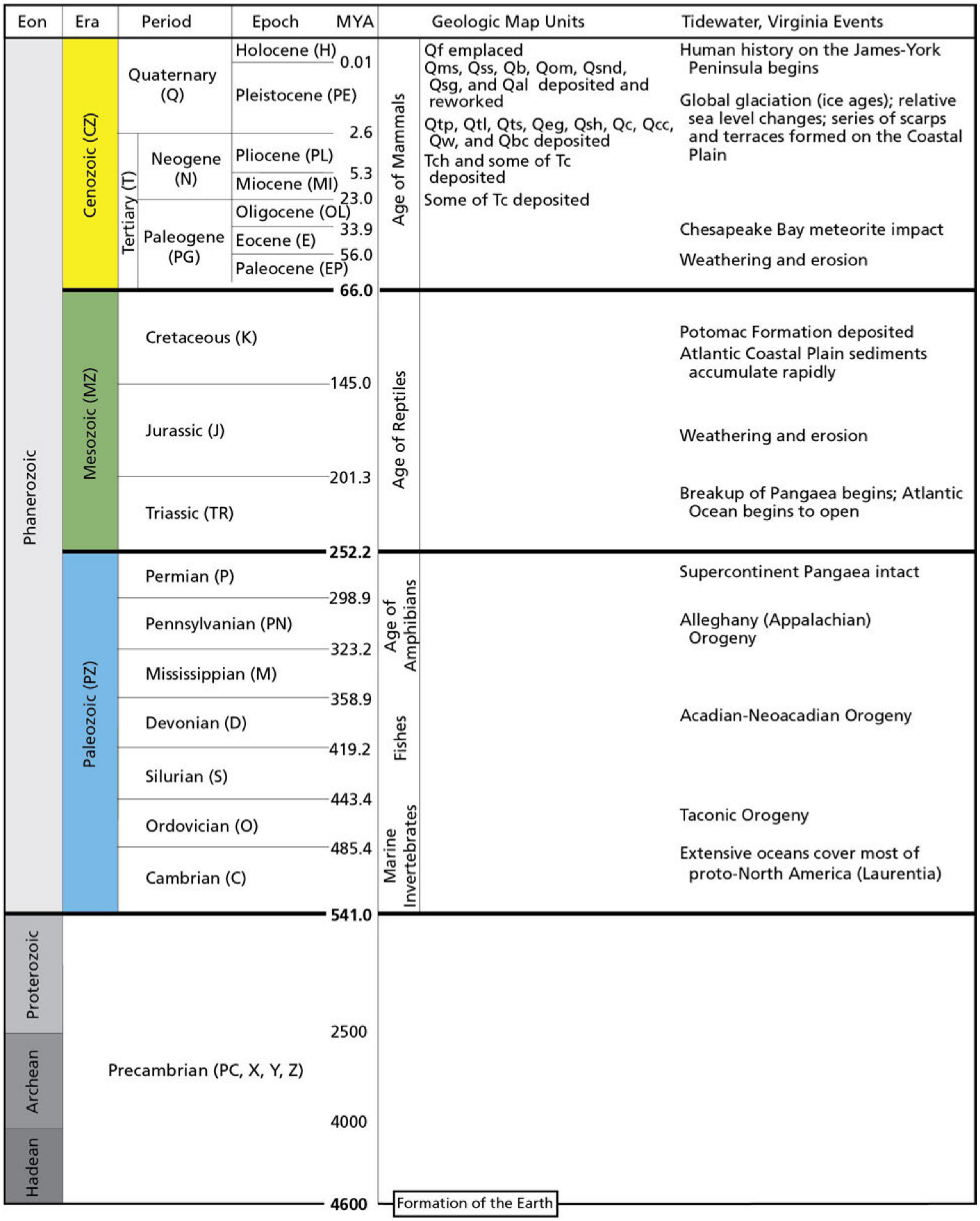


Figure 5. Geologic time scale. Geologic units occurring within Colonial National Historical Park are included. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 13 August 2014) and data from Berquist (2015).

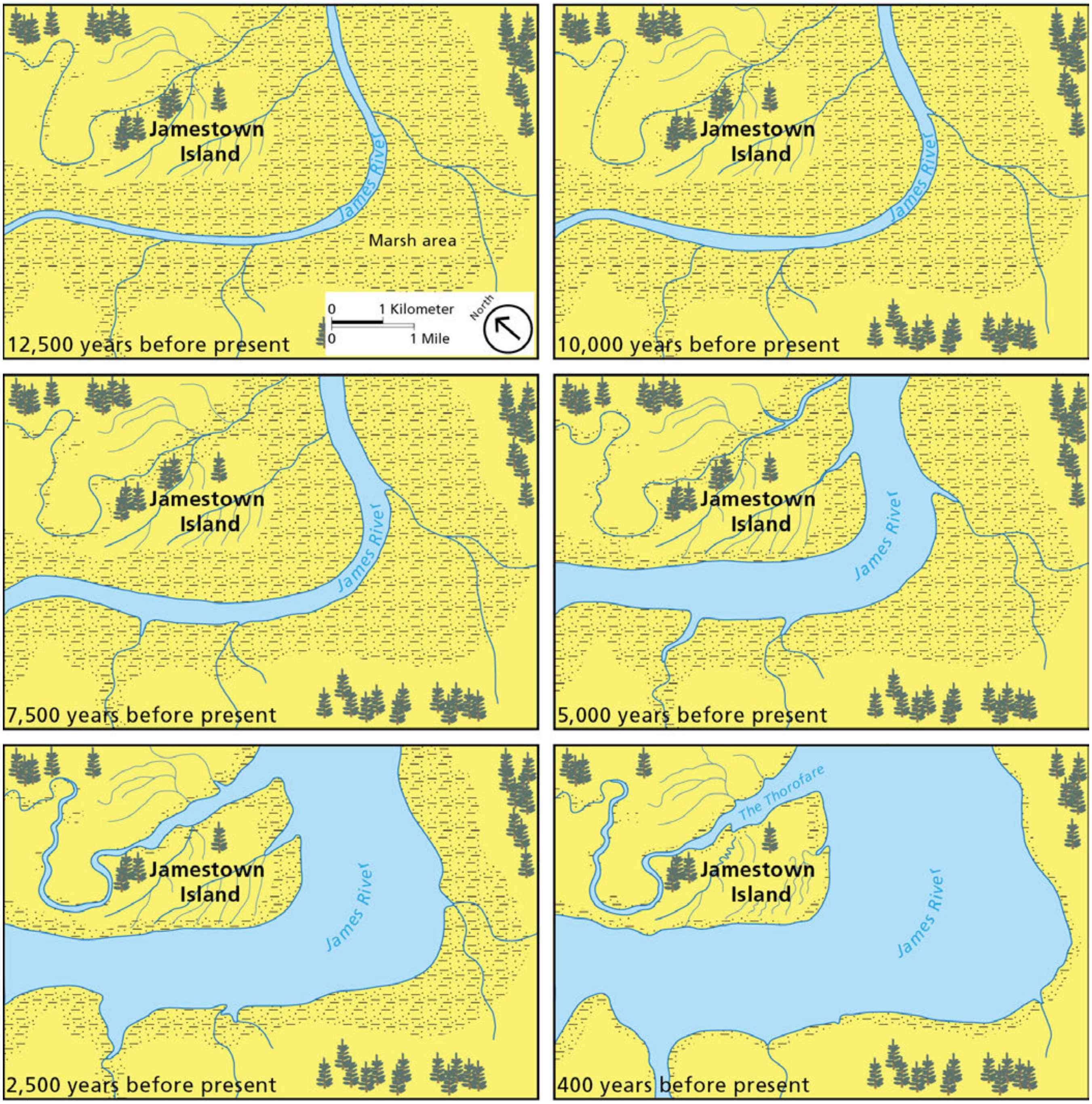


Figure 6. Illustration of the evolution of James River and Jamestown Island. Approximately 12,500 years ago, around the end of the last major global glaciation, sea level was much lower and the James River flowed across its floodplain in a narrow, incised channel. As sea level began to rise due to glacial ice melting, the river became wider. Eventually, sea level was high enough that tides began to affect the James River. By the time European colonists arrived in 1607, Jamestown Island was only connected to the mainland by a narrow isthmus. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from figure 20 of Johnson (2007).

surrounded by open water and almost impassable marshes. Sea level was 0.9 to 0.6 m (3 to 2 ft) lower than at present (Johnson et al. 1995). The combination of abundant timber, open water for navigation and trade, defensible uplands, and a nearshore, deepwater thalweg for anchorage made the island suitable for habitation. Freshwater came from shallow wells dug within James Fort (Johnson 2007).

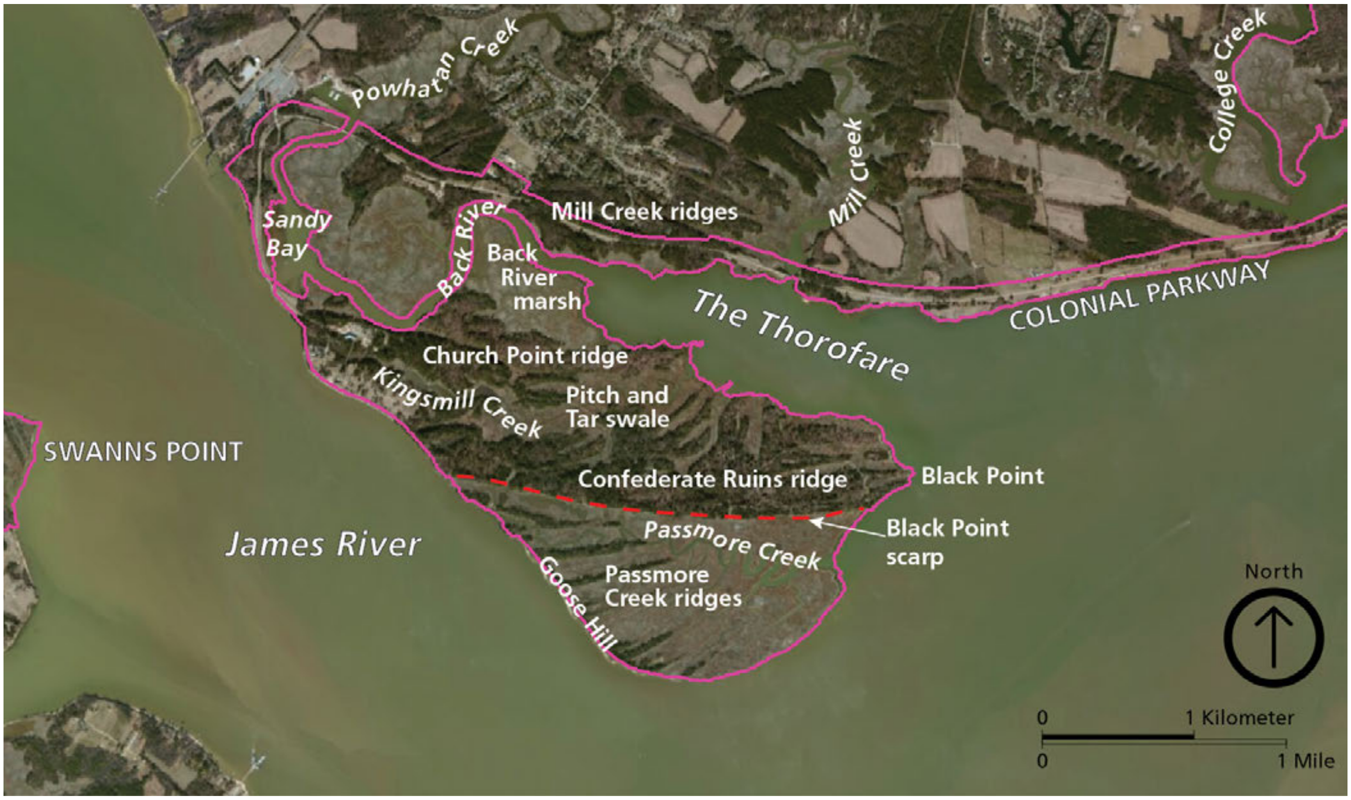


Figure 7. Map of topographic and fluvial features of Jamestown Island. Colonial National Historical Park (pink outline) encompasses the entire island which includes uplands: Church Point ridge, Confederate Ruins ridge, Passmore Creek ridges, and Goose Hill, as well as lowlands: Back River marsh, Pitch and Tar swale, and Passmore Creek. Red dashed line is the trace of the Black Point scarp which ends at Black Point, an area of shoreline loss. Map is adapted from figure 15 of Johnson (2007) by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap, (accessed 13 October 2014).

As described in the "Fluvial Features and Processes" section, archeological excavations on Jamestown Island revealed that the colonists used abundant local natural resources for brick making, masonry, goldsmithing, blacksmithing, glass making, and crafting tobacco pipes and other pottery (Kelso and Straube 2004). Colonists likely used sand (e.g., **Qb**) for iron casting, and clay (e.g., **Qtl**) for pottery and brick making at locations such as Indian Field Creek, the kiln at Greenspring, and William Rogers's kilns at Yorktown. William Rogers was the "poor potter" who operated one of the largest known pottery factories in colonial America and ultimately helped undermine the British economic hold over the colonies (National Park Service 2014b). Construction of the kilns themselves also required natural resources; large amounts of earth had to be mounded in place for insulation (GRI conference call participants, 12 November 2014). Exact locations of raw materials quarries remain largely unknown, but could be a potential project for the Geoscientists-in-the-Parks Program (http://go.nps.gov/gip). Despite the natural richness, the settlement was largely abandoned in 1699 after several fires and also possibly because of brackish water incursions caused by droughts and changing water levels (Stahle 2005; Thornberry-Ehrlich 2005; Thomson 2009).

Some of the earliest land use in the park region was tobacco plantations and other agriculture. Successful settlement transitioned the early colony into the "plantation period", which lasted from about 1745 until 1892. Plantations such as Greenspring relied on springs for fresh water, which tended to emerge where groundwater flowing along impervious layers contacted the ground surface (Carson 1954; Speiran and Hughes 2001; GRI conference call participants, 12 November 2014). During the plantation period, colonists removed many of the trees on Jamestown Island and excavated irrigation ditches (Vanasse Hangen Brustlin, Inc. 2009). Without having properly fertilized and cared for the soils, most plantations suffered widespread depletion of soil nutrients after several years. Glauconite (blue clay) and fossil shell material were mined from the Yorktown Formation (**Tymh** and **Tc**) to use as soil additives to boost tobacco production (Thornberry-Ehrlich 2005). Bellefield, a colonial plantation on the York River, part of which is within the park, was a site where marl and greensand were mined to put on agriculture fields (Rogers 1884). Greensand is shallow marine sediment that contains abundant rounded greenish grains or glauconies which consist of a mixture of clay minerals, such as smectite and glauconite. These additives were rich in phosphoric acid, sulphuric acid, silicic acid, sand, potash, magnesia, iron oxide, lime (carbonate), water, and other trace minerals; they increased the water retentive properties of the soil (Krijgsman 2001).

Iron-rich minerals, such as limonite and goethite, in the ledge-forming layers at the top of the Yorktown Formation and some overlying formations (**Tymh** and **Tc**) were removed in large slabs as iron ore by colonists and slaves and transported to iron furnaces (Thornberry-Ehrlich 2005). These iron-rich minerals formed as a type of residual cement or precipitate during calcium carbonate dissolution. The iron precipitated where carbonate shell material buffered the acidic water flowing downward from overlying sediments (Speiran and Hughes 2001).

Colonists also utilized the hydrogeologic system; flowing water was a source of power for colonial industry. Several of the park's waterways were dammed for use by the Jones, Augustus Moore, and Wormley mills in the park. Remnants of these mills are preserved today as mill ponds and earthen dams (Thornberry-Ehrlich 2005).

Geologic Features and War

Geologic features and processes of the James-York Peninsula impacted military strategy during the American Revolutionary and Civil wars. The proximity to two major rivers flowing into the Chesapeake Bay and out to the Atlantic Ocean made this location strategically valuable.

During the Revolutionary War, the British occupied Jamestown Island before losing it to the colonial forces. The deepwater thalweg of the James River made it an ideal location to outfit ships for combat (Vanasse Hangen Brustlin, Inc. 2009). However, when water travel was not an option due to inclement weather or other military actions (e.g., naval blockades), the peninsula became a trap. Such was the case for the British General Cornwallis and nearly 7,000 troops that were besieged by American and French troops at the end of the James-York Peninsula. The colonial forces dug progressively closer trenches and constructed earthworks in the unconsolidated to loosely consolidated coastal plain sediments (geologic map units **Tymh**, **Tc**, **Qw**, **Qeg**, and **Qsh**) at Yorktown. A fleet of French warships came up behind the peninsula and cut off a water-based escape route. Trapped against the bluffs of Yorktown and unable to cross the York River to Gloucester, General Cornwallis was forced to surrender on 19 October 1781. He signed terms at Moore House in the penultimate confrontation of the American Revolutionary War (Lowry 1989).

Cornwallis "cave," a cavern created by stone quarrying for building material, was once believed to be the "grotto" into which British General Cornwallis retreated to avoid bombardment during the Revolutionary War battle. Subsequent research suggested this is likely a legend. The cave was used for potato storage during colonial times and later for storage of Confederate munitions during the American Civil War in 1862. Large, visible recesses were cut into the front wall by Confederate forces to install support beams for a plank roof and walls that were then covered with earth to protect the munitions from Union warships offshore. The gated cave has since fallen into disrepair as a result of the natural processes of weathering and erosion and lack of maintenance (Johnson 2007).

The land surface also influenced military tactics. As described in the "Karst Topography and Cornwallis Cave" section, dissolution in calcium carbonate-rich sediments created a complex surface pockmarked by sinkholes, depressions, and slumps (Brockman et al. 1997). General Washington entrenched his forces along natural narrow ravines and karst depressions to tighten his military lines around the British forces.

Seeps and springs are other common topographic features and occur where the water table intersects the land surface. Washington's headquarters were located near a spring. Nearly 100 years after the Revolutionary War, Confederate troops dammed some of the spring drainages to flood the narrow valleys and create deep moats to protect their positions against advancing Union forces (Brockman et al. 1997).

Confederates also occupied Jamestown Island in an attempt to control access to the James River, but were forced to evacuate during Major General McClellan's Peninsula Campaign. The island then became a rendezvous for people escaping slavery (Vanasse Hangen Brustlin, Inc. 2009).

In addition to its strategic location, the iron-rich sediments atop the Yorktown Formation (**Tch**, **Tymh** and **Tc**) on the James-York Peninsula sparked some local interest during the American Civil War (Thornberry-Ehrlich 2005). Slabs of iron-cemented sand and limonite littered the ground, having eroded from the hillsides (Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, written communication, 24 August 2015). The relative lack of iron resources available to the Confederate States of America limited industry and military manufacturing compared to the United States of America. This meant any local sources were incredibly valuable.

Historically Significant Paleontological Resources

The fossiliferous marine shell beds ("shell hash") of the coastal plain of Virginia were utilized by American Indians prior to Europeans' arrival in 1607. Paleoindians (the first people who entered and inhabited the American continents during the late Pleistocene) used fossil shark (*Carcharodon* sp.) teeth as scrapers and used scallop (*Chesapecten* sp.) shells for drinking vessels (Johnson 2007).

Some of the earliest colonial uses of the resources were for making lime for mortar and in agriculture (Rogers and Rogers 1837). Other uses included aggregate for road surfaces and quarrying coquina (layers made up entirely of shells) for building material. Yorktown's Grace Episcopal Church was constructed of coquina in 1697 (Roberts 1932).

Fossils from the Yorktown Formation (geologic map units **Tymh** and **Tc**) once lived in open marine, lagoon or other restricted marine, and barrier environments. They first appeared in scientific literature in the 1680s as part of Martin Lister's Historiae Conchyliorum ("history of shells"). Due to their incredible preservation and appearance, they were initially identified as modern shells, not fossils. The fossil scallops may be as large as dinner plates whereas scallop shells of today are roughly palm-sized. Lister's illustration (fig. 8) likely represents the earliest published reference to a fossil from North America and this fossil, the mollusk *Chesapecten jeffersonius*, was named the Virginia state fossil in 1993 (Ward and Blackwelder 1975; Ray 1987; Kenworthy and Santucci 2006; Ward 2008; Tweet et al. 2014). Revolutionary War General Benjamin Lincoln, who served at the siege of Yorktown, described the fossil beds at the bluffs in detail (Lincoln 1783). German naturalist Johann David Schöpf, serving as a doctor for the British army, noted prolific shell beds in the vicinity (Roberts 1932; Ray 1983; Tweet et al. 2014). Fossils collected from the Colonial National Historical Park area grace museums such as the Smithsonian National Museum of Natural History in Washington, DC, the Laboratoire de Géologie in Paris, France, and the Natural History Museum in London, United Kingdom among many others (Tweet et al. 2014).

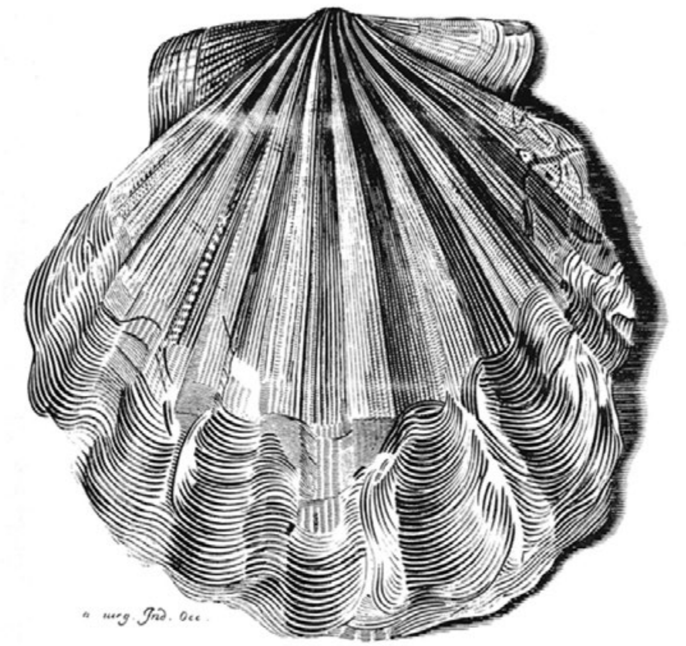


Figure 8. Martin Lister's 1687 illustration of a fossil shell later known as *Chesapecten jeffersonius*. Lister's illustration likely represents the earliest published reference to a fossil from North America and was named the Virginia state fossil in 1993. Illustration reproduced in Ward and Blackwelder (1975).

Soils

Soils form in a complex process that is in part controlled by the underlying geology. Soils in the park support the growth of several locally or globally rare forest types: Coastal Plain Mesic Calcareous Ravine Forest (found on ravine slopes that cut through Tertiary shell hash of the Yorktown Formation [geologic map units **Tymh** and **Tc**]), Coastal Plain Dry Calcareous

Forest (forms over calcareous sediments on southeast and southwest aspect slopes), and Tidal Bald Cypress Forest/Woodland (forms in a transition zone between open tidal water and tidal marsh at Swanns Point and Jamestown Island) (Lookingbill et al. 2012). Soils are not described in detail in this report. An NPS Soil Resource Inventory product for Colonial National Historical Park was updated in 2013 and is available at https://irma.nps.gov/App/Reference/Profile/1048845/.

Ecosystem Connections

The geology, soils, and landforms work in concert along with other factors including climate to create habitats that support biodiversity in the park. The park preserves these habitats amidst the heavily urbanized southeast region of Virginia. Freshwater, uplands, tidal marshes, estuaries, beaches, and bluffs ecosystems are present within Colonial National Historical Park (Stevens et al. 2010). Four dominant habitat types are present within the park: forest, grassland, nontidal wetland, and tidal wetland; current condition assessments rate these habitats as degraded or fair (Lookingbill et al. 2012).

Colonial National Historical Park has the second highest number of rare, threatened, and/or endangered species in National Park Service units of Virginia (Shenandoah National Park has the highest number) (Rafkind 1990; Vanasse Hangen Brustlin, Inc. 2009; Lookingbill et al. 2012). Lookingbill et al. (2012) presents detailed information about species of concern at the park which include sensitive joint-vetch (*Aeschynomene virginica*), barred owl (*Strix varia*), rare skipper (*Problema bulenta*), Rafinesque's big-eared bat (*Corynorhinus rafinesquii macrotis*), Mabee's salamander (*Ambystoma mabeei*), and the bald eagle (*Haliaeetus leucocephalus*).

Marshes and other wetlands form where the land surface and geologic substrate combine to maintain a water-saturated environment. Clay-rich layers either deposited or left as residual clays where other (carbonate) minerals dissolved away act as impermeable layers. The presence of these layers near the surface together with the park's gentle topography and proximity to sea level yields abundant marsh and tidal wetland habitat. Tidal marshes are considered globally rare (see "Soils" section). Monitoring in 2013 revealed the presence of 66 species of marsh birds, including rails and bitterns that are obligates of the tidal marsh and sensitive to changes within their breeding and foraging habitat; such habitat changes could occur due to relative sea-level rise (see "Sea Level Rise, Flooding, and Coastal Vulnerability" section) (Northeast Coastal and Barrier Network 2014).

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Colonial National Historical Park.

During the 2005 scoping meeting (see Thornberry-Ehrlich 2005) and 2014 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Fluvial Features and Processes
- Coastal Plain Sediments
- Slope Features and Processes
- Paleontological Resources
- Karst Topography and Cornwallis “Cave”
- Subsurface Geologic Features and the Chesapeake Bay Impact Crater
- Hydrogeologic System at Yorktown Battlefield

Fluvial Features and Processes

Meandering river channels, point bars, natural levees, and backswamp deposits are the primary fluvial features within and near the park. Fluvial processes in the park both construct (deposit) and erode landforms. The tidal James and York rivers and their tributaries (e.g., Powhatan Creek) acting on unconsolidated coastal plain sediments control sedimentation and geomorphology and hence the development of virtually all landforms in the James-York peninsula. Groundwater flow and more than 99 cm (39 in) of average annual precipitation supply the water for this river system (Speiran and Hughes 2001; Vanasse Hangen Brustlin, Inc. 2009). River currents can reach 1 m/sec (3 ft/sec), but are generally lower and therefore dominate sediment resuspension and transport processes in the lower depths of the water column only (see “Bottom Sediments” section) (Friedrichs 2009; Dallas et al. 2013). Erosion and river meandering, along with waves, contribute to a major resource management issue: protecting shorelines with coastal engineering (see “Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures” section).

A classic meandering river channel consists of a series of fairly uniform S-shaped curves. The curves form because abundant sediment near an active channel accumulates in the meander belt into an alluvial ridge that has a higher elevation than the adjacent floodplain (Saucier 1994). The ridge then diverts the river’s flow laterally, causing the channel to broaden, shallow, and meander. As a river flows around curves, the flow velocity (and thus erosive energy) is greatest on the outside of the bend. The river erodes into its bank on the outside of a curve (cutbank) and leaves point bar deposits on the inside of the bend (fig. 9). As the process continues, the outside bend retreats farther from the channel, while the inside bend builds into the channel, thus creating migrating meanders.

Point bars are crescent-shaped ridges of sand, silt, and clay deposited on the inside of meanders where the water’s velocity is slowest (fig. 9; Waterways Experiment Station 1951). A point bar’s shape conforms to the curvature of the channel, but bars may truncate each other forming a complex pattern as meander migration continues (Waterways Experiment Station 1951). As a meander migrates, successive point bars build up laterally. The curved, sand- and silt-cored ridges are separated by low, clay- and silt-rich swales. The alternating ridges and swales define classic point–bar accretionary topography (fig. 9) (Waterways Experiment Station 1951; Saucier 1994).

During high flows or floods, a river deposits natural levees of sand and silt along its banks. These deposits are the coarse-grained component of a river’s suspended sediment load and often form the highest reaches of an alluvial region. Natural levees also create well-drained farmland. By elevating the land surface with coarse sediment, porosity is increased and water is able to percolate downward and support crops without being swampy. Regular flood incursions also bring valuable nutrients to floodplains and levees. For these reasons, they have been the most significant landforms in human-settlement patterns, influencing building locations, transportation routes, agriculture, and industry development (Saucier 1994).

Backswamps are low-lying places that retain water during floods or high flow (fig. 9). They are separated from the river channel by natural levees (Waterways Experiment Station 1951). Low relief and dense vegetation characterize a backswamp. The slack

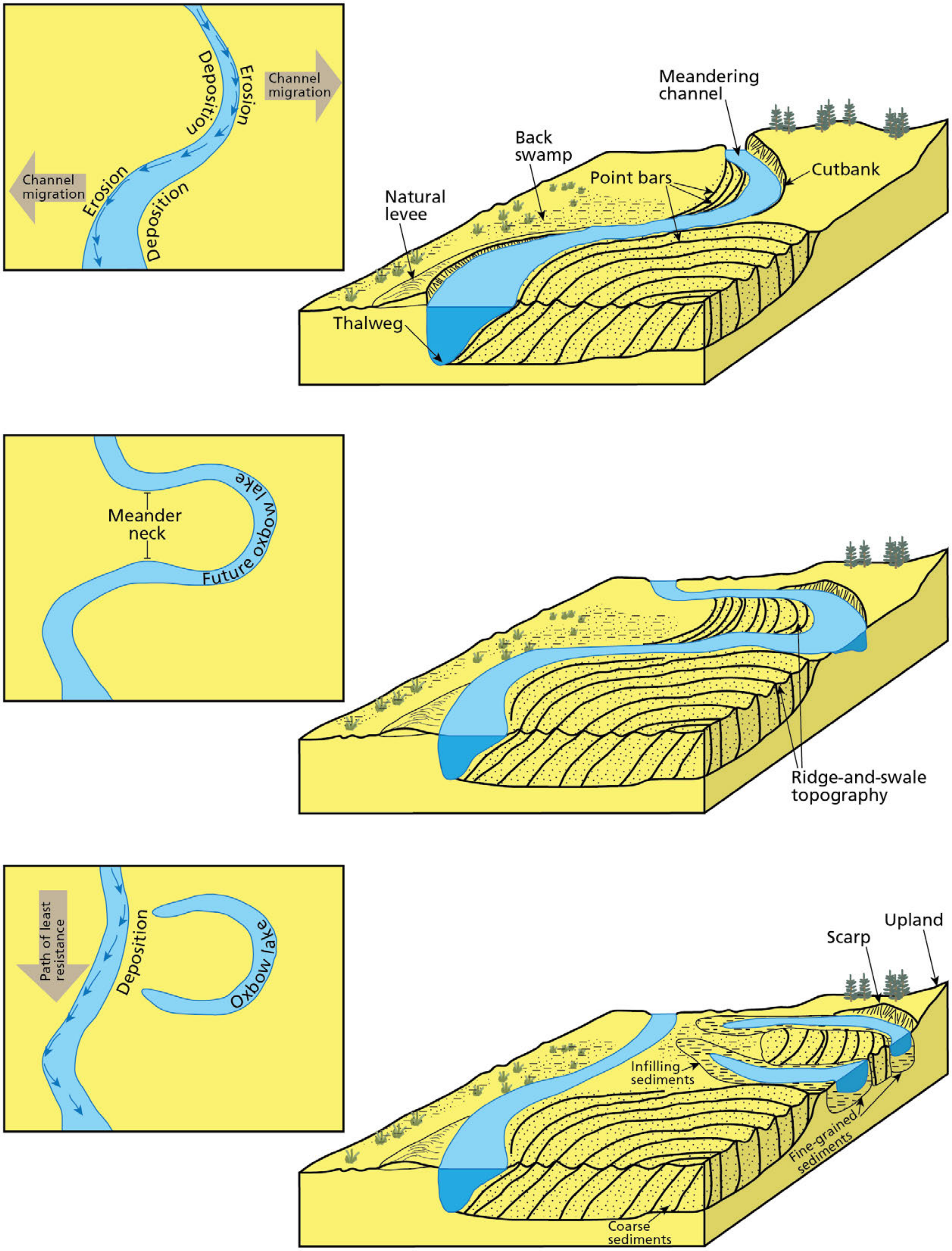


Figure 9. Illustration of fluvial processes of meandering. River meandering causes the formation of abandoned channels that infill with fine-grained sediments. Among the characteristic landforms resulting from river meander is ridge-and-swale topography visible at Jamestown Island. Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from Allen (1964).

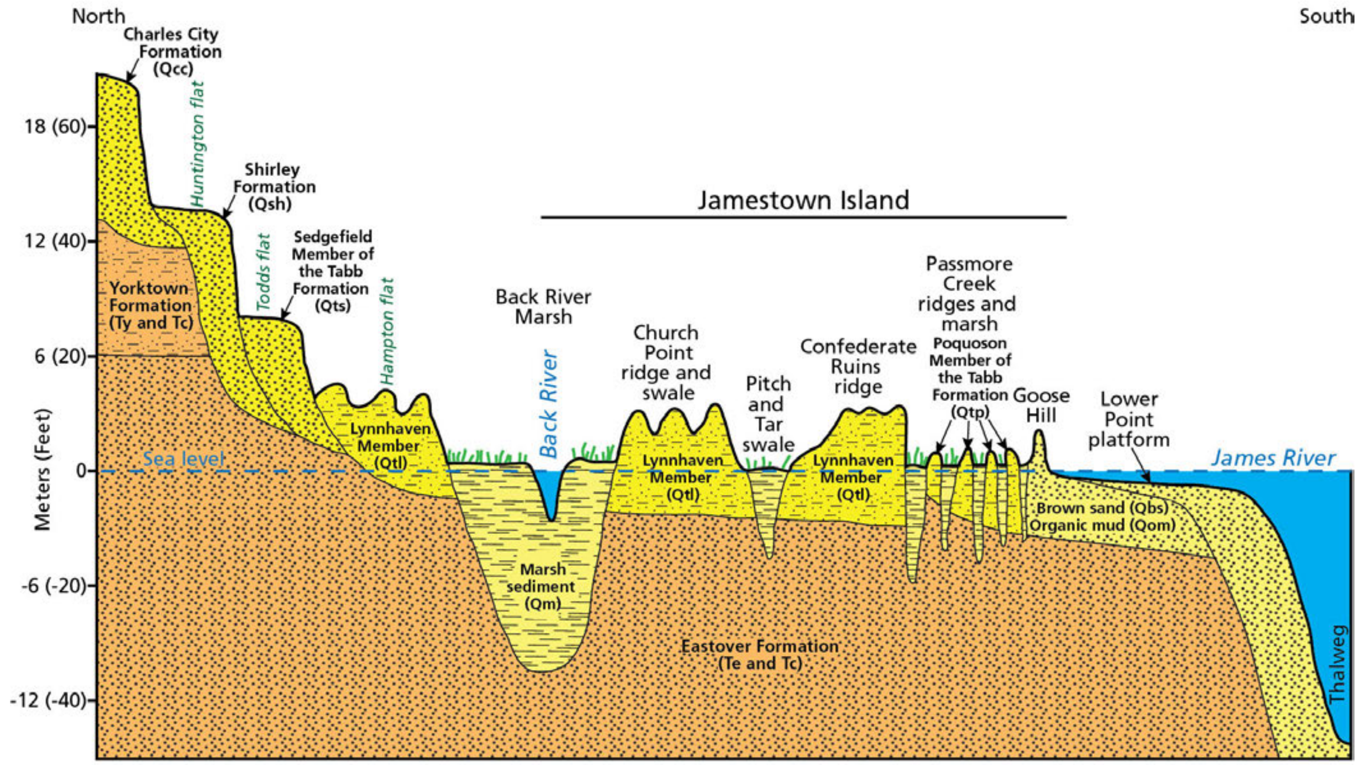


Figure 10. Cross section of Jamestown Island. Ridge-and-swale topography is obvious at Jamestown Island, particularly at Church Point, Confederate Ruins ridge, and the Passmore Creek ridges and marsh. Vertical scale is greatly exaggerated. Decreasing ridge elevations to the east are not visible on this graphic due to its north to south orientation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after figure 17 in Johnson (2007).

floodwaters deposit layers of (fine-grained) clays and organic material (Waterways Experiment Station 1951).

In addition to the two large rivers (York and James), water bodies within the park include Sandy Bay, the Thorofare, Pitch and Tar swale (swamp), Yorktown, Mill, Powhatan, Kingsmill, Passmore, Indian Field, Felgate's, King's, Queen's, Halfway, College, Papermill, Wormley, Beaverdam, and Ballard creeks; Great and Baptist runs; and the Back River (Lookingbill et al. 2012). Not counting the York and James rivers' shorelines, more than 39 km (24 mi) of perennial streams and 49 km (30 mi) of intermittent streams and drainages traverse the landscape within Colonial National Historical Park (National Park Service 2014a). The erosion and meandering of these streams through the unconsolidated coastal plain sediments shape and reshape the landscape across the James-York peninsula.

Jamestown Island exhibits some classic features of a river-influenced landscape such as a stair-stepped, ridge-and-swale topography (fig. 10). The uplands (ridge) consist of Church Point and Confederate Ruins ridges at about 3 to 4 m (10 to 13 ft) above sea level. They feature low, arcuate ridges formed in the Lynnhaven Member of the Tabb Alloformation (geologic map unit **Qtl**), which decrease in elevation towards the east. As mentioned in the "Geologic Significance and Connections" chapter, settlers made use of this valuable upland by siting James Fort, Jamestowne, and farms there (Johnson 2007). The lower ridges south of Passmore Creek are formed in the clays, silts, and sands of the Poquoson Member of the Tabb Alloformation (**Qtp**). Between adjacent ridges are low-lying swales and swamp or marshes (e.g., Pitch and Tar swale, Passmore Creek marsh, and Back River marsh.

Coastal Processes

The James and York rivers experience typical fluvial processes, but are also affected by coastal processes, such as tides, wind, and waves, which create brackish conditions in both rivers (salinity between 18 and 30 ppt at Yorktown and up to 18 ppt at Jamestown; Center for Coastal Resources Management et al. 2008). The fluvial and coastal processes transport sediment and shape the park's shorelines. Tides from the Atlantic Ocean cause water level fluctuations in the Chesapeake Bay of less than 1 m (3 ft) on average (Yorktown station 8637689; Thornberry-Ehrlich 2005; National Oceanographic and Atmospheric Administration 2014). The tides are semi-diurnal, consisting of two high tides and two low tides each day (Vanasse Hangen Brustlin, Inc. 2009). Wave energy varies depending on the fetch distance, wind regime, nearshore bathymetry, and the orientation of the shoreline (Dallas et al. 2013). Fetch lengths in the southern Chesapeake Bay are generally less than 8 km (5 mi) and limits the local wave climate (Dallas et al. 2013). Wind patterns shift seasonally from the north and northwest during late fall to southwest in spring (Hardaway and Byrne 1999; Hardaway et al. 2006; Dallas et al. 2013).

The most sediment transport and shoreline change occurs during major storms such as nor'easters, tropical storms, or hurricanes (e.g., Hurricane Isabel in 2003) (Dallas et al. 2013). The effects of major storms are described in the "Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures" section.

Bottom Sediments

Mapping riverine bottom sediments is useful for defining faunal habitat and potential subaqueous sand and gravel resources. Recent mapping in the James River, offshore of Jamestown Island, revealed the presence of black, organic-rich muds in the central channel. Mapping also identified subaqueous sand which appears to migrate upstream in waves, transported by river currents; the sand fills in the dredged Goose Hill channel (see Goose Hill on fig. 7; Berquist 2012). The GRI GIS data include several submerged mud and sand units (geologic map units **Qsnd**, **Qom**, **Qsg**, and **Qshom**), visible on the geologic map poster (in pocket) (Berquist 2010; Berquist 2015).

Coastal Plain Sediments

Loosely consolidated to unconsolidated sedimentary units underlie Colonial National Historical Park and represent the three main types of sedimentary rocks: clastic, chemical, and organic. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." Clastic sedimentary rocks are named after the size of clasts (see table 1 for park examples). High-energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in lakes, the water cannot transport even the smallest clasts and they are deposited. Wind also transports and deposits sand-sized or smaller clasts (table 1). Chemical sedimentary rocks form through precipitation; an example is carbonate rocks such as limestone (calcium) or dolomite (calcium and magnesium). Organic sedimentary rocks are composed of organic remains (e.g., coal) or were produced by the physiological activities of an organism (e.g., secretion of calcium carbonate to form coral reefs). Sedimentary rock types record the environment of their deposition and those environments can shift laterally as conditions change; in doing so, laterally related depositional environments can become superimposed. This situation results in time-transgressive sedimentary formations where the vertical and lateral sequences of sedimentary facies are the same (fig. 11). In other words, sedimentary facies that occur in conformable vertical successions of strata also occur in laterally adjacent environments.

The geologic formations mapped along riverbanks and excavations on the lower James-York Peninsula range in age from the late Miocene (about 11 million years ago) to the present surficial deposits (see "Surficial Deposits" section). The units are broadly divisible into two types

Table 1. Clastic sedimentary rock classification and characteristics.

Rock Name	Local Example	Clast Size	Depositional Energy	Depositional Setting
Conglomerate (rounded clasts) or Breccia (angular clasts)	Pebble layers in Bacons Castle Formation (Qbc) and Shirley Alloformation (Qsh)	>2 mm (0.08 in) [larger]	Higher Energy	Fluvial
Sandstone	Windsor Formation (Qw)	1/16–2 mm (0.0025–0.08 in)		Fluvial
Siltstone	Tabb Alloformation, Lynnhaven Member (Qtl)	1/256–1/16 mm (0.00015–0.0025 in)		Estuarine
Claystone	Clay layers in the Tabb Alloformation (Qt, Qtp, Qtl, Qtlp and Qts)	<1/256 mm (0.00015 in) [smaller]	Lower Energy	Estuarine

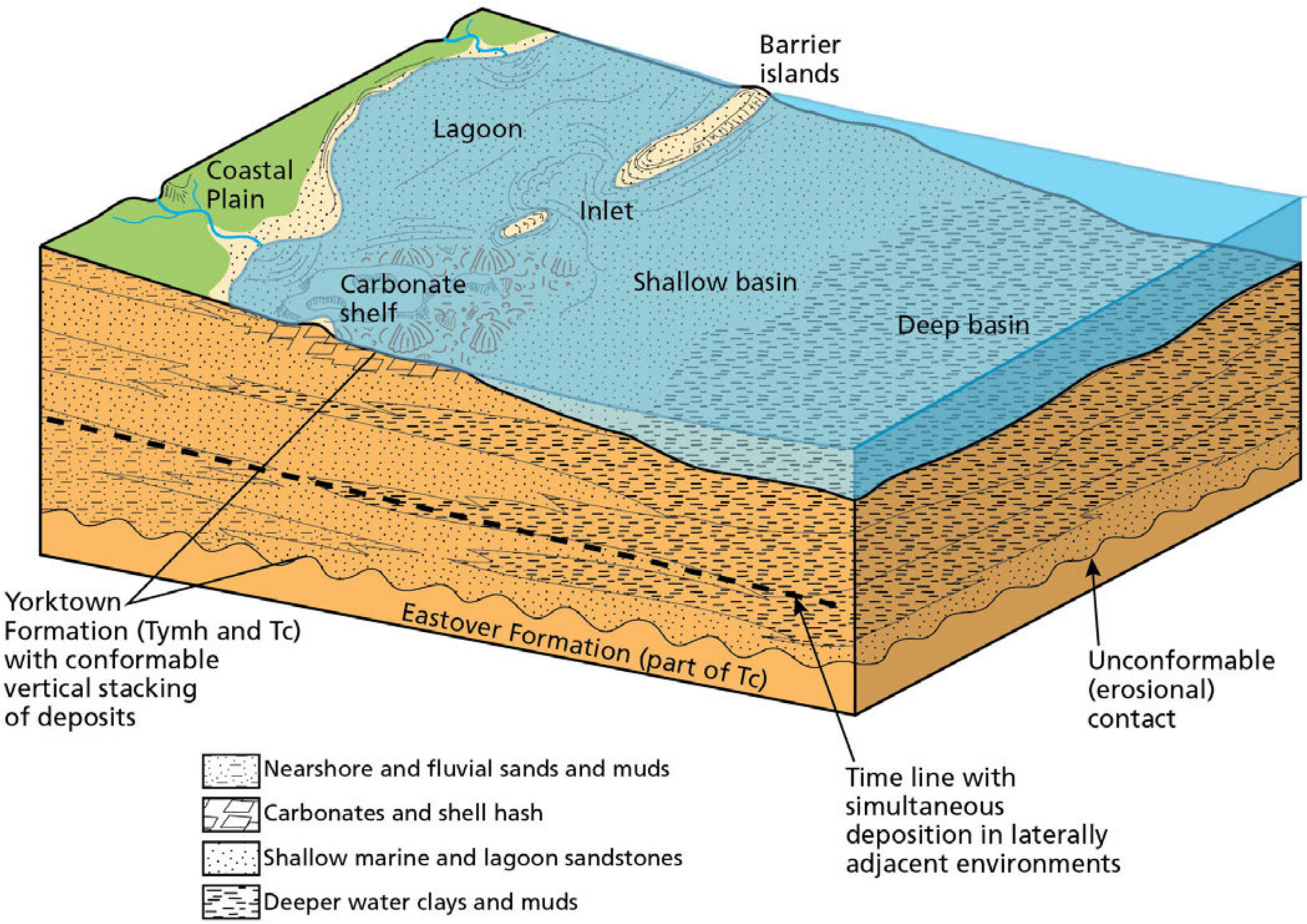


Figure 11. Illustration of the deposition of the Yorktown Formation (geologic map units Tymh and Tc). Because sedimentary environments vary spatially, sediments of different type are deposited at the same time within the same unit. Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from Berquist (2010).

(table 2): (1) older, relatively thin, fossiliferous, marine sediments with layers of relatively uniform thickness (flat) near their base, and (2) younger, fluvial-estuarine units with highly variable composition, thickness, and fossil content with undulating layers near their bases due to the in-filling of ancient valleys and shallower surfaces between valleys ("interfluves") (Johnson 2007). The younger fluvial-estuarine formations were deposited on a dissected terrain during global sea level rises and falls (transgressions and regressions) (Johnson 2007). The units are all described in detail in the Map Unit Properties Table. The history and spatial distribution of all these units are complex and still the subject of much study and debate among geologists. Areas of study include the lateral and vertical relationships among units and the number, distribution, and origin of formations that underlie the terraces on the coastal plain of Virginia (Johnson 2007). More investigation is needed to determine the nature of these units.

Table 2. Geologic formation types.

Type 1—mostly marine	Type 2—mostly fluvial or estuarine
Yorktown Formation (Tymh and Tc)	Tabb Alloformation (Qt, Qtp, Qtl, Qtlp and Qts)
Eastover Formation (Tc)	Shirley Alloformation (Qsh)
	Chuckatuck Alloformation (Qc)
	Charles City Alloformation (Qcc)
	Windsor Formation (Qw)
	Bacons Castle Formation (Qbc)

Rock Exposures, Stratigraphic Sections, and Type Localities

Exposures of sedimentary rocks within and near the park have been studied for well over 150 years, although many of the historic exposures are now obscured or destroyed by coastal engineering structures (fig. 12). Historic accounts of the fossil beds in the Yorktown Formation (geologic map units **Tymh** and **Tc**) of the steep banks along the York River after the American Revolutionary War attest to their prominence and visibility (see "Geologic Significance and Connections" chapter). The excellent exposures of the local Yorktown Formation also make them ideal targets for field-based research experiences in local schools, community colleges, and universities. Exposures along the James River recently provided the material and setting to study sedimentology, stratigraphy, paleoecology, and taphonomy (the study of the environmental conditions affecting the preservation of animal or plant remains) at Thomas Nelson Community College (Layou et al. 2010). Such outcrops could provide important interpretive locations.

Geologists use exposures to describe geologic units and sequences to create a "section." Sections used to officially designate a new geologic unit are called type sections. A type locality is the location of a type section where layers of rock (strata) were originally described. A type section is the standard for which exposures of the same strata in other locations may be compared. At least one type locality (Moore House Member of Yorktown Formation) is within the park as described below.

Type sections are typically selected for layers of sedimentary rocks that share similar characteristics, such as rock type (e.g., sandstone, shale, and siltstone), color, or distinctive features. Such a rock group is called a "formation." An "alloformation" a kind of formation, in which the unit is defined and identified on the basis of its discontinuities that surround it rather than a particular composition (Prothero and Schwab 2004). Alloformations are commonly used to distinguish between superposed deposits (e.g, a succession of similar river and lake deposits, separated by soil layers), contiguous discontinuity-bounded deposits (e.g., overlapping lobes of slope deposits from different cold-climate periods), and geographically separated bodies (e.g., river terrace deposits), all of similar composition (Rawson et al. 2002).

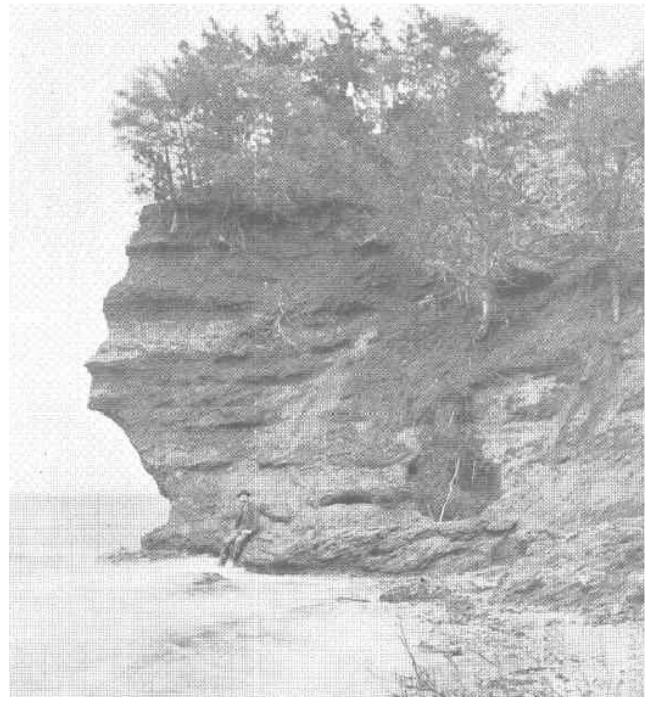


Figure 12. Photograph of cliff of Yorktown Formation ca. 1912. Exposures such as this were common along the York River in the vicinity of Yorktown prior to the installation of riprap and other shoreline engineering along much of the York River shore. Note person for scale. Photograph is from Clark et al. (1912) presented as COLO Figure 1 by Tweet et al. (2014).

Geologists usually name formations to reflect a geographic feature such as a river, mountain, or city (e.g., Yorktown Formation) where the layers are best seen. Formations can be lumped together into "groups" such as the Chesapeake Group or subdivided into "members" such as the Poquoson Member of the Tabb Formation. Type localities are searchable at the US Geological Survey's online database: http://ngmdb.usgs.gov/Geolex/search.

Yorktown, Virginia lends its name to the Yorktown Formation (**Tymh** and **Tc**), but there is no formal type locality and today, riprap covers most historic outcrops of the Yorktown Formation at Yorktown. The Yorktown Formation was divided into four members by Ward and Blackwelder (1980), in ascending order: Sunken Meadow, Rushmere, Morgarts Beach, and Moore House members. The Sunken Meadow member is considered the lower Yorktown Formation, whereas the latter three members compose the upper Yorktown Formation (Johnson 2007; Tweet et al. 2014).

The Moore House Member, at the top of the formation, was named for Moore House in Colonial National Historical Park. Exposures in the park provided the type locality and include westward dipping sandy shell beds and cross-bedded shell hash (see “Karst Topography and Cornwallis Cave” section). At the top of the member in the Williamsburg vicinity, brackish water mollusks signaled the sea level regression and freshwater input at the end of the Yorktown Formation deposition (Ward and Blackwelder 1980).

Slope Features and Processes

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and avalanches are common types of slope movements. These processes and the resultant deposits are also known as “mass wasting” and commonly grouped as “landslides.” Slope movements occur on time scales ranging from seconds to years. Refer to figure 13 for illustrations of slope movements. Slope movements create geologic hazards and associated risks in many parks. Hazards and risks associated with slope movements in Colonial National Historical Park are described in the “Geologic Resource Management Issues” chapter.

Slope movements are a natural geologic process and occur as small scale slumps and slope creep (fig. 14) on steep bluffs and ravines within Colonial National Historical Park. Areas undercut by erosion—itself a major issue in the park—are also prone to failure (see “Slope Movement Hazards and Risks” for more case studies).

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). All fossils are nonrenewable. Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. The NPS Fossils and Paleontology website, https://www.nps.gov/subjects/fossils/index.htm, provides more information. As of February 2016, 261 parks, including Colonial National Historical Park, had documented paleontological resources in at least one of these contexts. The park contains examples of all three.

Tweet et al. (2014) prepared a paleontological resource summary report that details the documented and potential fossil resources for Colonial National Historical Park and other parks within the Northeast Coastal and Barrier Inventory and Monitoring Network. Significant fossil specimens have been found within park boundaries. These fossils present opportunities for education, interpretation, and scientific research. Notable fossil localities within the Yorktown Formation (geologic map units **Tymh** and **Tc**) are described in Tweet et al. (2014). The exact locations are considered sensitive information. Refer to the “Paleontological Resource Inventory, Monitoring, and Protection” section for resource management issues associated with fossils in the park.

Local fossils are historically significant to paleontological history. Many species were discovered, described, and named from locations in the park. In some areas, fossils are quite abundant (see inside cover). As described in the “Geologic Significance and Connections” chapter, the bivalve (mollusk) *Chesapecten jeffersonius* was likely the first fossil to be described in North America. It was included in Martin Lister’s Historiae Conchyliorum in the late 1600s, although at the time, it was not recognized as a fossil. Ward and Blackwelder (1975) described the story of the fossil that would later become the state fossil of Virginia.

Tweet et al. (2014) provided detailed tables of fossils named from specimens found or possibly found within Colonial National Historical Park—in summary:

- 65 species of bivalves
- 33 species of gastropods
- 11 species of foraminifera
- 7 species of ostracods
- 2 species of barnacles
- 1 scaphopod mollusk
- 1 serpulid worm
- walrus

Other geologic map units occurring in Colonial National Historical Park have the potential to contain fossil resources. Notable among these is the potential for large, extinct Pleistocene mammal remains such as mammoths, mastodons, horses, and bison (Tweet et al. 2014). These are described in detail in Tweet et al. (2014) and on the Map Unit Properties Table.

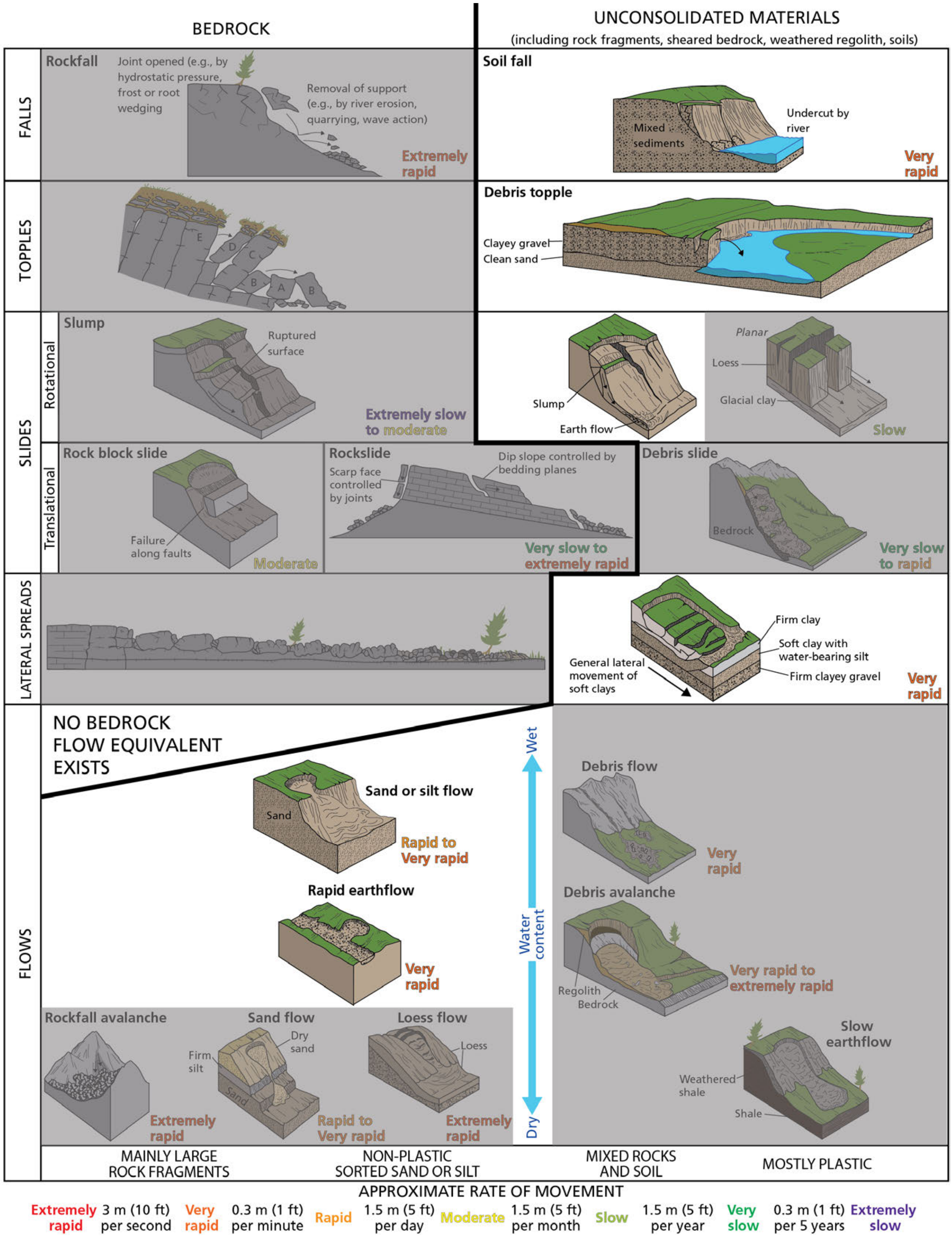


Figure 13. Illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed boxes refer to settings that are not known to exist at Colonial National Historical Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978).

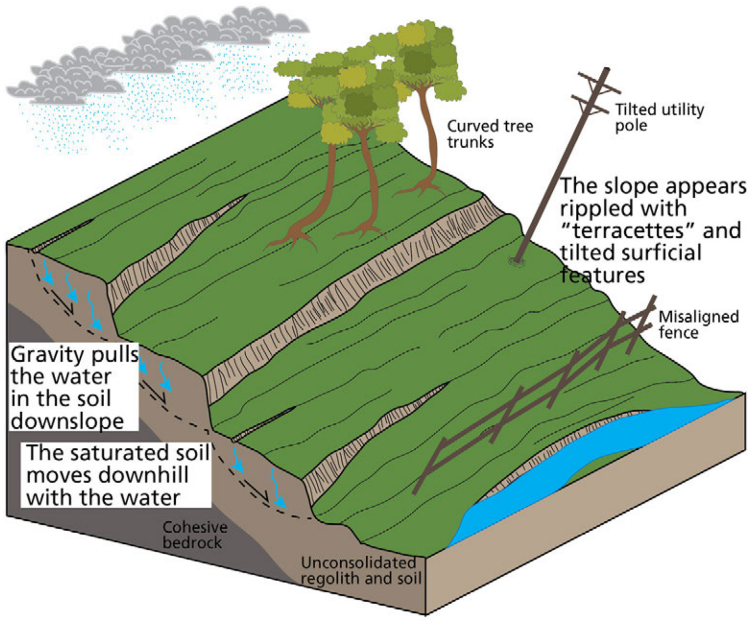


Figure 14. Illustration of slope creep. Creep is a very slow, more or less continuous downslope movement of material. Curved trees on park slopes are evidence of slope creep. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Fossil discoveries in the vicinity of Colonial National Historical Park continue. In 2013, a partial skeleton of a baleen whale—nicknamed "Cornwallis"—was recovered from the Eastover Formation (**Tc**) along the York River outside of the park (McClain 2014; Tweet et al. 2014).

Fossils from the park and/or surrounding area are curated in at least a dozen museums in the United States and Europe as summarized by Tweet et al. (2014).

Using Yorktown Formation Fossil Resources to Determine Past Climates and Ecosystems

Paleoecology, or the study of past interactions among organisms and their environment, seeks to determine (1) how the organisms interacted with the environment and each other, as well as how those interactions changed over time, and (2) what environmental factors controlled the abundances and distributions of the fossil species. Winkelstern et al. (2013) used fossil bivalves (*Mercenaria* spp.) from the Rushmere Member of the Yorktown Formation (geologic map unit **Tc**) to estimate sea surface temperature and climate at seasonal resolution during the Pliocene Epoch (5.3 million to 2.6 million years ago) on the mid-Atlantic Coastal Plain. Oxygen isotope ratios of the seasonal growth layers within the shells revealed the coldest winter temperatures recorded in the Yorktown Formation averaged 17±2°C (63±3°F) and the warmest summer temperatures averaged 25±2°C (77±3°F). This was part of the mid-Pliocene warm period (3.3 million to 3.0 million years ago)—among the most critical geologic intervals for studying a relatively warm with high concentrations of atmospheric CO_2, with increased Gulf Stream heat flow coupled with reduced cool-water input. This information in turn helps to understand the potential effects of modern global climate change.

The Yorktown Formation provided a case study for testing the methods of paleoecological investigation as to how the environment controlled the fossil assemblage. Samples were taken from King's Mill, Virginia among other nearby sites. The analysis showed that species richness increased on muddy and sandy substrates with low stress (i.e., low wave energy, relatively constant temperature, or moderate salinity) conditions (Bush and Daley 2008).

Karst Topography and Cornwallis "Cave"

Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, "losing streams," springs, and internal drainage are characteristic features of karst landscapes. Caves are naturally occurring underground voids such as solutional caves (commonly associated with karst), lava tubes, sea caves, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). As of December 2015, cave or karst resources are documented in at least 159 parks, including Colonial National Historical Park. The NPS Caves and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides more information. According to Land et al. (2013), eight percent of the land area within Colonial National Historical Park is karst. The only documented "cave" in the park is Cornwallis cave—discussed below—which is not a natural feature.

Sinkholes or "closed depressions" are common features of the lower Coastal Plain. Locally, sinkholes occur on the terrace treads, underlain by carbonate-rich sediments from the Norge Upland, southeastward to the Todds flat (see fig. 3). The deepest sinkholes and greatest concentration of karst features in the Colonial National Historical Park region occur on the Grafton and Huntington flats. These can resemble anthropogenic earthworks and other battlefield-related depressions.

The soluble carbonate rock in the park vicinity is most often fossiliferous layers of the Yorktown Formation, particularly the shell "hash" layers such as those that host Cornwallis cave (fig. 15; geologic map units **Tymh** and **Tc**). As those layers dissolve, overlying insoluble material, such as the clay-rich Windsor Formation (**Qw**) collapse or subside into the voids (Johnson et al. 1993; Thornberry-Ehrlich 2005; Johnson 2007; Berquist 2010). The thickness of these clay layers, which can vary extensively particularly where faults are present (see "Subsurface Geologic Features and the Chesapeake Bay Impact Structure" section), exerts substantial control over which karst features (e.g., sinkholes and springs) form there (Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, conference call, 12 November 2014). For example, west of a fault that crosses the southern part of the Yorktown unit (see "Subsurface Geologic Features and the Chesapeake Bay Impact Crater" section), the hash layer is 3 m (10 ft) thick; east of the fault on the uplifted side, the hash is 21 m (70 ft) thick and susceptible to extensive dissolution and the creation of subterranean voids; places like this are beneath the larger sinkholes at Yorktown Battlefield (Rick Berquist, conference call, 12 November 2014; Berquist 2015).

The park's subsidence sinkholes range in size from a few meters to more than 40 m (130 ft) in diameter and the deeper depressions can hold water for several weeks following a heavy rainfall. The size of the sinkhole varies with the elevation of the terrace (flat), thickness of the underlying carbonate layer, and proximity to adjacent streams, which may breach the sinkhole at any stage of development (Johnson et al. 1993). Deep sinkholes occur along Main Street in Yorktown, near the York River where the groundwater gradient is steepest. Karst ponds (or perennially wet sinkholes) include Grafton Pond complex and Brackens Pond (Thornberry-Ehrlich 2005).

The sinkholes tend to form in stages (fig. 16). Isolated,

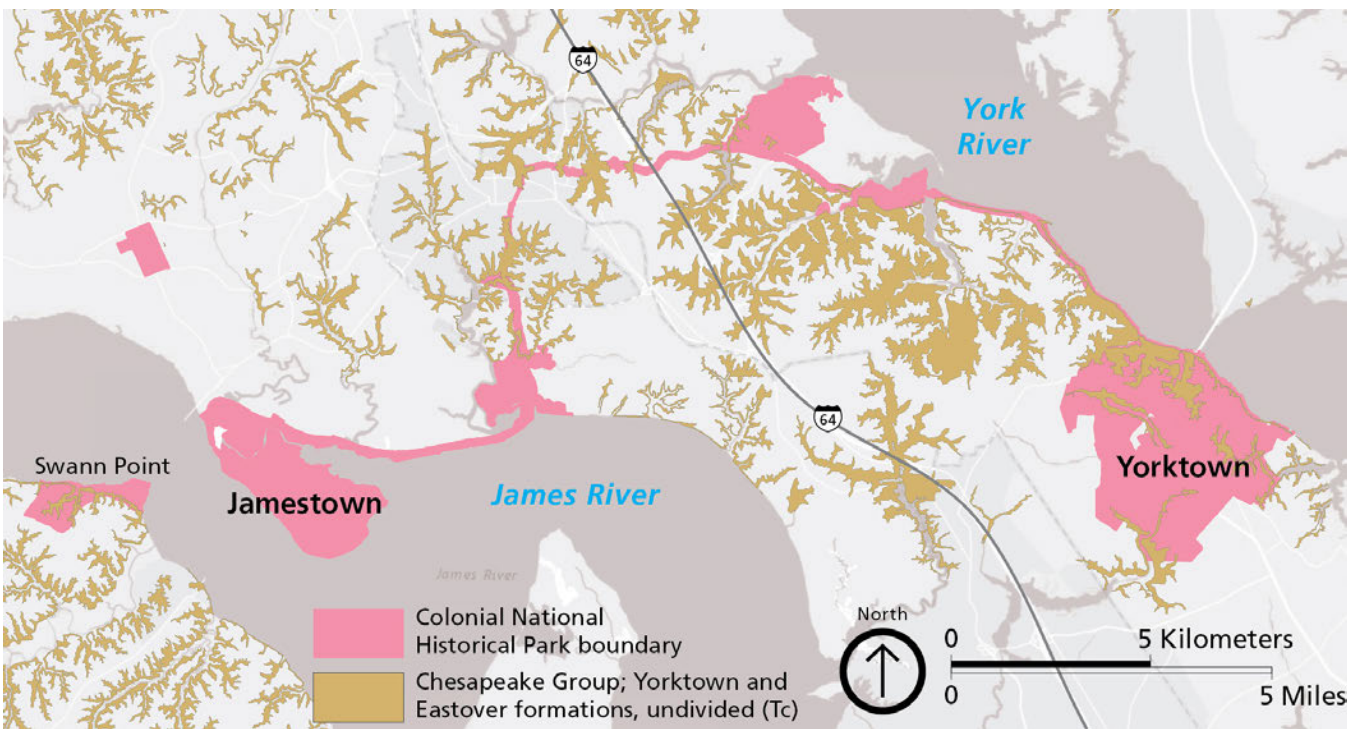


Figure 15. Map of the Yorktown Formation within park boundaries. The carbonate layers within the Yorktown Formation (geologic map units Tymh and Tc) are soluble and prone to karst-feature development including sinkholes and springs. Sinkhole formation is pronounced in the Yorktown Battlefield unit. Pink lines are park boundaries. Graphic by Jason Kenworthy (NPS Geologic Resources Division) using GRI GIS data and ESRI Light Gray Canvas basemap, (accessed 12 May 2016).

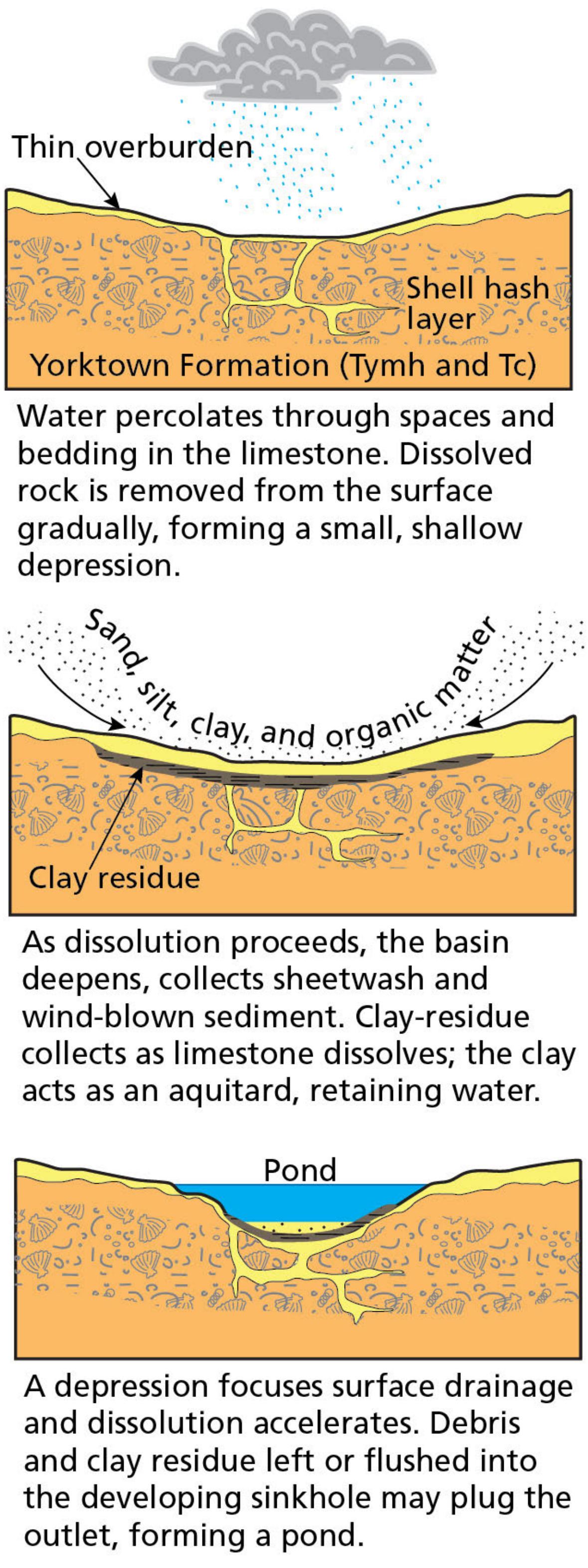


Figure 16. Illustration of dissolution sinkhole formation. Dissolution sinkholes form from dissolution and downward to lateral erosion of unconsolidated material into the underlying cavities. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figures by Tihansky (1999, p.126–127).

shallow basins, less than 1 m (3 ft) deep characterize the early stage. With time, the basins deepen, become more extensive (≤2 ha [5 ac]), coalesce laterally, accumulate sediment (more than 4 m [13 ft]) from sheetwash and wind-blown input, and flood for periods of time (Johnson et al. 1993). During the last phase of sinkhole development, the basins are nearly filled with sediment reducing the landscape's relief (Johnson et al. 1993).

Larger sinkholes have larger catchment areas and may become "self-perpetuating" as they become larger; they hold more water which increases dissolution, enlarging the sinkhole. (Johnson 2007). As the carbonate dissolves, a clay-residue layer is left behind and restricting groundwater flow across its surface. As the groundwater pools atop a clay-rich layer (called an "aquitard"), the dissolution and basin development progresses laterally, widening the sinkhole depression. Sinkhole development hampers development of surficial streams by reducing overland flow and erosion across the terrace surface (Johnson 2007). For more than 10,000 years, sinkholes of the James-York peninsula have been accumulating upwards of 4.5 m (14.8 ft) of organic material (an important paleoecological record), aeolian (wind-blown) detritus, and colluvium (Johnson 2007).

As described in the "Geologic Significance and Connections" chapter, Cornwallis cave at Colonial National Historical Park is not a natural cave, but instead a two-chambered quarry into cross-bedded coquina ("shell hash") beds of the Yorktown Formation (**Tymh** and **Tc**). In fact it is documented as an abandoned mineral land (AML) feature as described in that section of this report. The "cave" consists of two rooms; the larger is approximately 6.8 m by 3.4 m (22.3 ft by 11.2 ft). The weakly cemented Yorktown Formation coquina erodes and dissolves easily; at least 4.5 metric tons (5 tons) have crumbled from the cave since the 1790s (Santucci et al. 2001; Johnson 2007; Tweet et al. 2014). In addition to concerns about the feature's stability, fossils exist within the cave (see "Geologic Resource Management Issues" chapter).

Subsurface Geologic Features and the Chesapeake Bay Impact Crater

The typical depiction of the Coastal Plain sediments as a thick, undeformed, seaward-dipping wedge of sediment is not entirely accurate. A variety of faults, deformed sedimentary layers, and regional unconformities occur between sediment layers underlying Colonial National Historical Park and throughout the James-York Peninsula (Poag et al. 1991; Poag 1997; Johnson 2007). A fault is a fracture in rock along which rocks have moved. The three primary types of faults are normal faults, reverse faults, and strike-slip faults (fig. 17). Faults are classified based on the relative motion of rocks on either side of the fault plane as described in fig. 17. Discovery of the Chesapeake Bay impact crater in the 1990s helped to explain the presence of many of these subsurface structures, as well as the location of river valleys and the Chesapeake Bay.

The Chesapeake Bay impact structure is not visible at the surface, as it is buried by thick sediments that accumulated over 35 million years. The feature consists of a central crater and circular basin ("annular trough") surrounded by an outer fracture zone (fig. 18) (Johnson et al. 1998; Powars and Bruce 1999). Colonial National Historical Park straddles part of the annular trough and outer fracture zone. About 35 million years ago, a 3-km (2-mi) -wide bolide (meteor or comet) slammed into a shallow sea near present-day Cape Charles on the Eastern Shore of Virginia (Powars and Bruce 1999; Johnson et al. 2001a). According to Johnson (2007) and Johnson et al. (2001a), the impact vaporized, melted, and ejected the bedrock from the central crater, affecting "basement" rock to a depth of more than 1,800 m (6,000 ft). The impact shockwave fractured rocks and created numerous faults (see fig. 17 for schematic fault types) which down-dropped large and small blocks of rocks. The impact and subsequent rebound of Earth's crust produced a central peak and giant blocks of rock were dislodged within or tumbled into the crater forming a chaotic accumulation of material referred to as a "megabreccia".

The crater created an enormous depression that accumulated sediment for millions of years. Even after the crater was completely buried by sediments, subsidence and structural adjustments controlled post-impact depositional settings and stratigraphic relations within and among the younger geologic formations. Subsidence rates are higher in and adjacent to the crater. Units deposited across the disruption thicken into the ring-like depression (annular trough) adjacent to the crater itself (Powars and Bruce 1999). The massive weight of post-impact sediments in and around the impact structure reactivated some of the numerous faults. This created earthquakes. Seismic activity continues today, but the frequency and magnitude of these earthquakes have diminished (Johnson et al. 1998; Johnson 2007). These underlying geologic structures likely contributed to or controlled the development of the James and York rivers' locations; the parallelism of the step-wise scarps of the James-York peninsula suggests the strong influence of episodic differential movement along the buried, impact-related structures (see "Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures" section) (Powars and Bruce 1999; Thornberry-Ehrlich 2005). The impact structure may also have affected the distribution and

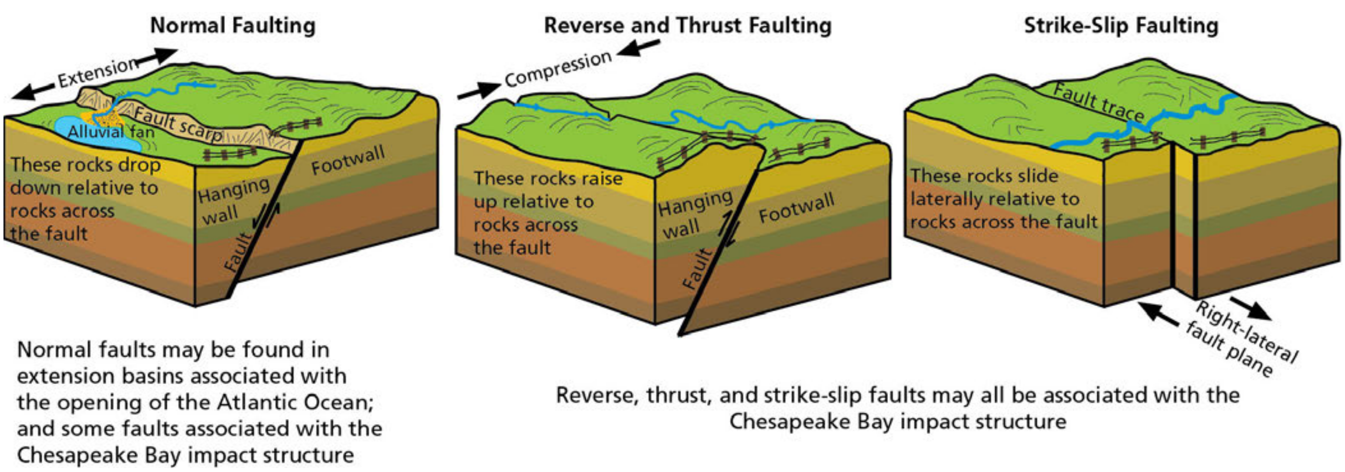


Figure 17. Illustration of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

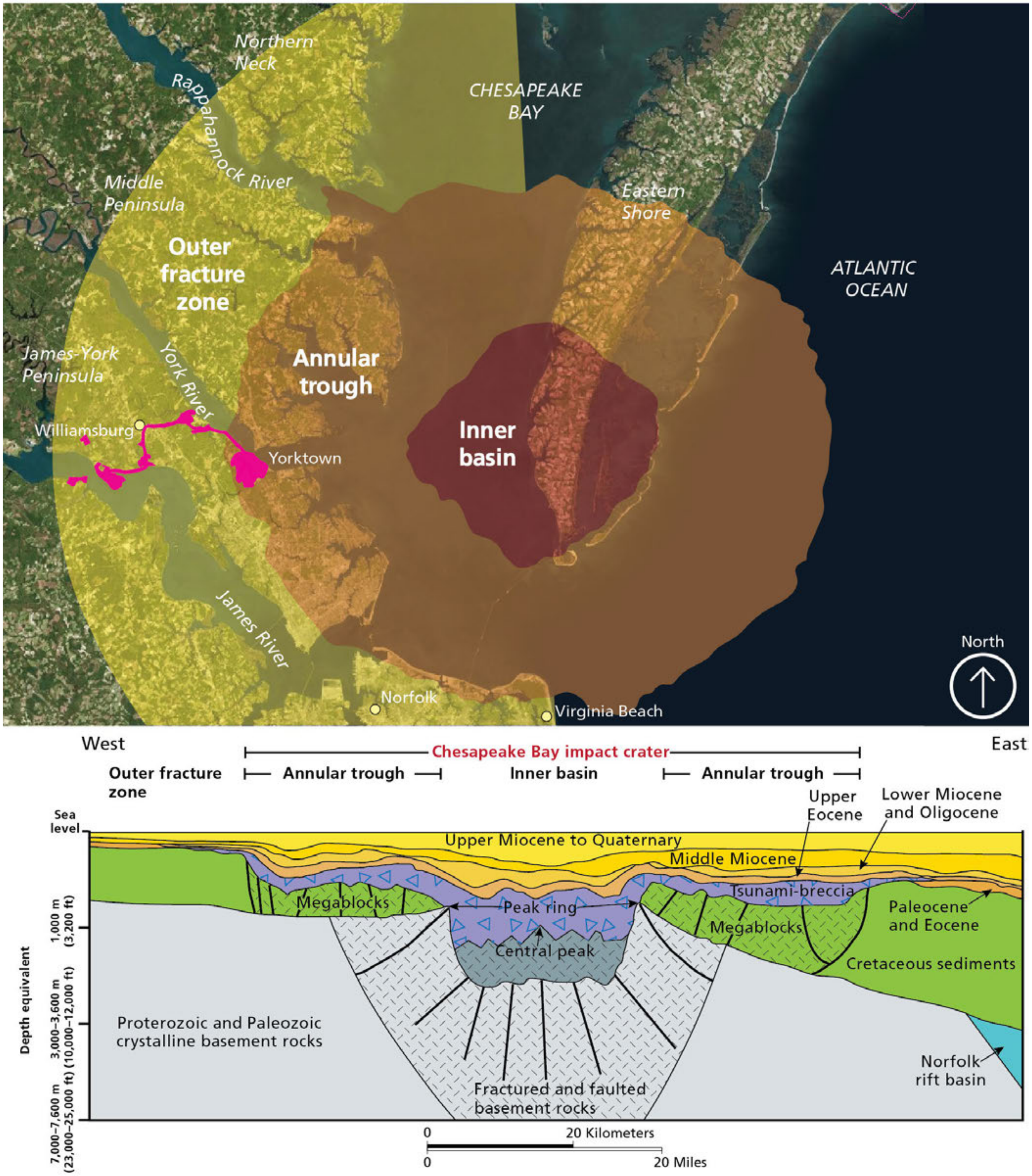


Figure 18. Map and cross section of the Chesapeake Bay impact structure. Colonial National Historical Park (pink outline) is within the outer fracture zone and part of the annular trough—a ring-shaped depression surrounding the peak ring of the central crater. The megablocks are fault-bounded packages of sedimentary units that slumped into the crater, juxtaposing units of different ages along angular unconformities. Graphic is adapted from Johnson (2007, figures 6 and 7) by Trista L. Thornberry-Ehrlich (Colorado State University) using ESRI World Imagery basemap, (accessed 8 October 2014).

quality of groundwater because it created marked boundaries in the subsurface, and movement along impact-related structures juxtaposed different units (Powars and Bruce 1999; Johnson 2007). A better understanding of the geometry and coastal plain stratigraphy is necessary and study is ongoing (Johnson et al. 2001a; Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, conference call, 12 November 2014).

Results from drilling, coring, and mapping efforts near Newport News suggest the presence of at least three north–south oriented faults, one of which crosses the park and the York River just east of Yorktown. The other two are south and east of Yorktown and have a down-to-the-west direction of movement. These are mapped on the GRI GIS source map (Berquist 2015). These features are likely associated with the Chesapeake Bay impact structure and could potentially be reactivated, particularly if a large earthquake occurs elsewhere (see "Geologic Hazards and Risks" section) (Rick Berquist, conference call, 12 November 2014). Any movement along these faults may impact the park's hydrogeologic system, karst features, and infrastructure, including the dams at Jones Mill Pond and Wormley Pond (Tim McLean, NPS Colonial National Historical Park, civil engineer, conference call, 12 November 2014). Aside from earthquake generation, these faults influence the flow of groundwater, the location of karst topography, the thickness of sediments, and other geomorphology. More field work and drilling are necessary to accurately delineate the positions of these features (Rick Berquist, conference call, 12 November 2014).

Recent mapping described by Gilmer and Berquist (2012) throughout the Coastal Plain of Virginia northwest of Colonial National Historical Park and east of Richmond has revealed the presence of regionally extensive faults. These down-to-the-east faults may indicate the presence of a now-buried basin that predates the Chesapeake Bay impact structure; this may correlate with other extensional basins along the east coast. Undeformed layers of the Bacons Castle Formation (geologic map unit **Qbc**) lie atop the faults, suggesting that significant movement predates its deposition. The faults were likely active during the deposition of the Yorktown Formation (**Tymh** and **Tc**). Faults and other shallow structures have the potential to affect groundwater flow dynamics (see "Hydrogeologic System at Yorktown Battlefield" section) in aquifers above the Cretaceous Potomac Formation—the oldest and most deeply buried Coastal Plain unit (Gilmer and Berquist 2012).

Hydrogeologic System at Yorktown Battlefield

The groundwater system at Colonial National Historical Park impacted historic events and today it is a management concern due to threats on its water quality and quantity (see "Groundwater Quantity and Quality" section). Speiran and Hughes (2001) delineated the aquifers and confining units at Yorktown Battlefield to understand how groundwater was moving through the subsurface and supplying water to streams and wetlands. The battlefield is underlain by a system of relatively impermeable confining units (aquicludes) layered with permeable aquifers within the Yorktown, Bacons Castle, Windsor, Chuckatuck, Shirley, and Tabb formations and alloformations (geologic map units **Tymh**, **Tc**, **Qbc**, **Qw**, **Qc**, **Qsh**, and **Qt**), as well as Holocene surficial units (possibly **Qal** and **Qms**). See Map Unit Properties Table for more information. The deep part of the system is generally more than 45 m (150 ft) below the surface and is poorly connected to the shallow part of the aquifer that nourishes the surface water features. The local shallow aquifer system consists of, with increasing depth, (1) the unconfined Columbia aquifer, (2) the Cornwallis Cave confining unit, (3) the Cornwallis Cave aquifer, (4) the Yorktown confining unit, and (5) the Yorktown-Eastover aquifer (fig. 19). The upper two units are laterally discontinuous because terrace deposits at different elevations are incised by stream valleys. The confining units are generally silty and clayey sediments that inhibit the flow of water. The aquifers consist of sandy and shelly sediments with abundant pore space for groundwater to permeate readily (Brockman et al. 1997; Speiran and Hughes 2001).

The primary source of groundwater from the region's shallow aquifer system is the Cornwallis Cave aquifer, the uppermost aquifer. It underlies nearly the entire Yorktown Battlefield except along Ballard Creek and the York River. The aquifer and surface water features are connected because streams have cut into the aquifer. Streams are not incised deeply enough to penetrate the deeper Yorktown-Eastover aquifer (Speiran and Hughes 2001).

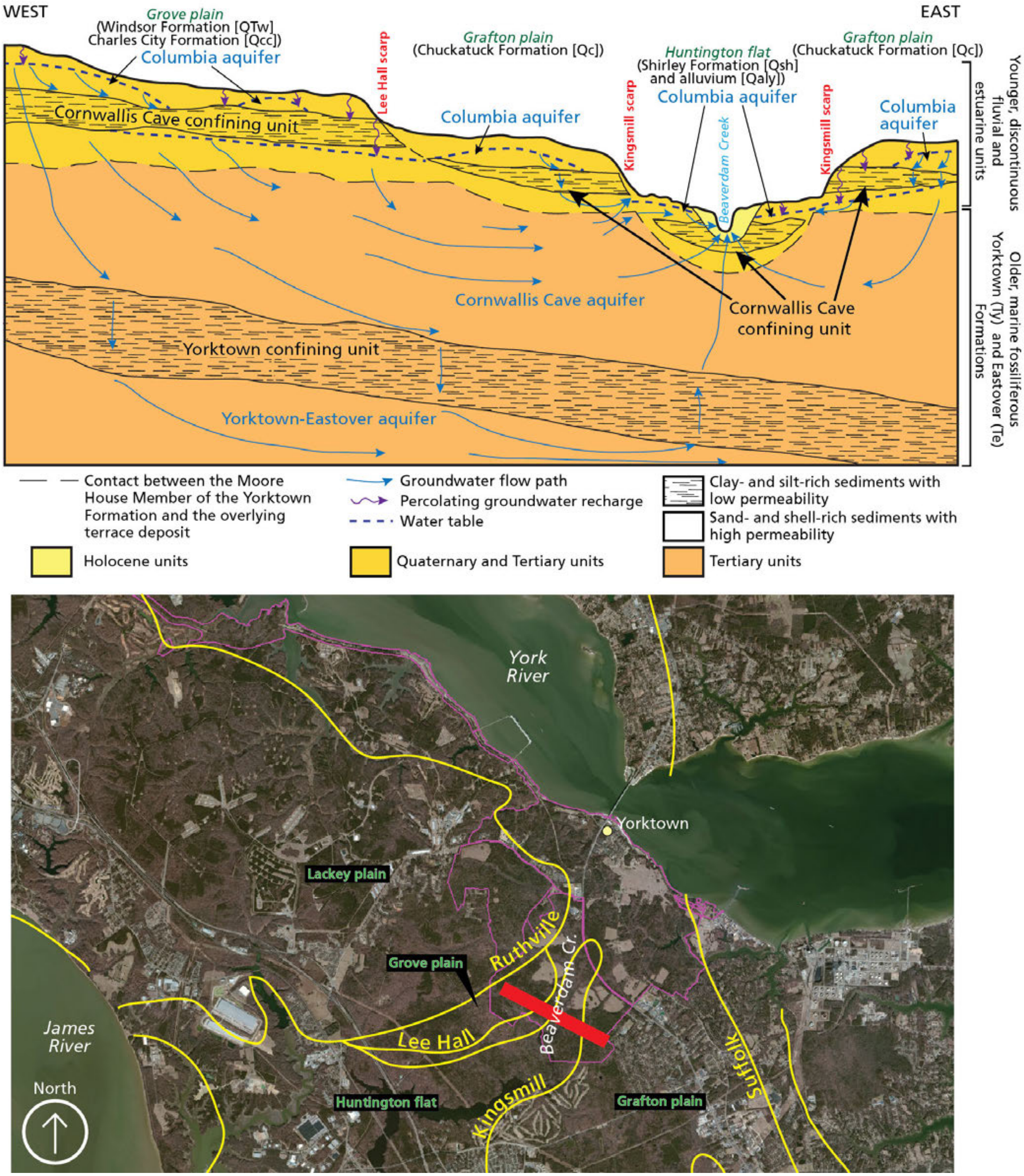


Figure 19. Map of generalized groundwater flow through hydrogeologic units at Yorktown Battlefield. Red line on aerial image is the general trace of the cross section. Yellow lines indicate scarps (see figs. 3 and 4); pink line is park boundary. Orange and yellow unit colors correspond to units on the geologic time scale. Graphic is not to scale and is vertically exaggerated. Note the discontinuous nature of the perched Columbia aquifers and Cornwallis Cave confining units due to the presence of the step-wise riverine scarps and incision of Beaverdam Creek. The Yorktown-Eastover aquifer is completely buried throughout the battlefield area. Graphic is adapted from Speiran and Hughes (2001, figure 11) with information from Johnson (2007) by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic Resource Management Issues

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

Unsurprisingly for a park that is located between two major rivers and about 48 km (30 mi) west of the mouth of the Chesapeake Bay, there are significant resource management issues associated with surface and ground water. During the 2005 scoping meeting (see Thornberry-Ehrlich 2005) and 2014 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Sea Level Rise, Flooding, and Coastal Vulnerability
- Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures
- Stormwater Management along Colonial Parkway and Upland Erosion
- Paleontological Resource Inventory, Monitoring, and Protection
- Geologic Hazards and Risks
- Groundwater Quantity and Quality
- Karst Landscape Management
- Yorktown Formation Shrink-and-Swell Clays
- Abandoned Mineral and Disturbed Lands

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

Lookingbill et al. (2012) provided a natural resource condition assessment that describes the natural features within the park in context of the geographic location, legislative mission, and history.

The park's most recent general management plan emphasized the need to manage the park's natural resources consistent with the National Park Service's philosophy on management of cultural zones (Colonial National Historical Park 1993).

The park has fostered partnerships with outside agencies to conduct in-park research, including Virginia's Water Quality Board, Department of Game and Inland Fisheries, Natural Heritage Program, and Department of Forestry; the US Geological Survey; the US Soil and Conservation Service; the US Fish and Wildlife Service; the Virginia Institute of Marine Science; the College of William and Mary; Hampton University; and the Virginia Division of Geology and Mineral Resources (VDGMR) (Rafkind 1990). These types of working relationships contribute greatly to knowledge of the natural resources, geologic foundation, and ecosystems within the park.

Sea Level Rise, Flooding, and Coastal Vulnerability

Colonial National Historical Park spans a peninsula between two major rivers and is within several meters of sea level. In addition, the York and James rivers are both tidally influenced in the park region. Within the park, tidal fluctuations average about 1 m (3 ft) on average (Yorktown station 8637689; Thornberry-Ehrlich 2005; National Oceanographic and Atmospheric Administration 2014). Therefore, park lands, as well as cultural and natural resources, are particularly vulnerable to changes in relative sea level and flooding associated with storms. Climate change models for Virginia and the rest of the southeast U.S. predict sea level rise, and an increase in the frequency, intensity, and duration of strong storms such as hurricanes (Melillo et al. 2014; Caffrey and Beavers 2015).

Caffrey and Beavers (2015), using data from the Intergovernmental Panel on Climate Change (IPCC 2013), reported sea level rise of 4.6 mm (0.18 in) per year from 1927 to 2013 at the Sewells Point tide gauge. Sea level rise presents management issues. Sea level rise in the 19th century raised the water table and caused brackish water incursions into what was previously nearly fresh groundwater. This had a profound impact on Jamestown Island agriculture as marshes and swamps migrated up the swales on Jamestown Island and other low-lying places. The cultural resources at the western end of Jamestown Island are particularly vulnerable to degradation (from saturated soil) and loss from rising water (eroding away; Johnson 2007). Sea level at Jamestown Island has risen slightly less than 1 m (3 ft) in the 400 years since European occupation (Johnson 2007).

Between 1950 and 2003, the mean sea level trend at the Gloucester Point gauge was an increase of 3.81 mm/year (0.15 in/year), much larger than the 20th century global average of 1.7 mm/year (0.07 in/year) and probably due to local subsidence (Church and White 2006; National Park Service 2011; Dallas et al. 2013). This process continues today and is a major concern for groundwater quality (see "Groundwater Quantity and Quality" section). The death of pine trees on the low ridges south of Passmore Creek is evidence of increased groundwater salinity as sea level continues to rise and groundwater becomes increasingly brackish (Johnson 2007). Local river salinity ranges from 18 to 30 ppt at Yorktown and up to 18 ppt at Jamestown (Center for Coastal Resources Management et al. 2008).

The park's Natural Resource Condition Assessment (Lookingbill et al. 2012) also identified sea level rise and increased severity and frequency of storms as a regional threat to natural and cultural resources. Global sea level has risen approximately 20 cm (8 in) over the past century and the rate of change is expected to continue increase into the next century (Melillo et al. 2014). A 1-m (3.3-ft) rise in sea level will inundate over 80% of Jamestown Island (fig. 20) (Saunders et al. 2010; Dallas et al. 2013). Caffrey and Beavers (2015) used Intergovernmental Panel on Climate Change (IPCC) data to project additional sea level rise at Colonial National Historical Park between 27 and 28 cm (10.6 and 11.0 in) by 2050 and between 64.0 and 81.4 cm (25.2 and 32.0 in) by 2100.

Flooding during storm events such as nor'easters and hurricanes is likely to increase in severity and frequency as climate continues to change, with projected storm intensity and rainfall rate increases (e.g., Melillo et al. 2014; Caffrey and Beavers 2015). The annual wettest month and wettest quarter are now considered extreme relative to historic conditions (Monahan and Fisichelli 2014). At present, places such as Pitch and Tar swale, Passmore Creek marsh, and large areas of Church

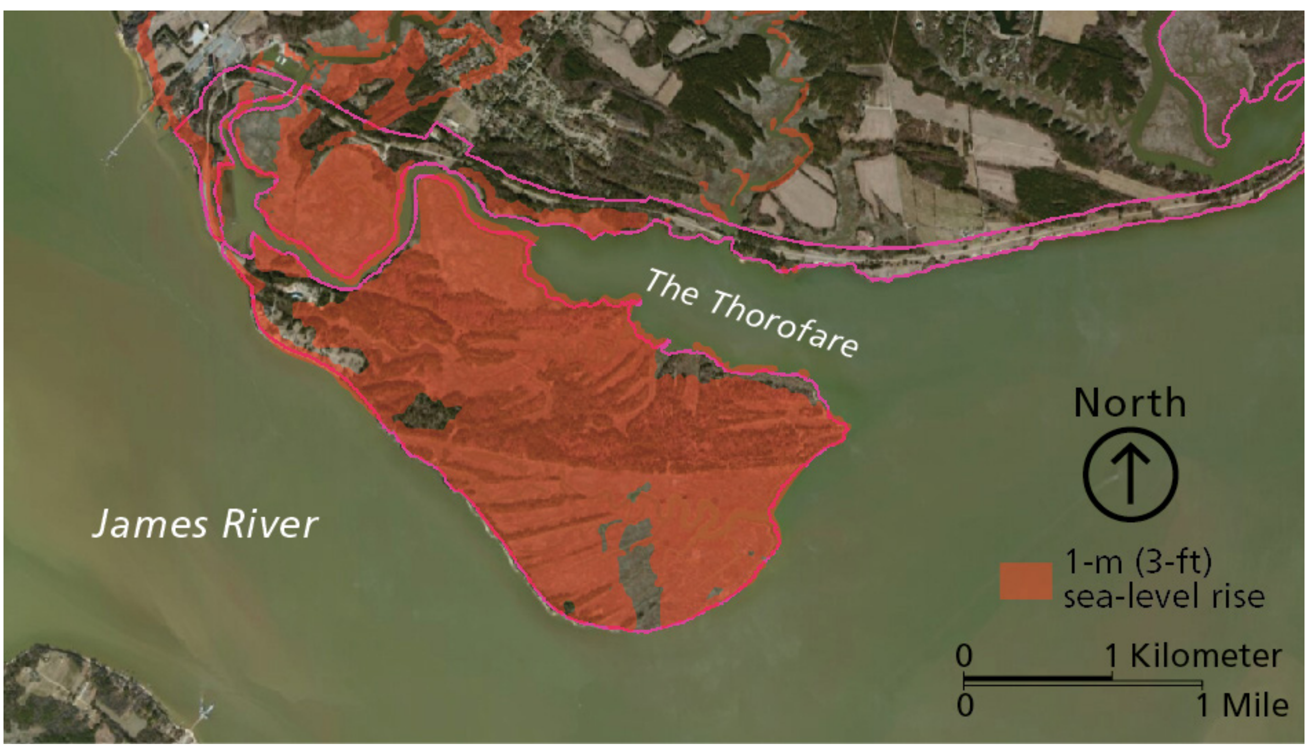


Figure 20. Map of flood-vulnerable areas of Jamestown Island. Sea level rise of 1 m (3 ft) will inundate a vast majority of Jamestown Island. Graphic is figure 20 in Dallas et al. (2013) adapted from Saunders et al. (2010).

Point and Confederate Ruins ridges flood during major storms. As just one example of infrastructure loss during such a storm, a nor'easter destroyed the pier and docks of Yorktown's waterfront in 1985 (Lookingbill et al. 2012).

The James River has long fetches on both the eastern and western ends of the island. In 2003, storm surges associated with Hurricane Isabel damaged shoreline stabilization structures, eroded beaches, washed away several archeological sites along the Parkway and on Jamestown Island, and severely damaged the Jamestown visitor center (damaging or destroying artifacts there) and several tour road bridges (Thornberry-Ehrlich 2005; Johnson 2007; Lookingbill et al. 2012). In addition to flooding, storms concentrate erosive waves on the park's shoreline, as detailed in the "Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures" section.

Caffrey and Beavers (2015) presented potential storm surge heights and extents within Colonial National Historical Park for hurricanes of category 1 and 3 on the Saffir-Simpson scale. They also projected a storm surge height of 5.27 m (17.3 ft) above current mean sea level at the Historic Jamestowne Visitor Center for a category 4 hurricane. The visitor center would likely remain dry during a category 1 hurricane; at least one such hurricane should be expected to reach the park by 2100 (Caffrey and Beavers 2015). Another storm-inundation estimate also known as sea, lake and overland surges from hurricanes (SLOSH) was completed using LiDAR for the elevations; this differed from the previous estimate as much as 27% of the time for category 1 hurricanes (Shaw and Bradley 2014; Amanda Babson, NPS Northeast Region, coastal climate adaptation coordinator, written communication, 26 March 2015). The geospatial data for this study, including inundation estimates for various sea level scenarios, are available at: https://irma.nps.gov/DataStore/Reference/Profile/2216861 (accessed 11 May 2016).

The US Geological Survey has conducted coastal vulnerability index (CVI) assessments for a number of units in the National Park System, but not yet at Colonial National Historical Park. CVIs have been completed for Assateague Island National Seashore and Cape Hatteras National Seashore, 87 km (54 mi) to the north and 96 km (60 mi) to the south of Colonial National Historical Park, respectively (Pendleton et al. 2004, 2005). CVIs use tidal range, wave height, coastal slope, shoreline change, geomorphology, and historical rate of relative sea level rise to create a relative measure of the coastal system's vulnerability to the effects of sea level rise. The approach takes into account a coastal system's natural ability to adapt to changing environmental parameters. Coarse data for the southeast region, including Virginia, presented in Melillo et al. (2014) showed the Tidewater area of Virginia to have "very high" vulnerability to sea level rise.

A park-specific CVI would provide data for resource management and park facilities plans at Colonial National Historical Park. The park submitted a vulnerability assessment request and is tentatively scheduled to receive one in 2019; however, an earlier date would be preferable (GRI conference call participants, 12 November 2014). For more information about CVIs, refer to the US Geological Survey CVI website: http://woodshole.er.usgs.gov/project-pages/nps-cvi/.

According to Monahan and Fisichelli (2014), climate change will likely affect all aspects of park natural and cultural resource management. Caffrey and Beavers (2015) noted the following potential impacts due to sea level rise and storm surge vulnerability at the park:

- Increasing sea levels may lead to loss of land and critical habitat.
- Increased erosion and/or accretion across the coastline by storms coupled with shorelines adjusting to new mean sea levels.
- Rising groundwater tables and possible salt water intrusion due to rising sea levels.
- Increased risk of impacts related to high intensity storm events.
- Potential loss of nearby freshwater ecosystems due to saltwater intrusion into groundwater as sea level rises.

Park resource managers are very concerned about the vulnerability of cultural resources in locations that models predict will be submerged and potentially lost (Jonathan Connelly, NPS Colonial National Historical Park, cultural resources manager, conference call 12 November 2014). Effective planning and management must incorporate an understanding of past dynamics, present conditions, and projected change (Monahan and Fisichelli 2014). NPS Policy Memorandum 14-02 (Jarvis 2014) identifies specific foci for adaptive research and management activities related to cultural resources, and provides guidelines for decision-making to avoid impairment of these resources in the face of climate change. The forthcoming NPS Coastal Adaptation Strategies Handbook (Beavers et al., in prep), expected in summer 2016, summarizes NPS guidance and strategies for cultural resources adaptation.

The summary report from the Preserving Coastal Heritage workshop (National Park Service 2014c) identified and described seven climate change adaptation options for cultural resources: no active intervention; offset stresses; improve resilience; manage change; relocate/facilitate movement; document and release; and interpret the change. Melnick et al. (2015) have expanded these options to apply them specifically to cultural landscapes.

Lookingbill et al. (2012) recommended proactively managing, intervening, and closely monitoring sea level markers and groundwater salinity. The National Park Service Climate Change Response Program facilitates climate change adaptation planning.

Melillo et al. (2014) focused on three types of options to adapt to rising sea level: (1) protect (e.g. building levees or installing riprap), (2) accommodate (e.g., raising structures or using wetland restoration), and (3) managed retreat (e.g. allowing areas to be exposed to flooding by removing coastal protection).

Stevens et al. (2010) proposed a climate change monitoring work plan for the ecosystems in Colonial National Historical Park as part of the Northeast Coastal and Barrier Network, excerpts of which are presented in table 3.

Table 3. Proposed climate effects monitoring plan.

Ecosystem type	Metric (indicator)	Status and/or recommendation as of 2010
Beaches and bluffs	Shoreline position, beach and dune topography	Currently monitored
	Precipitation, snow depth and cover, surface soil moisture, relative humidity, wind speed, air temperature, wave characteristics, tidal range, water surface elevation,	High priority recommendation
	Shoreline structures, beach nourishment	Medium priority recommended
	Depth to water table, salinity of groundwater, nearshore topography, bathymetry, bottom configuration, movement of sand supply	Future consideration
Estuarine	Water temperature, salinity, sediment parameters, turbidity	Currently monitored
	Precipitation, snow depth and cover, relative humidity, wind speed, air temperature, surface soil moisture, wave characteristics, tidal range, water surface elevation,	High priority recommendation
	Depth to water table, salinity of groundwater, benthic habitat mapping	Future consideration
Tidal marsh	Water temperature, salinity, water depth, marsh sediment elevation, accretion, erosion, and shallow subsidence, tidal marsh pool creek, ditch size category and distribution, turbidity	Currently monitored
	Tidal marsh capital and sediment budget, tidal range, frequency of inundation, precipitation, snow depth and cover, relative humidity, wind speed, air temperature, surface soil moisture, wave characteristics, water surface elevation	High priority recommendation
	Depth to water table, groundwater salinity, soil pore water salinity, tidal marsh soil temperature, bulk density, and organic matter, sediment processes	Future consideration
Uplands and freshwater	Soil characteristics, stream flow, lake and pond levels, stream pH and temperature, changes in land cover type, stream geomorphology	Currently monitored
	Precipitation, snow depth and cover, relative humidity, wind speed, air temperature, surface soil moisture	High priority recommendation
	Depth to water table, groundwater salinity, freshwater wetland and vernal pool levels, temperatures, and extents	Future consideration

Note: Biological and water quality indicators were omitted. Information is from Stevens et al. (2010)

In the *Geological Monitoring* chapter about coastal features and processes, Bush and Young (2009) described the following methods and vital signs for monitoring coastal features and processes: (1) shoreline change, (2) coastal dune geomorphology, (3) coastal vegetation cover, (4) topography/elevation, (5) composition of beach material, (6) wetland position/acreage, and (7) coastal wetland accretion.

NPS has multiple resources related to climate change adaptation. The forthcoming NPS Coastal Adaptation Strategies Handbook will include NPS policies relevant to climate change, guidance on evaluating appropriate adaptation actions, and adaptation opportunities for planning, incident response, cultural resources, natural resources, facilities and assets, and infrastructure. The handbook will also provide guidance on developing communication and education materials about climate change impacts, and it will detail case studies of the many ways that individual parks are implementing adaptation strategies for threatened resources.See also Appendix B.

Additional Reference Manuals that guide coastal resource management include NPS Reference Manual #39-1: Ocean and Coastal Park Jurisdiction, which can provide insight for parks with boundaries that may shift with changing shorelines (available at http://www.nps.gov/applications/npspolicy/DOrders.cfm); and NPS Reference Manual #39-2: Beach Nourishment Guidance (Dallas et al. 2012) for planning and managing nourishment projects.

The NPS Geologic Resources Division (GRD) and Climate Change Response Program (CCRP) are developing sea level rise and storm surge data that parks can use for planning purposes over multiple time horizons. The project, led by Maria Caffrey of GRD, should be completed by 2016 and will analyze rates of sea level coupled with potential storm surge in 105 of the vulnerable parks in order to project, for each park, the combined elevations of storms surge and sea level by 2030, 2050, and 2100. Gonzalez (2015) prepared a climate change summary for Colonial National Historical Park that serves as a quick reference guide to climate change trends and historical impacts for the region.

The NPS has also developed a report entitled "Adapting to Climate Change in Coastal Parks: Estimating the Exposure of FMSS-Listed Park Assets to 1 m of Sea-Level Rise" (Peek et al. 2015). This report includes the geospatial location and approximate elevation of over 10,000 assets in 40 coastal parks (not Colonial National Historical Park), based on information within the NPS Facilities Management Software System (FMSS) and supplemented with other datasets, collaboration with park staff, and field visits to locate assets. Assets were characterized based on their overall exposure to long-term (1 m [3 ft]) sea level rise and associated storm vulnerability, and were categorized as having either high exposure or limited exposure to sea level rise impacts.

Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures

In addition to inundation via flooding and sea level rise, there are significant resource management issues associated with shoreline erosion and sediment transport. Shoreline protection structures were installed in many reaches of the park in attempts to manage shoreline erosion. These coastal engineering structures reduce erosion in some places but also present resource management concerns.

Shoreline Erosion

Shoreline erosion is a natural process of river systems at all scales and is particularly evident when rivers cross landscapes consisting primarily of unconsolidated sediments, such as the coastal plain of Virginia. This process is exacerbated by storms such as hurricanes or nor'easters. In 2003, Hurricane Isabel produced 2-m (6-ft) -high waves every 5 seconds in the York River during a 12-hour storm surge that started from the north and swung south as the storm passed. This passing storm drove erosive waves in several different directions against the park's shorelines and damaged or destroyed several archeological sites. In Yorktown along the commercial waterfront, some nearshore breakwaters and other shoreline stabilization structures were damaged and the beach was completely washed away. An erosional scarp, in places only 1 to 2 m (3 to 6 ft) from the Colonial Parkway, formed along stretches of the York River (Thornberry-Ehrlich 2005).

National Park Service management policies (see Appendix B) typically allow natural processes to occur and only suggest intervention when there is no other feasible way to protect park resources or facilities. Because much of the historical significance and cultural resources in Colonial National Historical Park are associated with and located along the shoreline, erosion is a critical concern. Historic rates of shoreline change vary with location and amount of anthropogenic interference (i.e., shoreline nourishment and/or installation of shoreline protection structures). Between 1937 and 2009 the shoreline change rate (negative values for overall shoreline loss) in the Jamestown unit ranged from -1.2 to 7.0 m/year (-4.0 to 23.1 ft/year), with an overall average rate of 0.1 m/year (0.4 ft/year) (Milligan et al. 2010; Dallas et al. 2013). Between 1937 and 2002, rates of shoreline change for the York River varied between -1.3 to 0.5 m/year (-4.2 to 1.5 ft/year), with an overall average rate of -0.12 m/year (-0.39 ft/year) (Hardaway et al. 2006; Dallas et al. 2013).

Within the park, shoreline loss is more pronounced along the James River than the York River (fig. 21) (Lookingbill et al. 2012; GRI conference call participants, 12 November 2014). When European settlers arrived at Jamestown Island in 1607, the shoreline was more than 120 m (400 ft) to the west of its 2001 position (Johnson et al. 2001b). Since 1607, Jamestown Island was extensively eroded on almost all sides, except along Back River, by storm-generated high tides and strong waves and currents. It was long

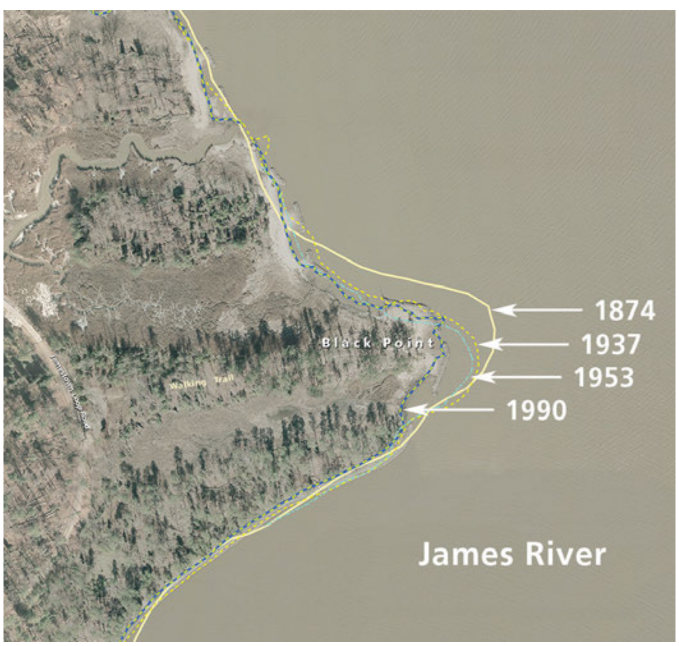


Figure 21. Map of shoreline loss at Black Point. Between the years 1874 and 2007 more than 61 m (200 ft) of shoreline was eroded by the James River. Aerial image taken in March 2007. National Park Service photograph courtesy of Colonial National Historical Park presented as a figure in Lookingbill et al. (2012, p. 27).

suspected that the site of the original Jamestowne settlement of 1607 had washed into the James River. However, archeological excavations at the behest of Preservation Virginia (http://www.preservationvirginia.org) uncovered the postholes of the original James Fort beneath American Civil War era earthworks on Jamestown Island. Further research showed one end of the fort had only partially washed into the river (Kelso and Straube 2004). Between 1894 and 1901, a seawall was constructed along the western edge of Jamestown Island to curb erosion; this present structure is still functioning and is now considered historic (US Army Corps of Engineers 2002; Johnson 2007; Eshleman 2009).

A Civil War era fort near College Creek was lost to erosion (GRI conference call participants, 12 November 2014). An isthmus that connected the island to the mainland was breached in the 1700s, necessitating construction of a now subsiding road and causeway in the early 1900s (Thornberry-Ehrlich 2005). The park is undertaking a large-scale effort to document and preserve cultural resources along the shores of Jamestown Island before erosion impacts or destroys them (Jonathan Connelly, NPS Colonial National Historical Park, cultural resource manager, conference call, 12 November 2014).

At an archeological site, slope wash and tidal undercutting are causing loss of material that is noticeable on a weekly scale. Trees are also washing into the channel's strong currents. This creates a dangerous situation for swimmers because these underwater trees are not visible from above and they shift position within the channel (GRI conference call participants, 12 November 2014).

The Yorktown unit and Colonial Parkway are located along the south bank of the York River, which is migrating southward. The southern shore of the river near Yorktown is eroding two to three times faster than the northern shore at Gloucester Point (Thornberry-Ehrlich 2005). Near kilometer five (mile three) of the Colonial Parkway, there is no protective riprap along the shoreline, and erosion is threatening the roadway. This and several other stretches of the parkway on both sides of the peninsula are at risk of being damaged (Tim McLean, NPS Colonial National Historical Park, civil engineer, conference call, 12 November 2014).

Erosion along the James River and York River shorelines within the park and along the Colonial Parkway ranges from 0 to 0.58 m (0 to 1.9 ft) per year (National Park Service 1999; Lookingbill et al. 2012). Shoreline erosion rates have been increasing over the past several thousand years as sea level has been rising throughout the Holocene, exposure to storms has increased, and the landscape relief has decreased (Johnson 2007).

Sediment Transport and Dredging

Rivers are not only agents of erosion, they also transport and deposit tremendous amounts of sediment. In order to maintain channels for large ships travelling upstream to Richmond, the US Army Corps of Engineers (ACOE) dredges channels in both the York and James rivers. Disposing of this material in a suitable and safe manner has been a long-term goal of the US ACOE (Zappi et al. 1990).

Dredge material from the "Hampton Roads" geographical area composes entire landforms such as Craney Island (also used for the disposal of dredge material for naval use), as well as Naval Channel, York River, Thimble Shoal, Wolf Trap, and Dam Neck disposal sites (Zappi et al. 1990). On the James River, dredging occurs about 30 to 60 m (100 to 200 ft) from the park boundary. Once the channel is dredged, the channel refills with sand moving between Hog Island and Jamestown Island. Side-scan imagery, used to map the bottom sediments presented in the GRI GIS data (e.g., geologic map units **Qsnd**, **Qom**, **Qsg**, and **Qshom**), identified significant shifting of bottom sediments.

It remains unclear if the net sand loss is coming from Jamestown Island or elsewhere (Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, conference call, 12 November 2014). By removing subaqueous sediment and changing river current patterns, dredging can exacerbate erosion along the Colonial Parkway between College and Middle creeks and threaten the stability of the road (Tim McLean, conference call, 12 November 2014).

Coastal Engineering Structures

Efforts to stabilize the shorelines and protect resources at Colonial National Historical Park include installation of breakwaters, bulkheads, piers, revetments, groins, sea walls, sills, riprap, lines of rock, sand replenishment ("beach nourishment"), marsh plants (creating wetlands), shoreline measuring stakes (to determine quantitative measures of accretion or retreat), stonewalls, and planting vegetative interfaces (fig. 22) (Thornberry-Ehrlich 2005; Dallas et al. 2013). Some of these structures were installed more than 100 years ago (fig. 23) (Simon 2012).

A coastal engineering inventory was completed by Dallas et al. (2013) and includes GIS data. The US ACOE (2002) also prepared a detailed environmental assessment of the shorelines of Jamestown Island and the adjacent peninsula. Refer to those reports for detailed descriptions and management options. In summary:

- 153 coastal engineering projects occur within or immediately adjacent to the park. These projects include 134 coastal structures (55 in or near the Yorktown unit and 79 in or near the Jamestown unit), 11 fill projects, and eight beach nourishment projects.
- About 39% of the shoreline within the park is stabilized, with coastal structures extending for 15,070 m (49,450 ft).
- Beach nourishment projects moved at least 30,000 m^3 (39,000 yd^3) of sediment between 1985 and 2009.
- Fill projects impacted approximately 0.48 km^2 (118 ac) of subaerial and submerged land within the park between 1931 and 1955 (Dallas et al. 2013). Artificial fill is included in the GRI GIS data (**Qf**) (see Map Unit Properties Table for more information; Berquist 2010).
- Armored shoreline is 28% of the total at Jamestown (fig. 24) (Dallas et al. 2013).
- Riprap was installed along the benchmark at Black Point on Jamestown Island. Sand is currently accumulating there, but visitor use of the beach has prevented stabilizing vegetation from flourishing (Johnson 2007; Eshleman 2009).
- At Yorktown, riprap currently covers much of the bluffs and outcrops; 66% of the shoreline is armored (figs. 25 and 26) (Thornberry-Ehrlich 2005; Dallas et al. 2013).
- Riprap was installed along reaches of the Colonial Parkway to prevent further erosion and compromising of the roadway.

These structures were designed to stabilize the shoreline in order to protect cultural resources, and have had

Figure 22. Photographs of shoreline stabilization structures. Riprap and artificial fill (geologic map unit Qf) were installed on many shorelines within the park. In some places, vegetation is able to grow behind the riprap, in others, refracted waves cause erosion behind the structure. National Park Service photographs taken by Melanie Peters (NPS Geologic Resources Division) in August 2005.

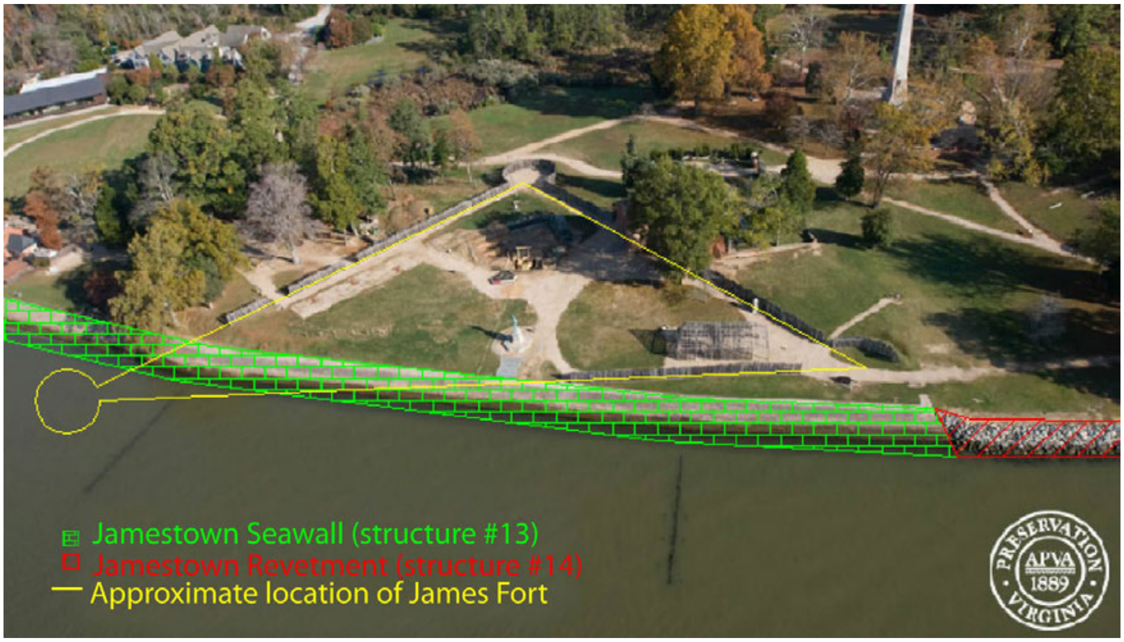


Figure 23. Aerial image of the Jamestown seawall and the James River. The north direction is toward the top of the image. The southwest corner of the James Fort was lost to erosion prior to the construction of the 730-m (2,395-ft) concrete seawall. The ACOE-constructed seawall is deteriorated and in need of repair as it is considered historic and is still functioning to protect the fort. It reduces sediment supply to shoreline downstream and may have necessitated more armoring downstream. View is to the northeast. Graphic is figure 16 in Dallas et al. (2013); numbers refer to references in that report.

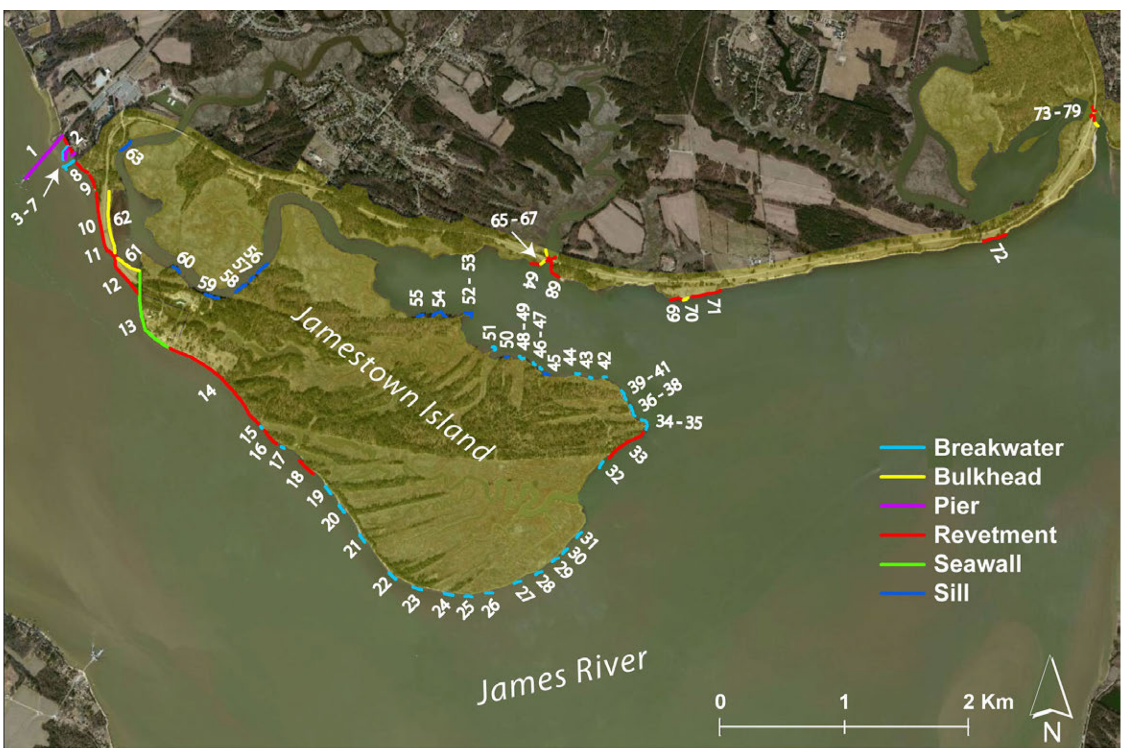


Figure 24. Map of coastal engineering structures along the shorelines in the Jamestown unit. The yellow shaded area is within Colonial National Historical Park boundaries. Graphic is figure 6 in Dallas et al. (2013); numbers refer to references in that report.

Figure 25. Map of coastal engineering structures along the shorelines in the Yorktown unit. The yellow shaded area is within Colonial National Historical Park boundaries. Yellow box indicates area enlarged in figure 26. Graphic is figure 9 in Dallas et al. (2013); numbers refer to references in that report.

Figure 26. Enlarged map of coastal engineering structures along the shorelines in Yorktown. The yellow shaded area is within Colonial National Historical Park boundaries. Graphic is figure 12 in Dallas et al. (2013); numbers refer to references in that report.

mixed results in meeting their objective illustrating the challenges associated with resource managment in such an environment (Dallas et al. 2013). Breakwaters installed at Yorktown between 1994 and 2005, and at Jamestown Island in 2002, have been somewhat successful in preserving a scalloped shoreline of trapped-sediment salients (projections of sediment that jut outward from the coast) and/or tombolos between the breakwaters and the shore (fig. 22). Passmore Creek, however, bypassed a riprap structure meant to confine the channel and created a new channel to the James River which threatened cultural resources (Thornberry-Ehrlich 2005). All of these structures can be overtopped during storms. Hurricane Isabel in 2003 clearly illustrated the park's vulnerability to inundation when storm surge breached revetments as high as 2 m (6 ft) along the York River (Dallas et al. 2013).

The coastal engineering structures also likely altered the natural sediment transport processes in the region (Dallas et al. 2013). Armoring within and adjacent to the park has limited the sediment supply to the region's beaches (Dallas et al. 2013). Given the overall erosive nature of the system, coupled with a lack of available sediment supply, unarmored regions are particularly vulnerable to wave action and erosion processes (Dallas et al. 2013). Shorelines are retreating from rock revetments put in place along reaches of the Colonial Parkway. It remains unclear at this time whether the revetments are exacerbating the situation and if they may need to be moved or removed completely (Tim McLean, conference call, 12 November 2014).

A Rutgers University research group used the Dallas et al. (2013) inventory to identify structures that could be removed for shoreline loss mitigation; results were expected in 2015 (Dorothy Geyer, NPS Colonial National Historical Park, natural resource specialist, conference call, 12 November 2014). Their preliminary report suggested removing breakwaters on the southeast end of Jamestown and restricting attempts to rebuild or improve protection structures along other selected sites in order to allow natural marshes and beaches to form and keep pace with relative sea level rise. The chosen study sites are located where structures do not protect park infrastructure, cultural landscapes, historic structures, or known archeological resources (Nordstrom and Jackson 2014).

A solution recently suggested for Assateague Island National Seashore is the development of living or hybrid shorelines (Schupp and Coburn 2015). Such shorelines involve removing existing hardened estuarine shorelines, such as bulkheads and riprap, and allowing reversion of the estuarine shoreline to a functioning natural habitat with natural sediment transport processes (Nordstrom and Jackson 2013). In places where this is not possible, hardened structures could be augmented with living shoreline components. Living shorelines can protect vulnerable shorelines while also providing or enhancing coastal ecosystems, water quality, and wildlife habitat (Cain et al. 2009). The propagation of a living shoreline attempts to incorporate natural elements and may be nonstructural, such as vegetation. Along low-energy estuarine shorelines, native plants can buffer wave energy to uplands while their roots stabilize the shore and hold soil in place to reduce erosion. Living shorelines may also serve as one natural component of hybrid techniques, which incorporate both nonstructural components and traditional approaches (e.g., breakwaters). The structures are situated in a manner that does not sever the physical connection to the riparian, intertidal and subaqueous areas. In general, hybrid techniques are typically applied in places of medium to high wave energy whereas nonstructural approaches are better suited to low wave energy environs (Bilcovic and Mitchell 2012).

Scoping participants in 2005 and conference call participants in 2014, as well as scientific literature, noted the following recommendations for managing fluvial processes and erosion:

- Perform several shoreline surveys per year to detect seasonal variations. This requires identifying points to monitor along the shorelines on both rivers. Update the aerial mosaics for shoreline evolution since 1937. Supplement these surveys with LiDAR (Brock et al. 2008; available at http://pubs.usgs.gov/of/2008/1326/start.html), GIS surveys, and aerial photographs.
- Cooperate with state and county agencies to study erosion rates and processes in surrounding vicinity and relate to the sediment budget of the different watersheds.
- Dallas et al. (2013) suggest focusing future research on developing a quantitative system-wide sediment budget with data for sediment sources and sinks.

- Promote revegetation in areas of significant gullying and erosion.
- Monitor loss of ridges within wetlands near Jamestown. Conduct comprehensive wetland mapping and monitoring throughout the park (Lookingbill et al. 2012).
- Monitor topographic changes due to surface and cliff erosion.
- Continue to promote coastal shoreline stability measures in places where cultural resources exist.
- Define the mappable shoreline in relation to tidal fluctuations.
- Determine whether shoreline stabilization structures are having negative impacts on aquatic ecosystems in the park.
- Educate the public about potential consequences of erosion and other impacts associated with sea level rise (Lookingbill et al. 2012).

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described additional methods for inventorying and monitoring geomorphology-related vital signs, including: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Hardaway et al. (1999a, 1999b, 2006) prepared shoreline management plans for specified areas within the park. The US ACOE (2002) presented a shoreline management plan for Jamestown Island that included a combination of sills, revetments, breakwaters, sand nourishment, and vegetation plantings.

In 2012, the park submitted an environmental assessment to repair and stabilize the York River shoreline in order to protect the Colonial Parkway. After agency and public review, the project will be implemented in phases as funding allows. The project will include rehabilitating or installing combinations of shoreline treatments such as rock revetments, rock spurs, continuous and gap sills, pocket beaches, and shore-attached breakwaters between the confluence of Felgates Creek and the York River downstream to the boundary with the US Coast Guard Training Center Yorktown (Colonial National Historical Park 2012).

Stormwater Management along Colonial Parkway and Upland Erosion

Streams and stormwater are diverted through 114 known culverts under the Colonial Parkway, constructed between 1930 and 1957. Today, they clog easily and are inadequate to handle peak flows and increased runoff along the Interstate-64 (I-64) corridor and urban development since the 1930s. Forty percent of the culverts within the 152-m (500-ft) right-of-way maintained by the park are rated poor, critical, or unknown (fig. 27) (Dallas et al. 2013; Tim McLean, NPS Colonial National Historical Park, civil engineer, conference call, 12 November 2014). Sheetwash and gully erosion, as well as sedimentation along the parkway, from stormwater and runoff from surrounding development are an issue along the length of the parkway (Thornberry-Ehrlich 2005; Lookingbill et al. 2012; GRI conference call participants, 12 November 2014).

Impervious surfaces in upstream areas (including the I-64 corridor) prevent infiltration and cause pulses of high-energy stormwater to erode the slopes and overwhelm the stormwater system of the parkway; impervious surface areas are increasing with expanding urban development throughout the region (Lookingbill et al. 2012). From 2012 to 2014, along kilometers five and eight of the parkway (north of Yorktown along the York River), surface runoff caused significant erosion of the embankments, which are also undercut by storm and tidal action (GRI conference call participants, 12 November 2014). In 2006, the parkway was damaged at Papermill Creek as a result of inadequate off-site stormwater control (Lookingbill et al. 2012).

Lookingbill et al. (2012) used impervious surface as a percentage of land area to represent human impact on the landscape in order to determine ecosystem impacts and habitat assessments They used the threshold of impervious surface area totaling less than 10% of total area to represent good ecological condition; the Colonial Parkway unit has more than 12% impervious surface and thus exceeds the threshold for good ecological conditions and may indicate watershed and habitat degradation (Lookingbill et al. 2012).

Other than a photo inspection by the Federal Highway Administration in 2013, additional monitoring along the I-64 corridor through the park has not yet taken place. The park resource managers are working with

Figure 27. Photographs of stormwater management structures along the Colonial Parkway. Many of the culverts and drains within the park are inadequate to handle the flow following common heavy precipitation. Structures are many decades old, cracked, and/or clogged. As impervious surfaces increase with urban development, more runoff is anticipated in the future. National Park Service photographs taken by Harold Pranger (NPS Geologic Resources Division) 28 September 2004.

Figure 28. Photographs of upland erosional features in Colonial National Historical Park. Gullying and sheetwash erosion can impact upland areas and archeological sites. National Park Service photographs by Harold Pranger (NPS Geologic Resources Division), 28 September 2004.

the Federal Highway Administration and Virginia Department of Transportation to control runoff and stormwater associated with the I-64 culverts (GRI conference call participants, 12 November 2014). Plans are in place to add an additional lane to the I-64 corridor through the park which will increase impervious surface area and likely increase stormwater runoff. GRI conference call participants noted the need for adequate stormwater management measures to be included in any construction. The park should consider development of a management plan for runoff, erosion, and stormwater along the parkway. Geomorphologists at the NPS Geologic Resources Division may be able to assist with a technical assistance request.

Shoreline erosion and erosion associated with stormwater is documented in the park. Stormwater erosion can also trigger or exacerbate slope movements. The runoff from storm events such as hurricanes erodes the park's slopes, which are largely vegetated and/or riprapped (Thornberry-Ehrlich 2005; GRI conference call participants, 12 November 2014). Erosion and gullying can expose tree roots (fig. 28), which may eventually lead to the collapse of the tree and exposure of its rootball to further soil loss (fig. 29) or slope movements. This can have a significant effect on cultural resources, potentially exposing buried remains or obscuring a historic landform. Similarly, the high winds that accompany large storms also cause trees to fall. This releases pulses of sediment to streams, as well as removing the stabilizing effects of intact tree roots on park slopes. Trees blown down during Hurricane Isabel uplifted rootballs, affecting graves from the pre-settlement era through the American Civil War (Thornberry-Ehrlich 2005).

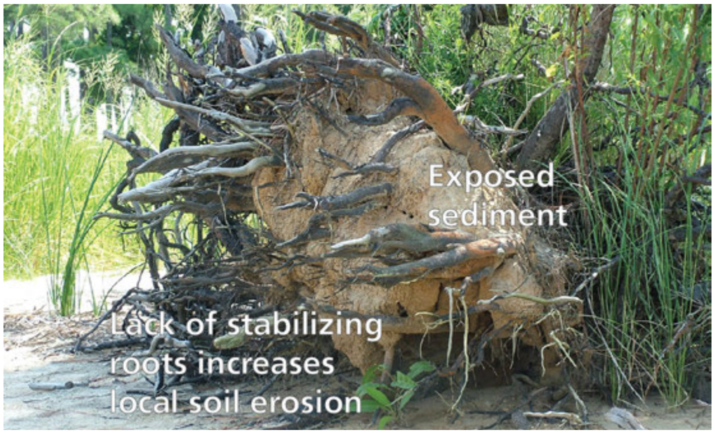


Figure 29. Photograph of exposed rootball at a fallen tree on Jamestown Island. Storm winds blew this tree down, exposing its rootball to weathering. Sediment weathered from the rootball washed into the nearest stream. The loss of the tree also may accelerate erosion by removal of the stabilizing roots. National Park Service photograph taken by Melanie Peters (NPS Geologic Resources Division) in August 2005.

Erosion along ridgelines and uplands has placed about 60 significant cultural and/or unexcavated archeological sites at risk of degradation or destruction (Thornberry-Ehrlich 2005). Slope erosion is currently threatening one of the redoubts at Yorktown Battlefield (GRI conference call participants, 12 November 2014).

Paleontological Resource Inventory, Monitoring, and Protection

As described in the "Geologic Setting and Significance" and "Geologic Features and Processes" chapters, fossils within Colonial National Historical Park are abundant, diverse, and historically significant.

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of May 2016, Department of the Interior regulations associated with the Act were being developed.

In addition to in situ fossils, fossils wash up on the shorelines of the York and James rivers (see inside front cover). Fossils cannot be collected in the park or any other NPS area. Unauthorized collecting likely occurs; however, the park does not yet have the resources or detailed paleontological resource survey to assess impacts or loss.

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a park-specific survey has not yet been completed for Colonial National Historical Park, a variety of publications and resources provide park-specific or servicewide information and paleontological resource management guidance. These are summarized by Tweet et al. (2014).

The management of fossils along coastlines such as in Colonial National Historical Park requires different approaches than "typical" upland fossil localities. Brunner et al. (2009) outlined these considerations and included applicable servicewide policy guidance to assess the full scale of unauthorized fossil collection and develop methodology to reduce the problem.

Tweet et al. (2014) also presented the following preliminary recommendations:

- A dedicated paleontological inventory for Colonial National Historical Park would be of great value. The park contains substantial quantities of fossils that are exposed to erosion, unauthorized collecting, and other issues that are of management concern (although protective shoreline structures have covered many exposures), and its fossils are of enormous historical interest, with untapped educational potential.
- Park staff should be encouraged to observe exposed sedimentary deposits for fossil material while conducting their usual duties. To promote this, they should also receive guidance regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, park staff should take advantage of them, if funding and time permit.
- Staff members should photodocument and monitor (see Santucci et al. 2009) any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock/sediments) should be documented but left in place unless they are subject to imminent degradation by artificially accelerated natural processes or direct human impacts.

- Fossils found in a cultural context (see Kenworthy and Santucci 2006) should be documented like other fossils. In addition, an archeologist should be consulted because any fossil within a cultural context may be culturally sensitive as well (e.g. subject to NAGPRA) and should be regarded as such until otherwise established.
- Quaternary fossils and deposits can be used to describe the effects of past climate and sea level changes, and to predict natural responses to future changes. Further study of these fossils and deposits in and around Colonial National Historical Park is encouraged.
- The fate of the Banks collection, a fossil collection formerly on display at Colonial National Historical Park, should be investigated. If some or all of the material still exists, it could be used in a new exhibit.
- Contact the NPS Geologic Resources Division for technical assistance with paleontological resource management issues.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. All of these are applicable to Colonial National Historical Park.

Geologic Hazards and Risks

Geologic hazards are natural or human-caused conditions that may impact park resources, infrastructure, or visitor safety. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see also Holmes et al. 2013). Colonial National Historical Park faces a variety of geologic hazards associated with its coastal location, including flooding and storm surge; those are described in previous sections of this report. Additional geologic hazards include slope movements ("landslides"), earthquakes, and radon.

Slope Movements

Slope movements are a common type of geologic hazard. Although a variety of movements can occur based on rock type, scale, trigger, and rate (fig. 13), slope movements are typically referred to as "landslides."

Bluffs of unconsolidated material are particularly susceptible to slope movements. For example, along the York River, north of Yorktown, slope failures and spalling required excavations to reduce the loss of cultural resources (GRI conference call participants, 12 November 2014). Slope processes wash sediments down around Cornwallis cave, but no large failures have occurred there yet (GRI conference call participants, 12 November 2014). Some bluffs have been armored to limit slope processes and erosion, although this limits the amount of sediment that is delivered to nearby beaches (Dallas et al. 2013).

Shoreline erosion, erosion associated with stormwater control, and disturbed lands (each of which is described in respective sections of the report) can trigger or be exacerbated by slope movements. All of these are of great concern at Colonial National Historical Park because of their threats to cultural and archeological resources of the park.

Anthropogenic activities can also exacerbate or cause slope movements. Such was the case of a 1989–1990 slope failure below a pier in the York River near Yorktown. Pile driving during pier widening caused the slope instability, threatening the existing pier (Martin and Seli 1998). The movement was likely caused by a combination of (1) unstable, water-saturated sediments of the slope, (2) increased pore pressure (within the saturated sediments) induced by pile-driving vibrations, (3) a reduction in cohesive strength in the deeper sediments due to pore pressure increases, and (4) lateral displacement of the existing piles due to lateral heave of the Yorktown Formation (geologic map units **Tymh** and **Tc**) during pile driving (Martin and Seli 1998).

Park resource management strategies to control slope erosion and mass wasting include natural vegetation barriers, no-cut zones for adjacent fields, repairing and expanding fencing and signing, and public service announcements (Rafkind 1990). Scoping participants in 2005 suggested developing a slope monitoring plan for the park; changing mowing schedules, locations, and techniques; and revegetating areas to decrease undercutting and slope erosion. Lookingbill et al. (2012) recommended decreasing mowing frequency. Martin and Seli (1998) demonstrated a test program to evaluate the possible mechanisms of a slope movement caused by pier repair near Yorktown. They installed slope inclinometers, pore pressure transducers, heave plates, and survey monuments to monitor the slope during anthropogenic activities. This information, combined with knowledge of the substrate, supported their recommendations for stable-slope development.

Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options. In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks.

Earthquakes and Fault Locations

Earthquakes are ground vibrations—shaking—that occurs when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The "magnitude" of an earthquake refers to the amount of energy released. A variety of scales measure magnitude, including the Richter scale. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety.

Park staff and residents reported shaking from the magnitude-5.8 earthquake that occurred in central Virginia, about 170 km (105 mi) northwest of Colonial National Historical Park, in August 2011 (US Geological Survey 2011; GRI conference call participants, 12 November 2014). Shaking from that earthquake was felt throughout the eastern seaboard, particularly along the fall zone—the line marking the boundary between the Atlantic Coastal Plain and the Piedmont province. This event caused no documented damage in the park, but it is a reminder that earthquakes, although rare, can shake this region.

Even though such large earthquakes are not common in the mid-Atlantic region, minor earthquakes (rarely felt by humans) occur along faults in southeastern Virginia. Inferred, buried, queried, and approximate fault locations are part of the GRI GIS data. It is likely that additional buried faults, possibly associated with the Chesapeake Bay impact structure, exist in the subsurface and may be intermittently active with small earthquake magnitudes (about 2.0–2.5) (Thornberry-Ehrlich 2005; Johnson 2007). Much of Colonial National Historical Park is on a subsiding (sinking) massive fault-bound block that is very slowly moving toward the impact structure (Johnson et al. 2001a).

New faults are being revealed by drilling and mapping projects since the GRI GIS data were created. Recent studies have revealed suspected faults in the subsurface of the James-York Peninsula (see "Subsurface Geologic Features and the Chesapeake Bay Impact Structure" section). As with any discontinuity in the subsurface, these faults could move because of a large earthquake elsewhere, such as that which occurred in 2011 (Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, conference call, 12 November 2014). There is a great need to accurately locate these faults to understand their effects on the region's geomorphology and groundwater system. Drilling within an area of significant cultural resources must follow regulations for accompanying archeological work. The VDGMR will be working with park resource managers over the next several years to decide the best way to accurately delineate the locations of these faults in the park.

Any moderate earthquake has the potential to damage park infrastructure, cause liquefaction in the marshes, or trigger slope movements, although such effects are unlikely. According to the US Geological Survey 2009 Earthquake Probability Map (http://geohazards.usgs.gov/eqprob/2009/index.php; accessed 14 October 2014), the probability that a magnitude-5.0 earthquake will occur near the lower James-York Peninsula in the next century is about 1–2% (fig. 30). These calculations were made prior to the 2011 earthquake in central Virginia, which may impact future models of earthquake probability.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and

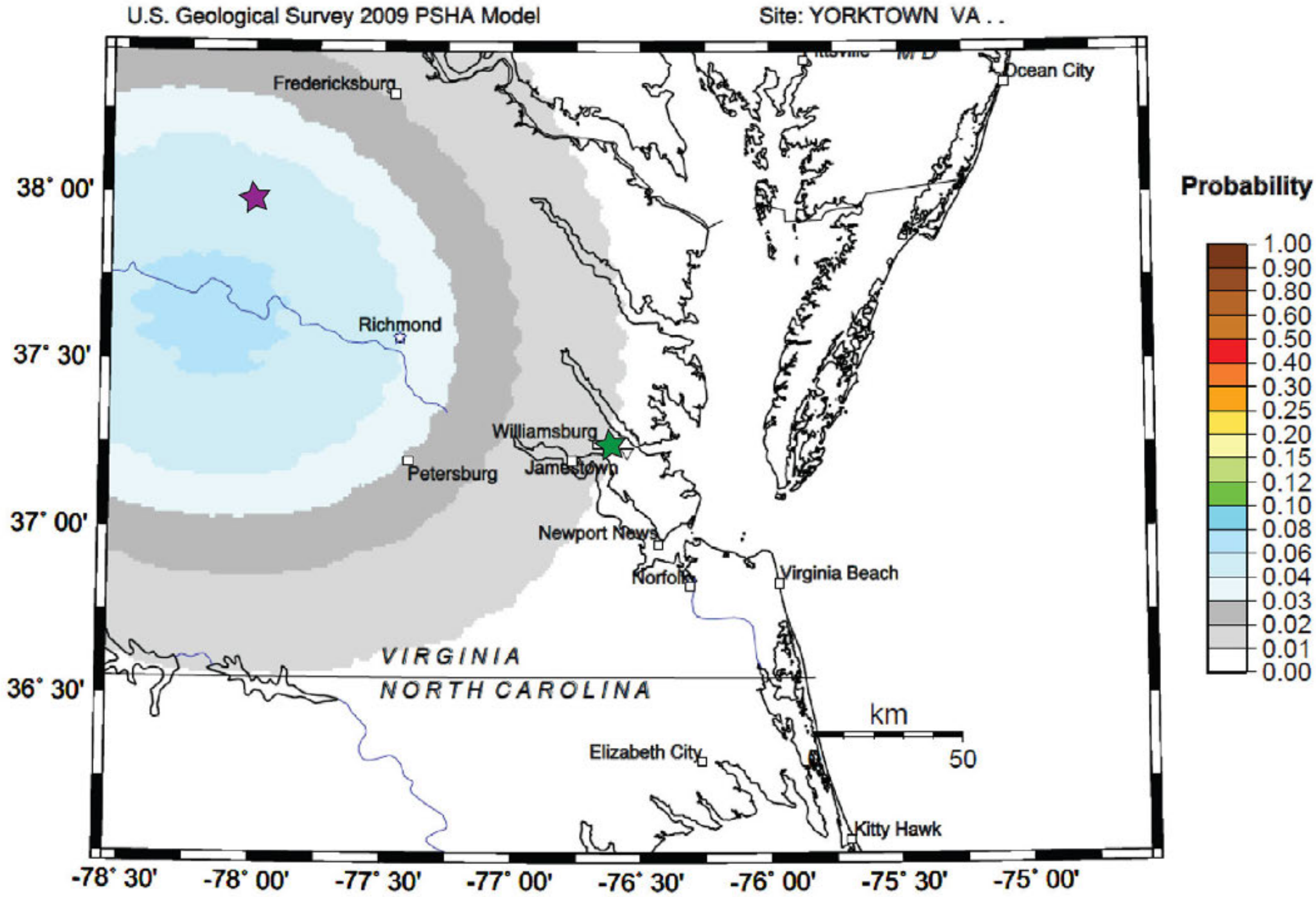


Figure 30. Probability map of earthquakes with magnitude greater than 5.0. This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Colonial National Historical Park, Virginia (green star). Purple star represents the approximate epicenter of the 5.8-magnitude earthquake from 2011; however these data are from a 2009 model and thus predate this event. Graphic was generated by the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php, accessed 14 October 2014) and annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://go.nps.gov/seismic_monitoring), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information.

Radon

Radon is a heavier-than-air, colorless, odorless, radioactive gas, which is a natural decay product from also naturally occurring uranium and thorium in the sediments beneath the park. Long term exposure to elevated levels of radon creates an increased risk for lung cancer. Refer to the Environmental Protection Agency (EPA) radon website for additional information: http://www.epa.gov/radon/. Radon naturally accumulates in caves, basements, and other subterranean cavities. Limited air circulation in these spaces concentrates radon gas to levels appreciably higher than outside. The EPA recommended maximum level of radon gas concentration is 4 picocuries per liter (pCi/L) (EPA 2013).

Sediments at the base of the Yorktown Formation where it overlies the Eastover Formation (geologic map unit **Tc**) commonly contain an accumulation of marine mammal bone enriched in phosphate and uranium. High levels of radon have been found in dwellings built within or just above this contact (Rick Berquist, Virginia Division of Geology and Mineral Resources, geologist, written communication, 24 August 2015). Tegan et al. (1991) tested radon levels in buildings and adjacent ground in James City County, near Williamsburg. Buildings located on the Bacons Castle Formation (**Qbc**), Shirley Alloformation (**Qsh**), and Yorktown Formation (**Tymh** and **Tc**) had elevated radon levels approaching the EPA recommended maximum level. Radon levels in the ground adjacent to these buildings were much higher than those in buildings themselves. Monitoring and ventilation remediate radon threats.

Groundwater Quantity and Quality

Since the establishment of the first colony at Jamestowne, access to fresh groundwater has been a priority and brackish incursions may have forced the abandonment of the agricultural endeavors on the island (Johnson et al. 1995). There is a great need to understand how groundwater is percolating through the subsurface system of interlayered, discontinuous aquifers and confining units (see "Hydrogeologic System at Yorktown Battlefield" section) because groundwater from the shallow aquifer system can contribute more than half of the flow in the park vicinity's streams and a large part of the water in the wetlands. The stream and wetland features provide (1) critical habitat for rare, threatened, and endangered species; (2) nurseries for important local fish species; and (3) opportunities for education, observation, and recreation (Speiran and Hughes 2001; Lookingbill et al. 2012). Groundwater in sinkhole complexes at Yorktown is critical to those habitats. Seasonal groundwater pulses also help to purge pore water (water among sediment grains) of accumulated salt and to export material to adjacent estuaries (Tobias et al. 2001a). If groundwater quantity or quality is compromised, the negative effects will ripple through the entire stream and wetland system.

Factors affecting groundwater-level fluctuations are complex and include variations in rainfall and evapotranspiration, aquifer rock types, geologic structures, tidal fluctuations, sea level rise, and human activity (Brockman et al. 1997; GRI conference call participants, 12 November 2014). Droughts and human water-use have the potential to deplete the shallow aquifer system. Depletions of the aquifer can also cause brackish water incursions from the adjacent tidal rivers. This situation is exacerbated by sea level rise (see "Sea Level Rise, Flooding, and Coastal Vulnerability" section). Adjacent urban developments have already changed the groundwater levels. Impervious surfaces associated with urban landscapes increase surface runoff and stormwater problems (see "Stormwater Management along Colonial Parkway and Upland Erosion" section). New residential, commercial, or industrial developments may threaten both the availability and quality of groundwater in the park. The colonial Greenspring, (see plate 1) an early water source for colonists, is an location of particular concern (Thornberry-Ehrlich 2005).

According to Speiran and Hughes (2001), the relatively deep Yorktown-Eastover aquifer has the potential to transport groundwater contaminants from sources outside the park boundaries into the park. Surface and groundwater contamination from surrounding lands is a major stressor for the park and park water was contaminated by several fuel spills on adjacent properties (Lookingbill et al. 2012). Both the Naval Weapons Station Yorktown and the Naval Field Station are mitigating hazardous materials sites (GRI conference call participants, 12 November 2014). According to Brockman et al. (1997), the hydrogeologic system of the weapons station station is similar to that of Yorktown with the same six units including the Columbia, Cornwallis cave, and Yorktown-Eastover aquifers. However, given the groundwater divides (i.e., a ridge in the water table from which the groundwater moves away in both directions) and the dissected, discontinuous nature of the shallow aquifers (due in part to the Chesapeake Bay impact structures), contamination potential from outside sources is considered low (Powars and Bruce 1999; Speiran and Hughes 2001). Despite this low potential, water monitoring has detected contaminants in the groundwater near Yorktown (GRI conference call participants, 12 November 2014).

Knowledge of groundwater ages and recharge rates helps to constrain groundwater-flow models within the shallow water aquifer system and can help remediation activities by providing estimates of the speed at which contamination moves through the hydrogeologic system and how this varies spatially (Nelms et al. 2001). Dating of shallow-aquifer groundwater in the nearby Naval Weapons Station Yorktown by Nelms et al. (2001) using chlorofluorocarbons gave an age range of one to 48 years with a median age of 10 years. The youngest water was from the unconfined Columbian aquifer and the oldest water was from the Yorktown-Eastover aquifer (see fig. 19). The confining units between the aquifers are leaky, allowing for vertical movement over the span of decades. Most recharge occurs during winter.

Colonial National Historical Park does not have a groundwater management plan (GRI conference call participants, 12 November 2014). A comprehensive understanding of the connections between the groundwater and surface-water features would facilitate management of the quantity and quality of water in the park's streams, wetlands, and associated riparian habitats. Water quality is a natural resource assessed by Lookingbill et al. (2012). Delineation of the hydrogeologic framework using borehole and geophysical logs, as well as geologic maps allow the conceptualization of the physical constraints that control the flow of groundwater and potential contaminants (Speiran and Hughes 2001). McFarland and Bruce (2006) presented a hydrogeologic framework for the Virginia Coastal Plain, but given the inherent spatial variability of the subsurface units and geologic structures, creating and refining a park-specific model would provide more pertinent information. Sources of information regarding groundwater in the vicinity include Brockman et al. (1997), who delineated the groundwater system at the Naval Weapons Station Yorktown outside the park. Tobias et al. (2001a) quantified groundwater discharge and seasonal variability through fringing wetlands at the Ringfield study site within Colonial National Historical Park at the confluence of Kings Creek and the York River (see plate 1). Their methodology could potentially be applied to other wetlands within the park to better understand the groundwater input.

Long-term monitoring of the system would provide information for evaluating long- and short-term trends (Speiran and Hughes 2001). Speiran and Hughes (2001) recommended future research on the Yorktown Battlefield aquifer system that could be expanded to the entire park with further study and installation of more wells for management of the water resources. Their suggestions included (1) continued development of the hydrogeologic framework (including installing more wells); (2) monitoring groundwater levels and quality, rates of discharge at springs, stream flow, and stream water quality; and (3) evaluation of the connections between the shallow aquifer system and the streams, wetlands, and riparian habitats.

Detailed water quality discussions are beyond the scope of this report. The park helped to prepare a water resources management plan in 1994 that sought to guide water resources-related activities over the following 10 years (Virginia Institute of Marine Science and National Park Service 1994). McFarland (2010) presented a groundwater-quality data and regional trends report for the Virginia Coastal Plain dating back to 1906. Contact the NPS Water Resources Division: http://www.nature.nps.gov/water/ for more information and assistance.

Karst Landscape Management

Cornwallis "cave" is not a natural feature and is managed as an abandoned mineral lands feature as described in the "Abandoned Mineral and Disturbed Lands" section of the report.

Karst features including sinkholes, subtle depressions, and karstic wetlands dot the landscape within and adjacent to the park (see "Karst Topography and Cornwallis 'Cave'" section). Karst forms in carbonate-rich layers within geologic map units **Tymh** and **Tc**. Sinkhole formation locally extends both laterally and vertically. A karstic wetland developed in the yard of a home in the Queens Lake subdivision near Williamsburg and sinkhole formation may threaten the stability of infrastructure throughout the park region (Rick Berquist, geologist, Virginia Division of Mineral Resources, professional communication, August 2005). With the increase in urban development adjacent to the park, particularly at Yorktown Battlefield, there may be long-term impacts to karst features within the park such as sinkholes and springs (GRI conference call participants, 12 November 2014). Karst features connect to the groundwater system. The quantity and quality of groundwater resources are additional resource management considerations addressed in that section of this report.

Yorktown Formation Shrink-and-Swell Clays

A layer of clay-rich silt, typically between 2 to 3 m (7 to 10 ft) thick, at the top the Yorktown Formation (**Tymh** and **Tc**) restricts groundwater flow as an "aquitard" and can shrink or swell depending on water content (Thornberry-Ehrlich 2005). Other so-called "shrink-and-swell clays" are present in the Morgarts Beach Member of the Yorktown Formation (see figs. 3 and 15) (Rick Berquist, conference call, 12 November 2014). Shrink-and-swell issues arise from the clay minerals absorbing water and expanding, then shrinking as they dry. This change in volume impacts roads, trails, building foundations, and other infrastructure. For example, the clays of the Yorktown Formation cause significant problems in recent road and building developments near Williamsburg, including the Queens Lake subdivision (Thornberry-Ehrlich 2005). Areas underlain by the uppermost Yorktown Formation should be assessed by a geologist when planning new infrastructure or modifying existing facilities.

Abandoned Mineral and Disturbed Lands

According to the NPS Abandoned Mineral Lands (AML) database (accessed 26 September 2014) and Burghardt et al. (2014), Colonial National Historical Park contains one AML feature at one site: Cornwallis "cave", which was excavated into coquina of the Yorktown Formation (geologic map units **Tymh** and **Tc**). The roof of Cornwallis cave is failing as moisture within the cave is increasing due to the sealing of the openings long ago. The park has requested a condition assessment from geomorphologists with the NPS Geologic Resources Division.

Additional potential AML features such as auger holes, clay pits, quarries, sand and gravel pits, sand pits, and test holes are in the area. Test holes, sand and gravel pits, and marl quarries exist within park boundaries. "Marl" is a calcium carbonate and clay-rich mudstone often used as a source of lime or building material. Park staff are unsure of the vintage of these features, but they could be added to the AML database if appropriate.

AML features typically present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil (Burghardt et al. 2014). AML features can also provide habitat for bats and other animals. Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the AML database (the NPS Geologic Resources Division may be able to provide assistance). An accurate inventory can identify human safety hazards, and facilitate closures, reclamation, and restoration of AML features (Burghardt et al. 2014). When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources. The NPS AML Program website, http://go.nps.gov/aml, provides further information.

Because Colonial National Historical Park is a narrow corridor across the heavily developed James-York Peninsula, adjacent land use can potentially negatively impact park resources. Disturbed areas surrounding the park region include several "Superfund" sites along the I-64 corridor; the Naval Weapons Station Yorktown Pier which disrupts sedimentation patterns; the pre-World War II Navy Mine Depot, Yorktown leaking contaminants such as acids, mercury, and heavy metals; and a location near Ballard Creek, which may be a source of mercury contamination (Thornberry-Ehrlich 2005; Global Security 2011; EPA 2015). Status of the "Superfund" sites is available from the EPA website: https://www.epa.gov/superfund/search-superfund-sites-where-you-live (accessed 11 March 2015).

According to the VDGMR, an abandoned borrow pit along the Colonial Parkway associated with the construction of I-64 has caused significant erosion problems as it channelizes surface water through park property, under the parkway, and into the York River. This setting alters water flow to and through the surrounding riparian ecosystem through park property. A GRD geologist visited the site in 2004 to suggest reclamation and stabilization options for the site. No formal monitoring of the area has taken place and erosion continues to be a problem along the parkway (see "Stormwater Management along Colonial Parkway" section) (GRI conference call participants, 12 November 2014).

Land use practices and visitor activities create disturbed areas that accelerate erosion which may impact park resources. Areas of heavy foot traffic, unofficial social trail use, mountain bike and off-road vehicle traffic, and overmowing expose soil and are susceptible to erosion on even moderate slopes (Thornberry-Ehrlich 2005; Lookingbill et al. 2012). Day and overnight use pose threats to stabilizing sand dune vegetation (Lookingbill et al. 2012). Erosion and downward movement of earth material occurs naturally along the slopes within the park, but informal trails along the Yorktown bluffs—containing remains of the British and Civil War earthworks—eroded the bluffs (Rafkind 1990). Camping, canoeing and kayaking, swimming, and hunting are not permitted in the park, and yet occur in forested lands and along beaches and shoreline (Lookingbill et al. 2012). These activities trample vegetation and soils, and contribute to erosion (Lookingbill et al. 2012). Walking, biking, or horseback riding that originate in adjacent land often result in the creation of unplanned trails, leading to trampling and erosion of natural resources (Lookingbill et al. 2012). Sheet erosion and gully erosion are both caused by these user impacts (Lookingbill et al. 2012).

Geologic History

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

The geologic history of Colonial National Historical Park includes the formation of a supercontinent, the construction and erosion of a massive mountain chain, the deposition of sediment along a coastline with fluctuating sea level, a spectacular bolide impact, and development of the modern Chesapeake Bay and tributary river systems.

Three Paleozoic Era orogenies (mountain building periods)—the Taconic (440 million to 420 million years ago), the Acadian-Neoacadian (360 million years ago), and the Alleghany (325 million to 265 million years ago)—culminated in the uplift of the Appalachian Mountains and the formation of the supercontinent Pangaea. Pangaea incorporated all of the major continents in existence. The Appalachian Mountains traversed the interior of the supercontinent (fig. 31A), and may have rivaled the modern Himalayas with elevations potentially exceeding 6,100 m (20,000 ft) (Means 1995; Harris et al. 1997; Southworth et al. 2009). Pangaea was not to last but endured for about 80 million years.

Mesozoic Era (252.2 million to 66.0 million years ago)—Origin of the Coastal Plain

During the Late Triassic Epoch, approximately 185 million years ago after the Allegany Orogeny (Southworth et al. 2009), the supercontinent Pangaea began pulling apart (rifting) into landmasses that would form the modern continents. As the African continent moved away from North America the Atlantic Ocean began to form (fig. 32); extension of the Earth's crust created down-dropped basins (grabens; see fig. 17) along the eastern margin of North America (Harris et al. 1997; Southworth et al. 2008). The Culpeper basin, home to Manassas National Battlefield Park (see GRI report by Thornberry-Ehrlich 2008), is one example of a Triassic extension basin.

Because collisional tectonic forces ceased during rifting, the Appalachian Mountains were no longer being pushed upward and erosion became the dominant process shaping the mountains. Erosion and weathering since the end of the Alleghany Orogeny may have removed about 6.5 km (4.0 mi) of rock (Southworth et al. 2009). Immense amounts of gravel, sand, and silt spread eastward to form the Atlantic Coastal Plain (fig. 31B) (Duffy and Whittecar 1991; Ramsey 1992; Whittecar and Duffy 2000; Southworth et al. 2008). The lowermost unit covering the bedrock and underlying most of the Coastal Plain is the Early Cretaceous Potomac Formation (145.5 million to 66.0 million years old) overlain by the progressively younger Aquia, Marlboro Clay, Nanjemoy, Piney Point, Chickahominy, Old Church, Calvert, Choptank, and St. Marys formations (Johnson et al. 2001a). As sea level rose and fell, deposition took place in a variety of environments such as marine, coastal, fluvial, and terrestrial.

Cenozoic Era (66.0 million years ago to present)—Building and Reshaping the Coastal Plain

Deposition of Coastal-Plain sediments was largely continuous and undisturbed until 35 million years ago when a meteor or comet impacted the continental shelf near the location of the modern mouth of the Chesapeake Bay (fig. 31C) (Poag et al. 1991; Poag 1997; Johnson et al. 1998; Powars and Bruce 1999). Estimates vary, but the crater may have been as large as 90 km (56 mi) across and 1.3 km (0.8 mi) deep (Poag 1997; Collins and Wünnermann 2005). The outer rim of the crater structure passes through Yorktown (fig. 18). The impact deformed the stack of Cretaceous (145.0 million to 66.0 million years ago), Paleocene (66.0 million to 56.0 million years ago), and Eocene (56.0 million to 33.9 million years ago) sediments that formed the Coastal Plain at that point in time. A succession of tsunamis swept across the Coastal Plain and Piedmont, causing the crater to fill with water-saturated debris. An impact breccia formed in the sediments and a lens of saltwater entered the breccia, causing permanent deep-groundwater salinity. The impact crater was a topographic low (i.e., depositional basin) for millions of years. Blocks of sediment slumped into the crater causing juxtaposition of sedimentary units of different age—angular unconformities (see fig. 18). The crater also strongly affected the positions and development of the York and James rivers, as well as the Chesapeake Bay (Poag 1997; Johnson et al. 1998; Tweet et al. 2014).

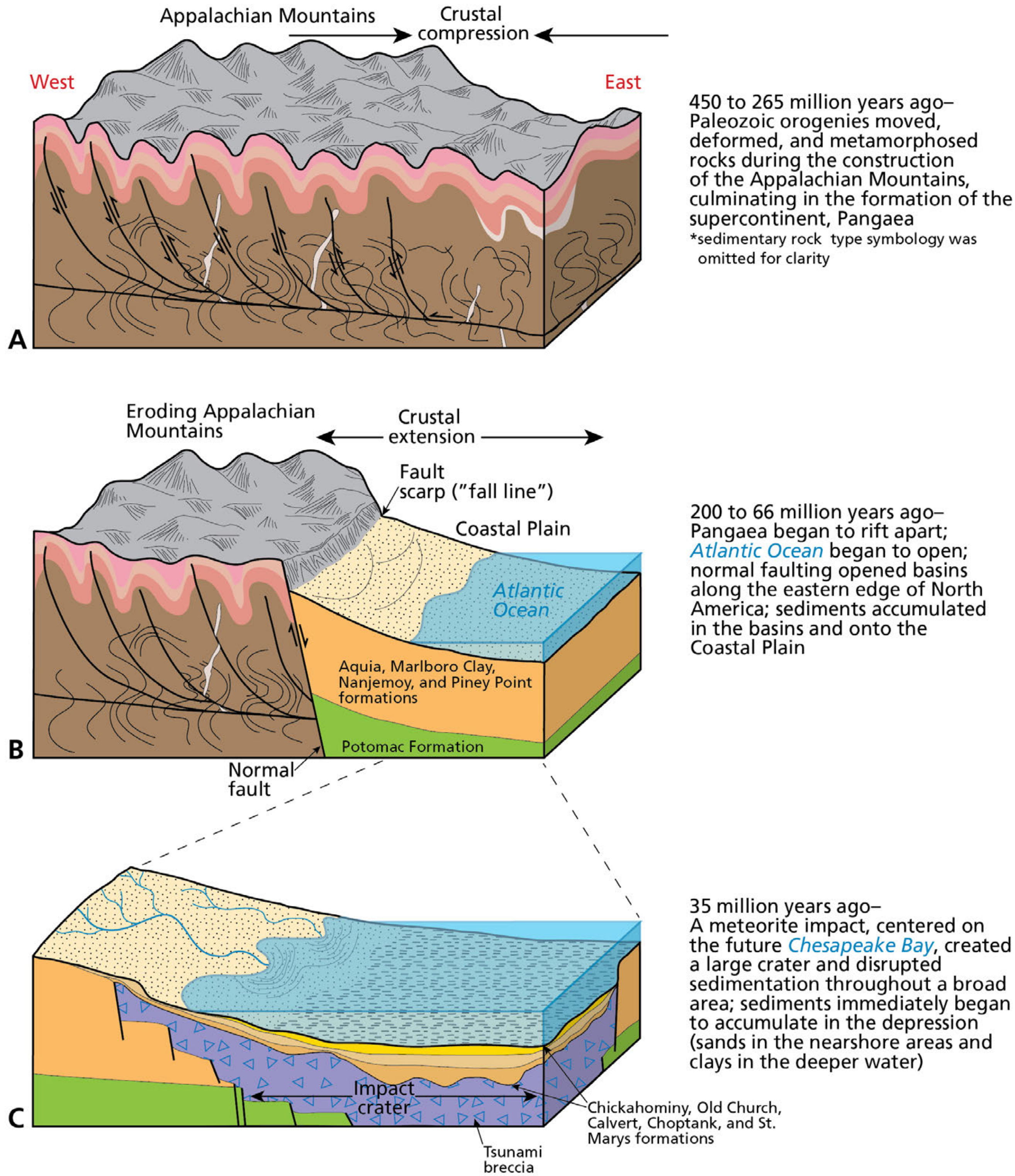
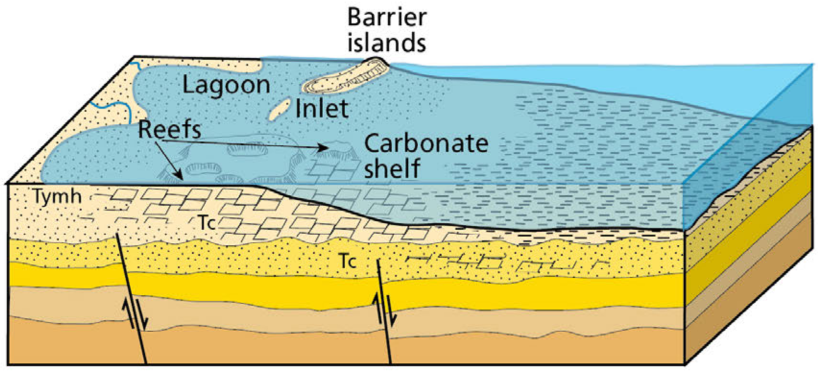
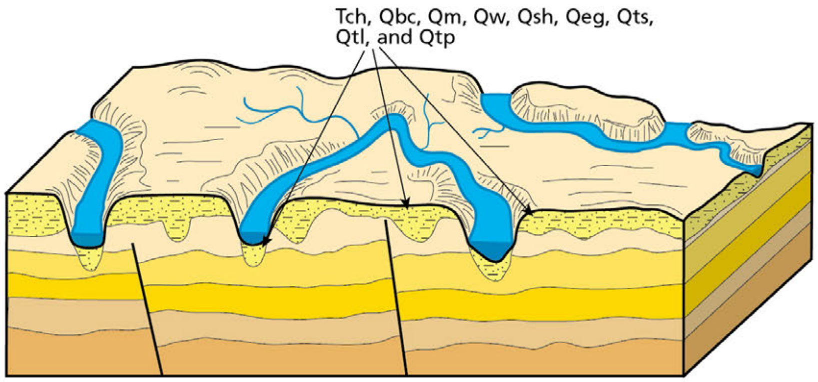


Figure 31A–C. Illustration of the evolution of the landscape and geologic foundation of Colonial National Historical Park. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Map symbols are included for the geologic map units mapped within the park. Figure continues on next page. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).



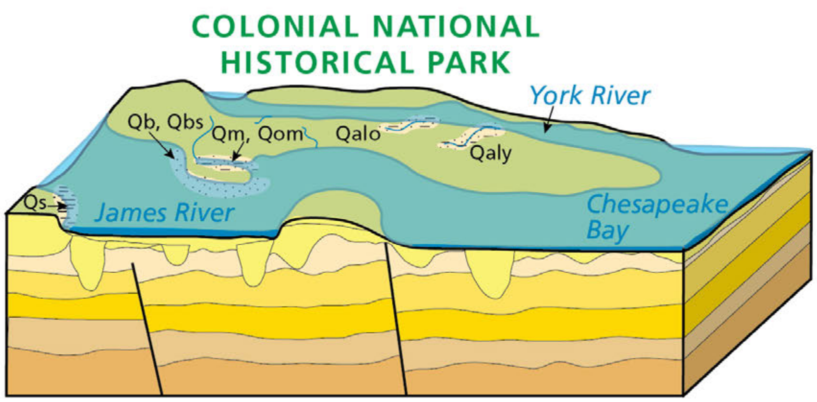
D

11 to 2.5 million years ago–
Shallow marine conditions are prevalent during the deposition of the Eastover Formation; after a period of erosion or nondeposition, the mixed sands, carbonates (shells), and muds of the Yorktown accumulate in a variety of shallow marine, open marine, lagoon, and barrier settings; faults from the impact structure are still active



E

2.5 million to 33,000 years ago–
Fluctuating sea levels prevailed; during sea-level lowstands, rivers carved deep canyons through the Coastal-Plain sediments and left discontinuous deposits in their channels; during sea-level highstands, these canyons were flooded and accumulated nearshore and marine sediments



F

Past 10,000 years–
Sea-level rise flooded the *James* and *York* river valleys and the *Chesapeake Bay* approached its modern morphology; modern swamp and marsh, alluvium, sand, beach, and dune deposits accumulated on the landscape

Figure 31D–F. Illustration of the evolution of the landscape and geologic foundation of Colonial National Historical Park, continued. Graphics are not to scale. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps, and correspond to the colors on the Map Unit Properties Table. Map symbols are included for the geologic map units mapped within the park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

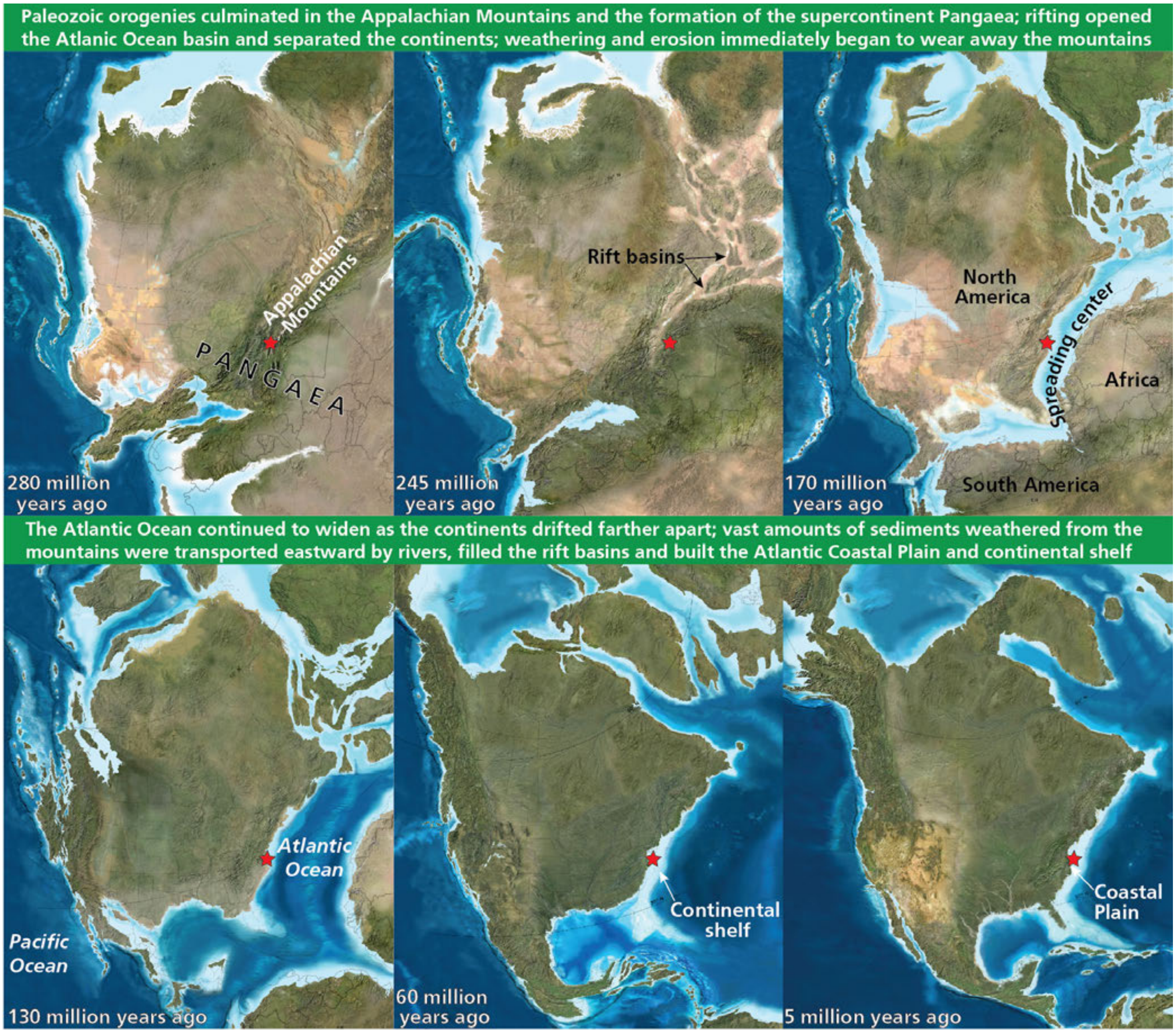


Figure 32. Paleogeographic maps of North America. The red star indicates the approximate location of Colonial National Historical Park. Graphic complied by Trista L. Thornberry-Ehrlich (Colorado State University). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which are available at http://cpgeosystems.com/index.html (accessed 24 September 2014).

The development of the landscape at Colonial National Historical Park was primarily affected by the deposition of Miocene (23.0 million to 5.3 million years ago; part of the Tertiary) and younger sediments in shallow marine, estuarine, and fluvial settings on a shallow shelf near the western edge of the crater (Brockman et al. 1997). Given the proximity of the sediments to sea level, fluctuations in global sea level profoundly affected the types that were deposited or eroded away from the landscape. The oldest unit (more than 5.3 million years old) mapped within the park is the Late Miocene Eastover Formation (part of geologic map unit **Tc**) (Bick and Coch 1969; Johnson 1972; Berquist 2010). After a period of erosion marked by a disconformable contact, the Eastover Formation accumulated in a mosaic of marine shelf, marginal marine, and nonmarine environments in two distinct episodes: an older, cooler, open marine phase, and a younger, subtropical, shallow marine phase (Ward and Blackwelder 1980; Newell and Rader 1985).

Following deposition of the Eastover Formation, the Pliocene Yorktown Formation (5.3 million to 2.6 million years old; **Tymh** and **Tc**), was deposited in primarily temperate-climate, marine settings (fig. 31D) (Bick and Coch 1969; Johnson 1972; Berquist 2010; Winkelstern et al. 2013). The first marine advance during Yorktown deposition eroded the Eastover Formation surface and deposited the lower Yorktown Formation (Newell and Rader 1985). A series of marine transgressions caused open-shallow marine, restricted marine (lagoons or bays), shell reefs, and barrier bars to shift around on the landscape collecting a complex record of characteristic sediments (Ward and Blackwelder 1980; Campbell 1993; Tweet et al. 2014). This setting was further complicated by the movement of still-active faults associated with the Chesapeake Bay impact structure. This caused certain submerged areas to rapidly uplift with respect to others, creating shallow-water environments that supported abundant marine life (now preserved as fossils). Waves and currents broke shells into sand-sized pieces. The shell hash then moved landward during sea level advances (Johnson et al. 1998; Johnson 2007).

During the Pleistocene Epoch, global climate shifts brought alternating periods of prolonged cold—ice ages—and relative warmth similar to modern climate. Continental ice sheets descended south from the Arctic, reshaping the landscape of much of the northern United States. Though glaciers from the Pleistocene ice ages never reached southeastern Virginia (the southern terminus was in central Pennsylvania), the colder climates of the ice ages played a role in the deposition of sediments underlying Colonial National Historical Park. During glacial advances, global sea level dropped as ocean water was entrained as ice. Weathering in the Appalachian Mountains was accelerated in the periglacial setting, supplying massive pulses of sediments to be reworked by streams and waves during warmer periods (Ramsey 1992). During cooler periods, the Pleistocene rivers carved deep channels and deposited fluvial gravels (fig. 31E) (Johnson et al. 2001a). The James River was at least 70 m (230 ft) below its present level (Johnson 2007). During interglacial warm periods, global sea level rose as the ice melted and the river canyons were flooded. These shifts in climate also changed which organisms were present (e.g., subtropical faunas in the Yorktown Formation followed by significant local extinctions in the Pleistocene) (Stanley 1986; Williams et al. 2009; Tweet et al. 2014).

The units deposited atop the Yorktown Formation (**Tch**, **Qbc**, **Qm**, **Qw**, **Qcc**, **Qc**, **Qsh**, **Qtp**, **Qtlp**, **Qtl**, **Qts**, and **Qt**) record a complex history of sea level change and shifting depositional environments and climates (table 4). Broadly, the transition was from typical marine settings to fluvial-estuarine (Ramsey 1992). As mentioned in the "Coastal Plain Sediments" section, the interrelationships and interpretations of these units are still the subject of debate and study. A complete, conformable sequence of these deposits does not exist owing to their spatial complexity (Bick and Coch 1969; Tweet et al. 2014). In some places, the boundaries between units are not clear, causing groupings of mapped units, for example, the Tabb Alloformation, Lynnhaven and Poquoson members, undifferentiated

Table 4. Climate and depositional setting for map units occurring within Colonial National Historical Park.

Age	Geologic Map Unit	Unit Symbol	Climate	Depositional Setting
Quaternary	Tabb Alloformation	Qt, Qtp, Qtlp, Qtl, and Qts	Cooler	Fluvial, estuarine, and marginal restricted marine
	Elsing Green Alloformation	Qeg	Cooler	Fluvial, estuarine?
	Shirley Alloformation	Qsh	Warmer	Fluvial, estuarine, and nearshore marine
	Windsor Formation	Qw	Warmer	Fluvial, estuarine, tidal flat, and restricted marine
	Bacons Castle Formation	Qbc	Cooler	Fluvial, estuarine, tidal flat, and possibly marine
Tertiary	Cold Harbor Formation	Tch	Warmer	Marginal marine, wave-dominated delta, shallow marine, tidal flats, tidal channels
	Yorktown Formation	Tymh and Tc	Subtropical	Shallow marine, open marine, lagoon, restricted marine, barrier
	Eastover Formation	Tc	Cooler/ Subtropical	Shallow marine

Note: Units listed with oldest on bottom and youngest on top. Refer to Map Unit Properties Table for more information.

(**Qtlp**). This grouped unit spans all but the most recent deposits of the entire stratigraphic column (see fig. 3) of units presented in the GRI GIS data (Berquist 2010). During sea level highstands, marine and estuarine deposits dominated in broad shelves throughout the region. Between marine transgressions, when climates were generally cooler and sea level dropped, eroded surfaces and deep channel incisions dominated, forming dissected terrains. Complex arrangements of erosional scarps and channel fills developed. The youngest deposits at Colonial National Historical Park are found at the lowest elevations, along riverways, close to sea level, deposited during a Holocene fill episode (Bick and Coch 1969; Johnson and Berquist 1972; Berquist 2010; Tweet et al. 2014).

Modern deposits are still accumulating and being reworked by Earth surface processes on the Colonial National Historical Park landscape today (fig. 31F). Sands (**Qsg**, **Qsnd**), beach and dune (**Qb**), shelly bottom sediments (**Qshom**), and alluvial deposits (**Qaly**, **Qalo**) accumulate in high-energy environments such as river channels, and wave-worn shorelines. Quiet-water environments such as wetlands and lagoons collect organic-rich, fine-grained sediments (**Qms**, **Qss**, **Qom**) such as mud and peat (Berquist 2010). Estuarine deposition began less than 5,000 years ago when the rivers became tidal; local marshes had formed by at least 3,000 years ago (Sager et al. 1994; Johnson 2007). For more than 10,000 years, humans have been present in the park vicinity, leaving a record of their activities (National Park Service 2001). Humans have been changing the landscape at Colonial National Historical Park in myriad ways. Mappable areas of artificial fill or disturbed earth materials (**Qf**) occur within the GRI GIS map data (Berquist 2010).

Geologic Map Data

This chapter summarizes the geologic map data available for Colonial National Historical Park. A poster (in pocket) displays the GRI GIS data draped over imagery of the park and vicinity. The Map Unit Properties Table (in pocket) summarizes this report's content for each map unit in the GRI GIS data. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Source Maps

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

Berquist, C. R., Jr. 2015. Geologic Map of the Williamsburg 30- x 60-minute Quadrangle, Virginia (scale 1:100,000). Unpublished. Virginia Division of Geology and Mineral Resources, Charlottesville, Virginia.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument using data model version 2.2. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the GRI GIS data:

- A GIS readme file (colo_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 5);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (colo_geology.pdf) that contains information captured from source maps;
- An ESRI map document (colo_geology.mxd) that displays the digital geologic data; and
- A version of the data viewable in Google Earth (colo_geology.kmz; see table 5).

Table 5. Geology data layers in the Colonial National Historical Park GIS data.

Data Layer	On Poster?	Google Earth Layer?
Impact Structure Lines	Yes	Yes
Faults	Yes	Yes
Geologic Contacts	No	Yes
Geologic Units	Yes	Yes

GRI Poster

A poster of the GRI GIS data draped over a shaded relief image of the park and vicinity is included with this report. Geographic information and park features have been added to the poster. Elevation data and added geographic information are not included in the GRI GIS data, but are available from a variety of sources. Contact the GRI team to locate these data.

Map Unit Properties Table

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

Use Constraints

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

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

Glossary

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

abandoned mineral lands (AML). Lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources.

abandoned mineral lands (AML) feature. An individual element of an AML site, such as vertical shaft, adit, open stope, open pit, highwall, and prospect. Features include structures such as headframes, mills, wellheads, and storage facilities; landform modifications such as access roads, drainage diversions, and drill pads; and piles of ore, protore (marginal-grade ore), waste rock, soil stockpiles, and hardrock or placer tailings.

abandoned mineral lands (AML) site. An area composed of AML features grouped by past ownership, geographical, or other logical grouping containing facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation operations.

accretion (sedimentary). The gradual addition of new land to an existing landmass by the deposition of sediment, for example, on a beach by the washing up of sand from the sea.

accretion (streams). The filling-up of a stream channel as a result of such factors such as silting or wave action.

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

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvium. Stream-deposited sediment.

aquiclude. A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients. Replaced by the term "confining bed."

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

aragonite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; the second most abundant cave mineral after calcite, differing from calcite in its crystal structure.

astronomical tide. The periodic rise and fall of a body of water resulting from gravitational interactions between the Sun, Moon, and Earth. Synonymous with "tide," but used to emphasize the absence of atmospheric influences.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

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

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

base level. The lowest level to which a stream channel can erode. The ultimate base level is sea level, but temporary, local base levels exist.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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

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

bathymetry. The measurement of ocean or lake depths and the charting of the topography of the ocean or lake floor.

beach. The unconsolidated material at the shoreline that covers a gently sloping zone, typically with a concave profile, extending landward from the low-water line to the place where there is a definite change in material or physiographic form (e.g., a cliff), or to the line of permanent vegetation (usually the effective limit of the highest storm waves).

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

benthic. Pertaining to the ocean bottom or organisms living on or in substrate; also, referring to that environment.

bivalve. Having a shell composed of two distinct, but equal or nearly equal, movable valves, which open and shut.

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

body fossil. Evidence of past organisms such as bones, teeth, shells, or leaf imprints.

breakwater. Shore-parallel structures that reduce the amount of wave energy reaching a harbor or stretch of shoreline located behind the structure. Breakwaters are similar to natural bars, reefs or nearshore islands and are designed to dissipate wave energy. The reduction in wave energy causes sediment deposition in the sheltered area behind the breakwater.

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

brecciation. Formation of a breccia, as by crushing or breaking a rock into angular fragments.

bulkhead. Vertical structures or partitions, usually running parallel to the shoreline, for the purpose of retaining upland soils while providing protection from wave action and erosion.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

calcium carbonate. $CaCO_3$. A solid occurring in nature as primarily calcite and aragonite.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

cape. An extensive, somewhat rounded irregularity of land jutting out from the coast into a large body of water, either as a peninsula (e.g., Cape Cod, Massachusetts) or as a projecting point (e.g., Cape Hatteras, North Carolina). Also, the part of the projection extending farthest into the water.

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of a sedimentary rock, thus binding the grains together.

cementation. The process by which clastic sediments become lithified or consolidated into hard, compact rocks, usually through deposition or precipitation of minerals in the spaces among the individual grains of the sediment; may occur simultaneously with sedimentation or at a later time.

cephalopod. A marine mollusk of the class Cephalopoda, characterized by a head surrounded by tentacles and, in most fossil forms, a straight, curved, or coiled calcareous shell divided into chambers. Range: Cambrian to Holocene.

channel. The bed where a natural body of surface water flows or may flow. Also, a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water.

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

chronology. The arrangement of events in their proper sequence in time.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

clay mineral. Any mineral occurring in the clay-sized fraction with the understanding that size imposes physical and chemical characteristics.

claystone (sedimentary). An indurated rock with more than 67% clay-sized minerals.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

compression. A decrease in volume of material (including Earth's crust) as it is pressed or squeezed together.

confined aquifer. An aquifer bounded above and below by confining beds. An aquifer containing confined groundwater.

confined groundwater. Groundwater under pressure significantly greater than that of the atmosphere. Its upper surface is the bottom of a confining bed.

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

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

contact. The surface between two types or ages of rocks.

continental. Formed on land rather than in the sea. Continental deposits may be of lake, swamp, wind, stream, or volcanic origin.

continental drift. A term for the process by which continents move relative to one another; it is a consequence of plate tectonics.

continental crust. Earth's crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 km) thick.

coprolite. Fossilized feces.

coquina. Limestone composed of cemented shell fragments.

coral. Any of a large group of bottom-dwelling, sessile, marine invertebrate organisms (polyps) that belong to the class Anthozoa (phylum Cnidaria), characterized by production of an external skeletons of calcium carbonate; may exist as solitary individuals or grow in colonies. Range: Abundant in the fossil record in all periods later than the Cambrian.

core (drill). A cylindrical section of rock or sediment. usually 5–10 cm (2–4 in) across and up to several meters long, taken as a sample of the interval penetrated by a core bit, and brought to the surface for geologic examination and/or laboratory analysis.

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

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

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

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

cross-stratification. Arrangement of strata inclined at an angle to the main stratification. This is a general term that is commonly divided into cross-bed, which is cross-strata thicker than 1 cm (0.4 in); and cross-lamination, which is cross-strata thinner than 1 cm (0.4 in).

crust. Earth's outermost layer or shell.

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

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

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

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

depocenter. An area or site of maximum deposition.

detritus. Loose rock and mineral material that is worn off or removed by mechanical processes.

differential erosion. Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away; harder and more resistant rocks remain to form ridges, hills, or mountains.

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

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

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

dolomite (mineral). A carbonate (carbon + oxygen) mineral of calcium and magnesium, $CaMg(CO_3)_2$.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a rock containing dolomite, especially one that contains 5%–50% of the mineral dolomite in the form of cement and/or grains or crystals.

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

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. A region or area bounded by a drainage divide and occupied by a drainage system, specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

dredge (engineering). A floating machine for excavating sedimentary material from the bottom of a body of water.

dredge (oceanography). An ocean-bottom sampler that scrapes material from the sea floor as the device is dragged behind a slowly moving ship.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

entrenched meander. An incised meander carved downward into the surface of the valley in which the meander originally formed; preserves its original pattern with little modification, suggesting rejuvenation of a meandering stream as a result of rapid vertical uplift or a lowering of base level; exhibits a symmetric cross profile in a gorge or canyon setting.

entrenched stream. A stream, often meandering, that flows in a narrow canyon or valley (i.e., "trench") cut into a plain or relatively level upland; specifically a stream that has inherited its course from a previous cycle of erosion and that cuts into bedrock with little modification of the original course.

epicenter. The point on Earth's surface directly above the initial rupture point of an earthquake.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

estuary. The seaward end or tidal mouth of a river where freshwater and seawater mix.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

fabric. The complete spatial and geometrical configuration of all components that make up a deformed rock, including texture, structure, and preferred orientation.

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

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

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fluvial channel. A natural passageway or depression produced by the action of a stream or river.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

footwall. The lower wall of a fault.

foraminifer. Any protozoan belonging to the subclass Sarcodina, order Foraminiferida, characterized by the presence of a test of one to many chambers composed of secreted calcite (rarely silica or aragonite) or of agglutinated particles; most foraminifers are marine but freshwater forms are known. Range: Cambrian to Holocene.

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

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

friable. Describes a rock or mineral that is easily crumbled.

gastropod. Any mollusk belonging to the class Gastropoda, characterized by a distinct head with eyes and tentacles and, in most, by a single calcareous shell that is closed at the apex, sometimes spiraled, not chambered, and generally asymmetrical. Range: Upper Cambrian to Holocene.

geodetic surveying. Surveying that takes into account the figure and size of Earth, with corrections made for curvature; used where the areas or distances involved are so great that the desired accuracy and precision cannot be obtained by plane (ordinary field and topographic) surveying.

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

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

glauconite. A greenish silicate (silicon + oxygen) mineral, $(K,Na)(Fe,Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$, characterized by a micaceous structure, commonly interstratified with smectite; may serve as an indicator of very slow sedimentation.

Gondwana. The late Paleozoic continent of the Southern Hemisphere and counterpart of Laurasia of the Northern Hemisphere; both were derived from the supercontinent Pangaea.

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

graben. An elongated, downdropped trough or basin, bounded on both sides by high-angle normal faults that dip toward one another.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

groundwater basin. An area of bedrock in a karst spring that collects drainage from all the sinkholes and sinking streams in its drainage area.

gully. A small channel produced by running water in unconsolidated material.

hanging wall. The upper wall of a fault.

heterogeneous. Consisting of dissimilar or diverse ingredients or constituents.

highstand. The interval of time during one or more cycles of relative sea level change when sea level is above the edge of the continental shelf in a given area.

horst. An elongated, uplifted block that is bounded on both sides by normal faults that dip away from one another.

hurricane. The term applied in the Northern Hemisphere for an atmospheric low-pressure system with a closed, roughly circular, wind motion that is counterclockwise, and sustained near-surface wind speed equal to or exceeding 64 knots (73 mph).

hydraulic conductivity. The ease with which water moves through spaces or pores in soil or rock.

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

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

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

incised meander. An old stream meander that has become deepened by rejuvenation and that is more or less closely bordered or enclosed by valley walls. The term is used collectively and includes "entrenched meanders" and "ingrown meanders."

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

ingrown meander. A continually growing or expanding incised meander formed during a single cycle of erosion by the enlargement of an initial minor meander while the stream was actively downcutting; exhibits a pronounced asymmetric cross profile (a well-developed, steep undercut slope on the outside of the meander, a gentle slip-off slope on the inside) and is produced when the rate of downcutting is slow enough to afford time for lateral erosion.

interfluve. The area between rivers, especially the relatively undissected upland or ridge between two adjacent valleys containing streams flowing in the same general direction.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

karstification. The action of water, mainly solutional but also mechanical, that produces features of karst topography.

karst. A type of topography that is formed on limestone, gypsum, and other soluble rocks, primarily by dissolution. It is characterized by sinkholes, caves, and underground drainage.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

lagoon. A narrow body of water that is parallel to the shore and between the mainland and a barrier island; characterized by minimal or no freshwater influx and limited tidal flux, which cause elevated salinities. Also, a shallow body of water enclosed or nearly enclosed within an atoll.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

Laurasia. The late Paleozoic continent of the Northern Hemisphere and counterpart of Gonwana of the Southern Hemisphere; both were derived from the supercontinent Pangaea.

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

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

levee. A long broad low embankment of sand and coarse silt built by floodwater overflow along both banks of a stream channel.

light detection and ranging/LiDAR. A method and instrument that measures distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses; the measured interval is converted to distance.

lime. Calcium oxide, CaO.

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

liquefaction. The transformation of loosely packed sediment into a more tightly packed fluid mass.

lithosphere. Earth's relatively rigid outer shell that consists of the entire crust plus the uppermost mantle. It is broken into about 20 plates, and according to the theory of plate tectonics, movement and interaction of these plates is responsible for most geologic activity.

lunar tide. The part of the tide caused solely by the tide-producing force of the Moon.

mantle. The zone of the Earth below the crust and above the core.

marl. A term loosely applied to a variety of materials, most of which occur as loose, earthy deposits consisting primarily of a mixture of clay and calcium carbonate; specifically an earthy substance containing 35%–65% clay and 65%–35% carbonate.

marlstone. A sedimentary rock composed of marl.

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

matrix. The fine-grained material between coarse grains in an igneous or sedimentary rock. Also refers to rock or sediment in which a fossil is embedded.

meander. One of a series of sinuous curves, bends, or turns in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

mechanical weathering. The physical breakup of rocks without change in composition.

medium-grained. Describes an igneous rock and texture in which the individual crystals have an average diameter in the range of 1 to 5 mm (0.04 to 0.2 in.). Also, describes sediment or sedimentary rock and texture in which the individual particles have an average diameter in the range of 1/16 to 2 mm (0.002 to 0.08 in), that is, sand size.

megabreccia. A rock produced by brecciation on a very large scale; individual blocks are as much as 400 m (1,300 ft) long.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

metamorphic rock. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

meteoric water. Water of recent atmospheric origin.

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

mollusk. A solitary invertebrate such as gastropods, bivalves, and cephalopods belonging to the phylum Mollusca. Range: Lower Cambrian to Holocene.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

orogeny. A mountain-building event.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Range: Lower Cambrian to Holocene.

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

oxide. A mineral group composed of oxygen plus an element or elements, for example, iron in hematite, Fe_2O_3; or aluminum in corundum, Al_2O_3.

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

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

Pangaea. A supercontinent that existed from about 300 million to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangaea and that of the present continents—Pangaea split into two large fragments, Laurasia in the Northern Hemisphere and Gondwana in the Southern Hemisphere.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

peat. An accumulation of partly decomposed plant remains in swampy lowlands. It is an early stage or rank in the development of coal.

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

perched aquifer. An aquifer that is separated from ("perched" above) the water table by an unsaturated zone.

period. The fundamental unit of the worldwide geologic time scale. It is lower in rank than era and higher than epoch. The geochronologic unit during which the rocks of the corresponding system were formed.

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

phreatic. Of or relating to groundwater.

phreatic zone. The zone of saturation.

pier. A platform extending over water from a shore that is supported by piles or pillars, used to secure, protect, and provide access to ships or boats.

piping. Erosion or solution by percolating water in a layer of subsoil, resulting in the formation of narrow conduits, tunnels, or "pipes" through which soluble or granular soil material is removed.

plate boundary. A zone of seismic and tectonic activity along the edges of lithospheric plates, resulting from the relative motion among plates.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

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

platform. Any level or nearly level surface.

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

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

Precambrian. A commonly used term to designate all rocks older than the Cambrian Period of the Standard Global Chronostratigraphic Scale. It includes the Archean and Proterozoic eons and represents 90% of geologic time.

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

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

rebound. Upward flexing of Earth's crust. Synonymous with "upwarping."

recharge. The addition of water to the saturated zone below the water table.

reef. A ridgelike or moundlike structure, layered or massive, built by sedentary calcareous organisms (e.g., corals) and consisting mostly of their remains.

regolith. From the Greek "rhegos" (blanket) + "lithos" (stone), the layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil.

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

rejuvenation. The renewal of any geologic process.

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

revetment. A cover or facing of material placed directly on an existing slope, embankment or dike to protect the area from waves and strong currents. Revetments are designed to armor and protect the land behind them.

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

rift valley. A depression formed by grabens along the crest of a mid-ocean ridge or in a continental rift zone.

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

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

riprap. A layer of large, durable rock fragments placed in an attempt to prevent erosion by water and thus preserve the shape of a surface, slope, or underlying structure.

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

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

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

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

sapping. The natural process of erosion along the base of a

saturated zone. A subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere; separated from the unsaturated zone (above) by the water table.

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

scour. The powerful and concentrated clearing and digging action of flowing water, air, or ice.

seawall. Vertical structures used to protect backshore areas from heavy wave action, and in lower wave energy environments, to separate land from water. They can be constructed using a range of materials including poured concrete, steel sheet pile, concrete blocks, gabions, sandbags, or timber cribs.

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

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. Also, a rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

shear. Deformation resulting from stresses that cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

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

sheetflood. A broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well-defined channels; its distance of flow is short and its duration is measured in minutes or hours, commonly occurring after a period of sudden and heavy rainfall.

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

sheetwash. A sheetflood occurring in a humid region. Also, the material transported and deposited by the water of a sheetwash. Used as a synonym of "sheet flow" and "sheet erosion."

shoal. A relatively shallow place in a stream, lake, sea, or other body of water.

sill. Combination of elements from offshore breakwaters and rock revetments, typically built relatively close to shore, continuous and low-lying. Sills are generally built in lower wave energy regimes with the intent of reducing the wave climate and establishing marsh ecosystems or beaches.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

silting. The accumulation of silt suspended throughout a body of standing water or in some considerable portion of it. In particular, the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir. Synonymous with "siltation."

siltstone. A clastic sedimentary rock composed of silt-sized grains.

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

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slope wash. Soil and rock material that is or has been transported down a slope under the force of gravity and assisted by running water not confined to channels; also, the process by which slope-wash material is moved.

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

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

solar tide. The part of the tide caused solely by the tide-producing force of the Sun.

sorted. Describes an unconsolidated sediment consisting of particles of essentially uniform size.

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

spalling. The process by which scales, plates, or flakes of rock, from less than a centimeter to several meters thick, successively fall from the bare surface of a large rock mass; a form of exfoliation.

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

storm surge. An abnormal, sudden rise of sea level along an open coast during a storm, caused primarily by strong winds offshore, or less frequently, a drop in atmospheric pressure, resulting in water piled up against the coast. It is most severe during high tide.

storm tide. The total observed seawater level during a storm, resulting from the combination of storm surge and the astronomical tide. An erroneous synonym of "storm surge."

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

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

stratigraphic. Of or pertaining to strata.

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

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

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

stream terrace. A planar surface alongside a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

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

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, primarily on a moderate to small scale. The subject is similar to tectonics, but the latter term is generally used for the analysis of broader regional or historical phases.

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

subaerial. Describes a condition or process that exists or operates in the open air on or immediately adjacent to the land surface.

subaqueous. Describes conditions and processes, or features and deposits, that exist or are situated in or under water.

subsidence. The sudden sinking or gradual downward settling of part of Earth's surface.

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks.

system (stratigraphy). The fundamental unit of chronostratigraphic classification of Phanerozoic rocks; each unit represents a time span and an episode of Earth history sufficiently great to serve as a worldwide reference unit. It is the temporal equivalent of a period.

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

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

terrane. A fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes or bounding continents.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

thalweg. The line connecting the lowest/deepest points along a stream bed; the line of maximum depth.

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

tombolo. A sand or gravel bar or barrier that connects an island with another landmass.

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

trace (structural geology). The intersection of a geological surface with another surface, for example, the trace of bedding on a fault surface, or the trace of a fault or outcrop on the ground.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

transform fault. A strike-slip fault that links two other faults or plate boundaries such as two segments of a mid-ocean ridge.

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

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

type area. The geographic area or region that encompass the stratotype or type locality of a stratigraphic unit or stratigraphic boundary.

type locality. The place where a geologic feature such as an ore occurrence, a particular kind of igneous rock, or the type specimen of a fossil species was first recognized and described.

type section. The originally described sequence of strata that constitute a stratigraphic unit. It serves as an objective standard with which spatially separated parts of the unit may be compared, and it is preferably in an area where the unit shows maximum thickness and is completely exposed (or at least shows top and bottom).

unconfined groundwater. Groundwater that has a water table; water not confined under pressure beneath a confining bed.

unconformable. Describes strata that do not succeed the underlying rocks in immediate order of age or in parallel position, especially younger strata that do not have the same dip and strike as the underlying rocks. Also, describes the contact between unconformable rocks.

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

unsaturated zone. A subsurface zone between the land surface and the water table that includes air, gases, and water held by capillary action. Synonymous with "vadose zone" and "zone of aeration."

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

upwarping. Upward flexing of Earth's crust on a regional scale as a result of the removal of ice, water, sediments, or lava flows.

vadose water. Water of the unsaturated zone.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

wash. A broad, gravelly, dry stream bed, generally in the bottom of a canyon that is periodically swept by a torrent of water. The term is used especially in the southwestern United States.

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

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Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of May 2016. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: https://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- Virginia Division of Geology and Mineral Resources: https://www.dmme.virginia.gov/dgmr/divisiongeologymineralresources.shtml
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Colonial National Historical Park, held on 1 August 2005, or the follow-up report writing conference call, held on 12 November 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2005 Scoping Meeting Participants

Name	Affiliation	Position
Rick Berquist	Virginia Division of Mineral Resources	Geologist
Mark Duffy	NPS Northeast Coastal and Barrier Network	
Dave Frederick	NPS Colonial National Historical Park	
Scott Hardaway	Virginia Institute of Marine Science	
Bruce Heise	NPS Geologic Resources Division	Geologist, GRI program coordinator
Matt Heller	Virginia Division of Mineral Resources	Geologist
Tom Nash	NPS Colonial National Historical Park	
Chuck Rafkind	NPS Colonial National Historical Park	Natural Resource Specialist
Melanie Ransmeier	NPS Geologic Resources Division	GIS Specialist
Karen Rehm	NPS Colonial National Historical Park	
Dan Smith	NPS Colonial National Historical Park	
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Report author

2014 Conference Call Participants

Name	Affiliation	Position
Amanda Babson	NPS Northeast Region	Coastal climate adaptation coordinator
Rebecca Beavers	NPS Geologic Resources Division	Coastal geologist
Rick Berquist	Virginia Division of Geology and Mineral Resources	Geologist
Jim Comiskey	NPS Northeast Region	Program manager for Inventory & Monitoring
Jonathan Connelly	NPS Colonial National Historical Park	Cultural resources manager
Ken Doak	NPS Colonial National Historical Park	Chief ranger
David Frederick	NPS Colonial National Historical Park	GIS specialist
Dorothy Geyer	NPS Colonial National Historical Park	Natural resource specialist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Tim McLean	NPS Colonial National Historical Park	Civil engineer
Marcie Occhi	Virginia Division of Geology and Mineral Resources	Geologist
Cheryl Green	NPS Colonial National Historical Park	Administrator
Dan Smith	NPS Colonial National Historical Park	Superintendent
Sara Stevens	NPS Northeast Coastal and Barrier Network	Program manager
Trista Thornberry-Ehrlich	Colorado State University	Geologist, Author, Graphic designer
Steven Williams	NPS Colonial National Historical Park	Deputy superintendent

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of May 2016. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).
Coastal Features and Processes	**NPS Organic Act, 16 USC § 1 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq.** requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089 (coral reefs) (1998)** calls for reduction of impacts to coral reefs. **Executive Order 13158 (marine protected areas) (2000)** requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas.	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area.	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/ historic properties. **Section 4.8.1.1** requires NPS to: -Allow natural processes to continue without interference, -Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, -Study impacts of cultural resource protection proposals on natural resources, -Use the most effective and natural-looking erosion control methods available, and -Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13653** (Preparing the United States for the Impacts of Climate Change) (2013) outlines Federal agency responsibilities in the areas of supporting climate resilient investment; managing lands and waters for climate preparedness and resilience; providing information, data and tools for climate change preparedness and resilience; and planning. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. **President's Climate Action Plan** (2013), http://www.whitehouse.gov/sites/default/files/image/president27sclimateactionplan.pdf	None applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

NPS 333/133343, June 2016

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

www.nature.nps.gov

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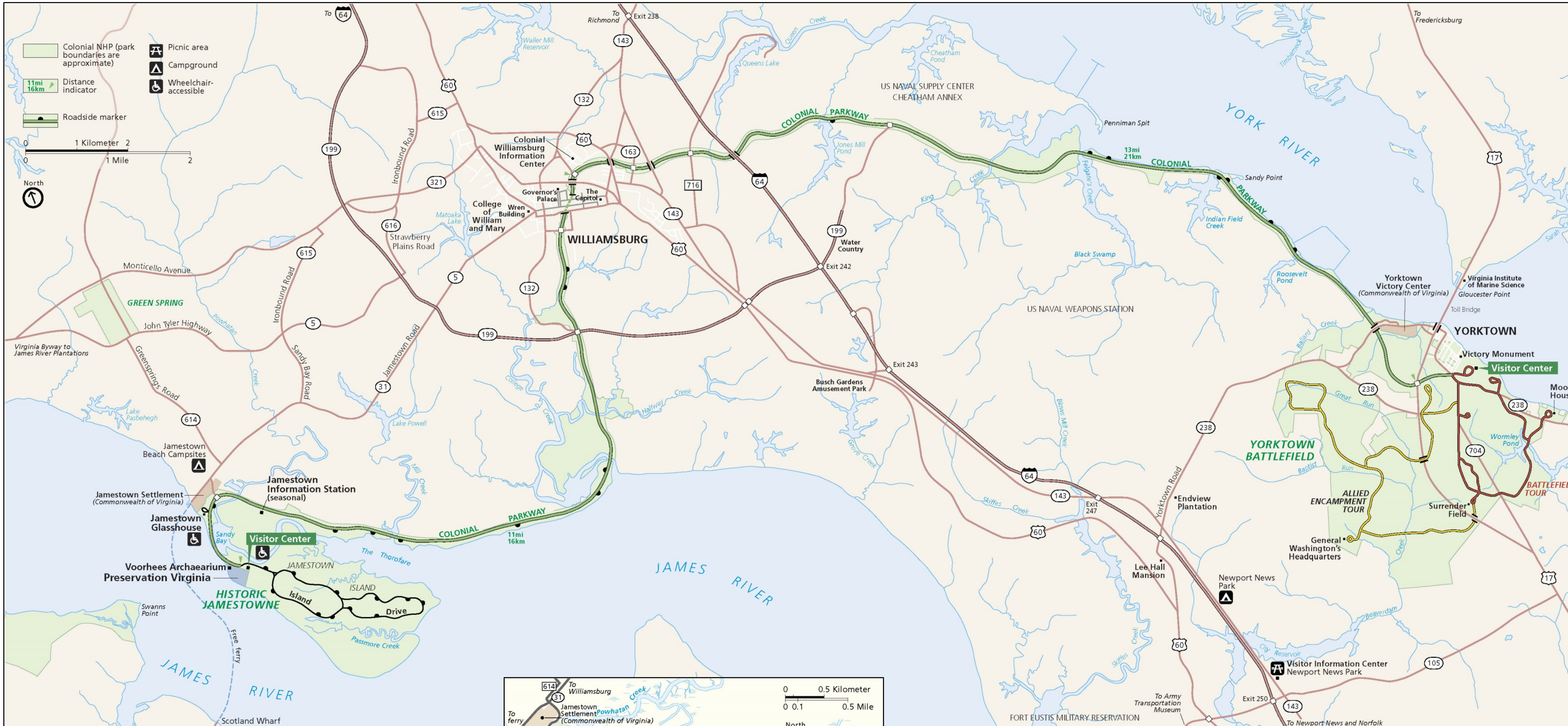


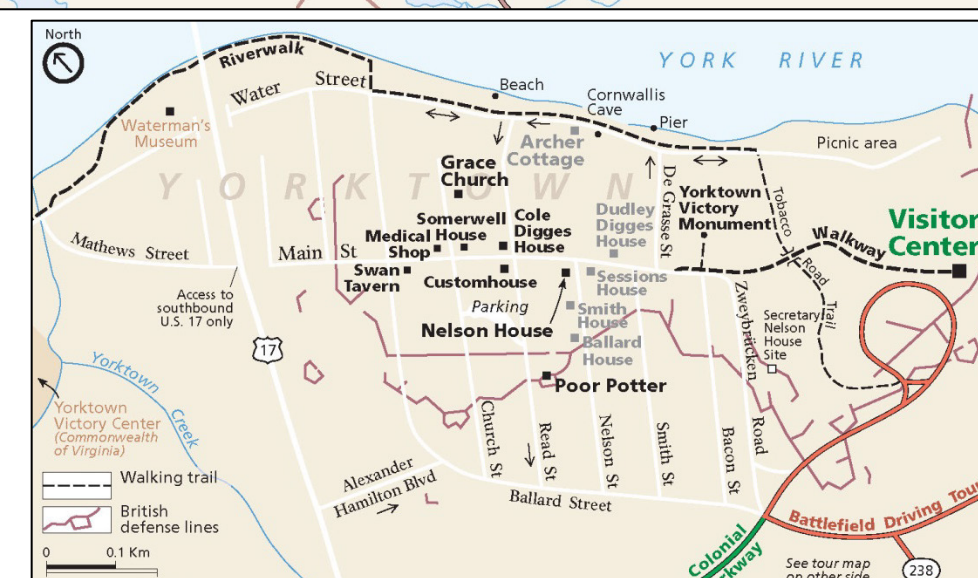


Plate 1. Maps of Colonial National Historical Park. National Park Service maps, available at https://www.nps.gov/hfc/cfm/carto.cfm (accessed 28 June 2016).

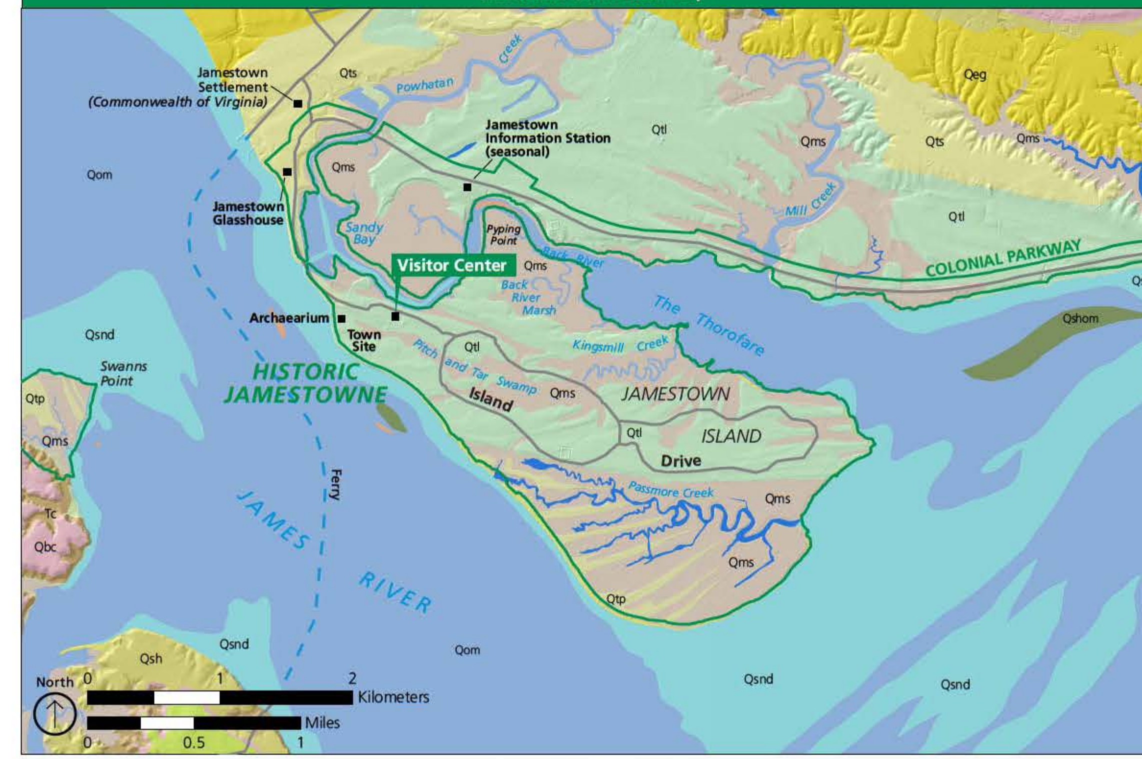
Geologic Map of Colonial National Historical Park

Virginia

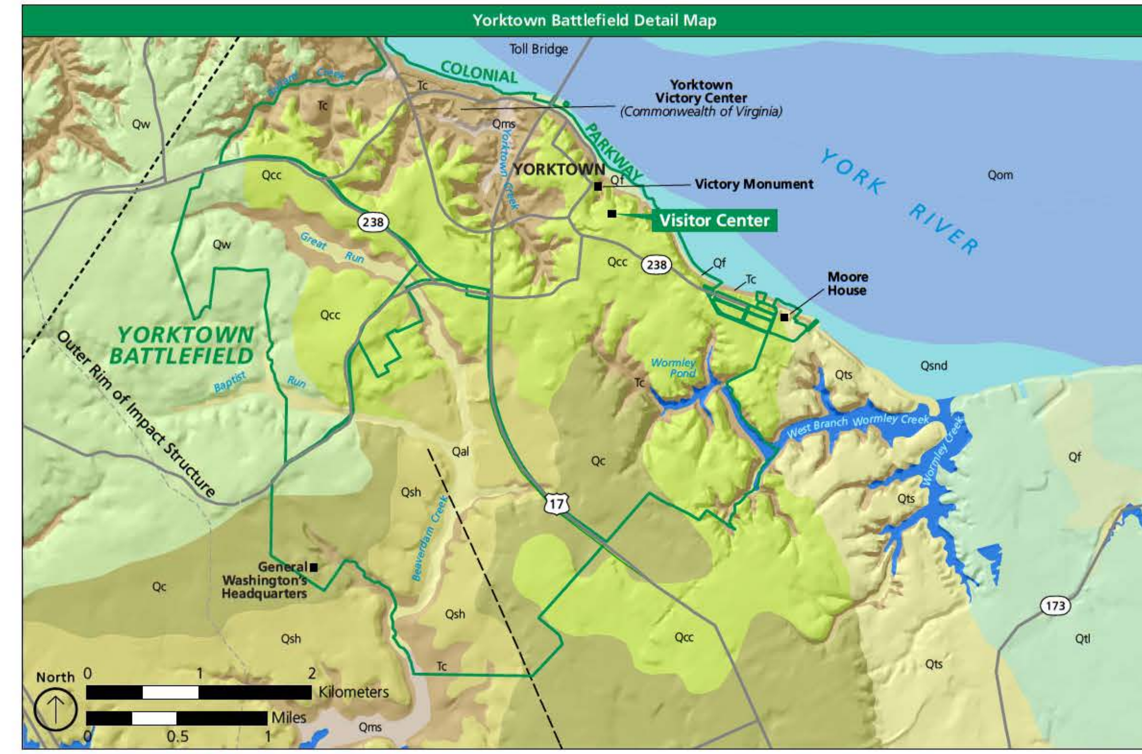
National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science

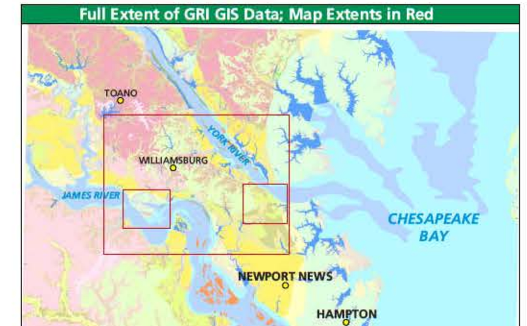
Jamestown Island Detail Map



Yorktown Battlefield Detail Map



Full Extent of GRI GIS Data; Map Extents in Red



NPS Boundary

- point of interest
- highways

Impact Structure Lines

- outer rim of impact structure, inferred

Faults

- normal fault contact (not exposed at surface), inferred
- unknown offset/displacement fault, approximate
- unknown offset/displacement fault, inferred
- unknown offset/displacement fault, queried and inferred

Geologic Units

Symbol	Unit
	water
Qf	Fill (Recent)
Qms	Marsh sediment (Recent)
Qss	Swamp sediment (Recent)
Qb	Beach and dune (Recent)
Qshom	Shelly organic mud (Recent)
Qoy	Oysters (Recent)
Qpe	Peat (Recent)
Qom	Organic mud (Recent)
Qsnd	Sand (Recent)
Qsg	Sand and gravel (Recent)
Qal	Alluvium (Recent)
Qt	Tabb Alloformation, undivided (late Pleistocene)
Qtp	Tabb Alloformation, Poquoson Member (late Pleistocene)
Qtlp	Tabb Alloformation, Lynnhaven and Poquoson Members, undivided (late Pleistocene)
Qtl	Tabb Alloformation, Lynnhaven Member (late Pleistocene)
Qts	Tabb Alloformation, Sedgefield Member (late Pleistocene)
Qeg	Elsing Green Alloformation (late Pleistocene)
Qsh	Shirley Alloformation (middle Pleistocene)
Qc	Chuckatuck Alloformation (middle (?) Pleistocene)
Qcc	Charles City Alloformation (early Pleistocene)
Qw	Windsor Formation (early Pleistocene)
Qm	Moorings Unit of Oaks and Coch (1973) (early Pleistocene)
Qbc	Bacons Castle Formation (early Pleistocene)
Tch	Cold Harbor Formation (late Pliocene)
Tymh	Yorktown Formation, Moore House Member (late Pliocene)
Tc	Chesapeake Group, Yorktown and Eastover Formations, undivided (Pliocene and early Pliocene)

This map was produced by Georgia Hybels (Colorado State University) in June 2016. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

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

Berquist, C. R., Jr. 2015. Geologic Map of the Williamsburg 30- x 60-minute Quadrangle, Virginia (scale 1:100,000). Unpublished. Virginia Division of Geology and Mineral Resources, Charlottesville, Virginia.

As per source map scale and U.S. National Map Accuracy Standards, geologic features represented here are expected to be within 51 m (167 ft) of their true location.

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

Map Unit Properties Table: Colonial National Historical Park

Gray-shaded map units are not mapped within Colonial National Historical Park. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Recent)	Fill (Qf)	Unit **Qf** consists of unsorted, jumbled, undifferentiated material such as sand or gravel used for fill. Modified or disturbed earth materials also fall into this unit type. **Qf** is mapped at Jamestown Island, Yorktown, and along the Colonial Parkway.	None documented	**Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures**—this unit composes many of the coastal engineering structures along the James and York rivers in place to protect reaches of the shoreline.	**Building and Reshaping the Coastal Plain**—unit **Qf** reflects human attempts to reshape the landscape and resist changes brought about by Earth surface processes such as shoreline erosion and flooding.
	Marsh sediment (Qms)	**Qms** accumulates in marshes, bogs, and wetland areas. **Qms** is rich in organic deposits such as plant debris and includes fine sand and clay interlayers. **Qms** occurs at Swanns Point, Jamestown Island, Yorktown, and along the Colonial Parkway.	**Paleontological Resources**—**Qms** contains organic material that may include plant debris and fossil pollen. Foraminifera, spores, conifer and angiosperm pollen, and pine and angiosperm phytoliths on occur on Jamestown Island, dating from about 37,000 years ago to the present. On the York River, **Qms** may contain late Pleistocene bivalves and gastropods and potentially host mastodon remains. **Hydrogeologic System at Yorktown Battlefield**—**Qms** may be part of the interlayered shallow system of aquifers and confining layers. Sandy sediments are part of the Columbia and Cornwallis Cave aquifers. Clay-rich layers are part of the Cornwallis Cave confining unit.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—these are among the youngest geologic map units occurring on the landscape at Colonial National Historical Park. These units reflect the ongoing processes of deposition of sediments weathered from the highlands and fluvial and other earth surface processes acting on the sediments that compose the Coastal Plain. **Qms** and **Qss** formed in estuarine, marsh, and swamp environments. **Qb** formed in beach and shoreline environments. **Qshom** and **Qoy** may be Pleistocene in age.
	Swamp sediment (Qss)	**Qss** accumulates in swamps and other still-water areas. **Qss** is rich in organic deposits such as peat and includes silt, fine sand, and clay interlayers. **Qss** is mapped at Swanns Point and along the Colonial Parkway.	**Paleontological Resources**—**Qss** contains organic material that may include plant debris and fossil pollen.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan.	
	Beach and dune (Qb)	**Qb** consists of fine- to coarse-grained quartz sand. The sand is poorly to well-sorted. As mapped, this unit may include shoreline stabilizing riprap adjacent to water. **Qb** occurs at Jamestown Island and may have been used for iron casting.	None documented	None documented	
	Shelly organic mud (Qshom)	**Qshom** contains organic mud with abundant fossil and modern shells, fragments of shells, and some interbedded sand. Most of this unit is exposed at the shoreline or under water.	**Fluvial Features and Processes**—**Qshom** is mapped submerged beneath the James River near Jamestown Island and along the York River bottom and may be a sand resource. **Paleontological Resources**—**Qshom** contains fossil shells and shell debris. Shell types include oyster, *Rangia*, and other shells.	**Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures**—these units are among the bottom-sediment units mapped in the James and York rivers. These sediments are constantly in flux in the channel and may be dredged periodically. **Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan.	
	Oysters (Qoy)	**Qoy** contains live oysters and oyster shells in a sandy or muddy substrate. **Qoy** may form reef-like forms. **Qoy** is part of the submerged bottom sediment mapping.	**Paleontological Resources**—**Qoy** contains oyster shells and shell debris.		

Gray-shaded map units are not mapped within Colonial National Historical Park. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (Recent)	Peat (Qpe)	**Qpe** consists of decomposed plant remains commonly mixed with sand or mud.	**Paleontological Resources**—**Qpe** contains fossil shells roots of inundated marsh and swamp plants.	**Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures**—these unitsare among the bottom-sediment units mapped in the James and York rivers. These sediments are constantly in flux in the channel and may be dredged periodically. **Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan.	**Building and Reshaping the Coastal Plain**—these are among the youngest geologic map units occurring on the landscape at Colonial National Historical Park. These units reflect the ongoing processes of deposition of sediments weathered from the highlands and fluvial and other earth surface processes acting on the sediments which compose the Coastal Plain. **Qpe** may be Pleistocene in age. **Qom** formed in estuarine, marsh, and swamp environments. **Qsnd** formed in beach and shoreline environments. **Qsg** and **Qal** formed in fluvial environments as channels incised through Coastal-Plain sediments.
	Organic mud (Qom)	**Qom** consists of black, dark gray or dark brown clay and silt. Organic material is abundant. **Qom** is mapped at Jamestown Island.	**Fluvial Features and Processes**—**Qbs** is mapped submerged beneath the James River near Jamestown Island. **Paleontological Resources**—**Qom** contains organic material that may include plant debris and fossil pollen. Foraminifera, spores, conifer and angiosperm pollen, and pine and angiosperm phytoliths occur on Jamestown Island, dating from about 37,000 years ago to the present.		
	Sand (Qsnd)	**Qsnd** is fine- to coarse-grained, poorly to well-sorted quartz sand similar to **Qb**. **Qsnd** may include granules, small pebbles, and organic material. **Qsnd** is gray in channel bottoms and brown in areas adjacent to cliffs, beaches, and active erosion. As mapped, this may include shoreline stabilizing riprap adjacent to water. **Qsnd** is mapped within Swanns Point and Jamestown Island and along the length of the Colonial Parkway fronting the York River.	**Fluvial Features and Processes**—**Qsnd** is mapped submerged beneath the James River near Jamestown Island and may be a sand resource for shoreline nourishment.	**Shoreline Erosion, Sediment Transport, and Coastal Engineering Structures** —these units are among the bottom-sediment units mapped in the James River. These sediments are constantly in flux in the channel and may be dredged periodically.	
	Sand and gravel (Qsg)	**Qsg** is similar to **Qbs**, but with coarser grainsize. It consists of brown, coarse-grained sand, granules and pebbles. **Qsg** is mapped along the Back River near Jamestown.	**Fluvial Features and Processes**—**Qsg** is mapped submerged beneath the James River near Jamestown Island and may be a sand and/or gravel resource.		
	Alluvium (Qal)	Alluvium is deposited by rivers and streams in their channels. **Qal** consists of pebbly sand and sand with common silt layers and abundant organic material such as plant debris. **Qal** is mapped at Yorktown and along the Colonial Parkway.	**Paleontological Resources**—**Qal** contains organic material that may include plant debris and fossil pollen. **Hydrogeologic System at Yorktown Battlefield**—**Qal** may be part of the interlayered shallow system of aquifers and confining layers. Sandy sediments are part of the Columbia and Cornwallis Cave aquifers. Clay-rich layers are part of the Cornwallis Cave confining unit.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Groundwater Quantity and Quality** —this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	

Gray-shaded map units are not mapped within Colonial National Historical Park. Bold text refers to sections in report.

Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (late Pleistocene)	Tabb Alloformation, undivided (Qt)	**Qt** contains clay-rich, fine- to coarse-grained sand.	**Coastal Plain Sediments**—**Qt** consists of fining-upward sequences. **Paleontological Resources**—**Qt** may contain pollen and phytoliths (small mineral deposits within plants), as well as spores, and foraminifera that may yield a paleoecological reconstruction of the area for the past 37,000 years. These fossil remains may be part of **Qm** or **Qom**. None have been located within park boundaries to date. **Hydrogeologic System at Yorktown Battlefield**—**Qt** is part of the interlayered shallow system of aquifers and confining layers. Sandy sediments of **Qt** are part of the Columbia aquifer. Clay-rich layers in **Qt** form part of the Cornwallis Cave confining unit. **Qt** is part of the Cornwallis Cave aquifer.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—**Qt** and overlying sediments (see **Qm** and **Qom**) may contain a record of paleoecological conditions for the past 37,000 years. Northern boreal forests dominated the area until 11,000 to 8,000 years before present when oak, hickory, and other temperate species thrived. **Qt** accumulated in fluvial, estuarine, and marginal and restricted marine environments.
	Tabb Alloformation, Poquoson member (Qtp)	**Qtp** consists of layers of sand, silt, and clay. **Qtp** is up to 5 m (15 ft) thick. **Qtp** is mapped at Swanns Point and Jamestown Island.	**Fluvial Features and Processes**—**Qtp** forms part of the low ridges south of Passmore Creek at Jamestown Island. **Coastal Plain Sediments**—**Qtp** is among the younger, fluvial-estuarine deposits with highly variable compositions.	None documented	**Building and Reshaping the Coastal Plain**—see description for **Qt**. **Qtp** and **Qtl** accumulated approximately 50,000 to 33,000 years ago.
	Tabb Alloformation, Lynnhaven and Poquoson members, undifferentiated (Qtlp)	**Qtlp** contains mixtures of fine- to coarse-grained sand and clay-rich sand.	**Coastal Plain Sediments**—**Qtlp** is among the younger, fluvial-estuarine deposits with highly variable compositions.	None documented	**Building and Reshaping the Coastal Plain**—see description for **Qt**.
	Tabb Alloformation, Lynnhaven Member (Qtl)	**Qtl** contains layers of silt, fine-grained sand, and clay. **Qtl** is up to 6 m (20 ft) thick. **Qtl** crops out at Jamestown Island and underlies the high ground first settled by the Europeans. It may have been a supply in early pottery and brick making.	**Fluvial Features and Processes**—**Qtl** underlies low, arcuate ridges on Jamestown Island. **Coastal Plain Sediments**—**Qtl** is among the younger, fluvial-estuarine deposits with highly variable compositions. **Paleontological Resources**—**Qtl** includes paleochannel fill deposits that can include plant fragments or peat.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan.	**Building and Reshaping the Coastal Plain**—see description for **Qt**. **Qtp** and **Qtl** accumulated approximately 50,000 to 33,000 years ago.
	Tabb Alloformation, Sedgefield Member (Qts)	**Qts** is coarser grained than **Qt** and contains pebbly sand, sand, and clay-rich silt layers. **Qts** is up to 15 m (50 ft) thick. **Qts** is mapped at Yorktown.	**Coastal Plain Sediments**—**Qts** is among the younger, fluvial-estuarine deposits with highly variable compositions. **Paleontological Resources**—**Qts** includes paleochannel fill deposits that can include plant fragments or peat. **Qts** may contain marine fossils.		**Building and Reshaping the Coastal Plain**—see description for **Qt**. **Qts** dates at least in part to approximately 130,000 to 80,000 years ago.
QUATERNARY	Elsing Green Alloformation (Qeg)	**Qeg** consists of muddy, fine- to medium-grained sand grading downward to coarse-grained sand, granules, and pebbles. Phosphate mineral occur locally. **Qeg** is up to 4 m (15 ft) thick, with thicker areas in paleochannels in the York and James rivers. **Qeg** is mapped at College Creek and along the Colonial Parkway fronting the York River.	**Coastal Plain Sediments**—**Qeg** is among the younger, fluvial-estuarine deposits with highly variable compositions.	None documented	**Building and Reshaping the Coastal Plain**—**Qeg** dates at least in part to approximately 125,000 to 130,000 years ago.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (middle Pleistocene)	Shirley Alloformation (Qsh)	**Qsh** contains pebble to boulder sand layers, silt and clay layers, with scattered organic-rich beds of silt and peat. **Qsh** is up to 24 m (80 ft) thick in paleochannels. The contact with the overlying **Qt** is disconformable. **Qsh** is mapped at Jamestown Island, Yorktown, and along the Colonial Parkway.	**Coastal Plain Sediments**—**Qsh** is among the younger, fluvial-estuarine deposits with highly variable compositions. **Paleontological Resources**—**Qsh** contains organic material that may include plant debris and fossil pollen. *In situ* tree stumps, leaves, and seeds of cyprus, oak, and hickory trees are common in **Qsh**. *Crassostrea virginica*, *Mulinia*, *Noetia*, and *Mercenaria*, among other mollusks also occur in **Qsh**. An *Astrangia* (coral) fossil was dated for an approximate age of 184,000 years before present in **Qsh**. None have been located within park boundaries to date. **Hydrogeologic System at Yorktown Battlefield**—**Qsh** is part of the interlayered shallow system of aquifers and confining layers. Sandy sediments of **Qsh** are part of the Columbia aquifer. Clay-rich layers in **Qsh** form part of the Cornwallis Cave confining unit. **Qsh** is the part of the Cornwallis Cave aquifer.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Geologic Hazards and Risks**—**Qsh** underlies local buildings with relatively elevated radon levels. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—**Qsh** was part of a series of complex erosional surfaces, channel incisions, and sedimentary fill events during local sea level changes. **Qsh** accumulated in spatially complex fluvial, estuarine, and nearshore marine settings. **Qsh** accumulated on the York-James Peninsula approximately 400,000 to 250,000 years ago.
QUATERNARY (middle(?) Pleistocene)	Chuckatuck Alloformation (Qc)	**Qc** consists of pebbly sand, sand, silt, and clay layers. **Qc** is locally up to 8 m (26 ft) thick. Upper and lower contacts of **Qc** are unconformable. **Qc** is mapped at Yorktown Battlefield.	**Coastal Plain Sediments**—**Qc** is among the younger, fluvial-estuarine deposits with highly variable compositions. **Paleontological Resources**—**Qc** contains *Ophiomorpha* burrows as trace fossils. None have been located within park boundaries to date. **Hydrogeologic System at Yorktown Battlefield**—**Qc** is part of the interlayered shallow system of aquifers and confining layers. Sandy sediments of **Qc** are part of the Columbia aquifer. Clay-rich layers in **Qc** form part of the Cornwallis Cave confining unit. **Qc** is the part of the Cornwallis Cave aquifer.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—**Qc** formed in fluvial, estuarine, and restricted marine environments associated with sea level changes during the Pleistocene.
QUATERNARY (early Pleistocene)	Charles City Alloformation (Qcc)	**Qcc** is similar in composition to **Qsh** with pebble to boulder sand, interlayered with cross-bedded sand, and silt and clay. **Qcc** is mapped at Yorktown Battlefield and near College Creek at the Colonial Parkway.	**Coastal Plain Sediments**—**Qcc** is among the younger, fluvial-estuarine deposits with highly variable compositions.	None documented	**Building and Reshaping the Coastal Plain**—**Qcc** was part of a series of complex erosional surfaces, channel incisions, and sedimentary fill events during local sea level changes.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
QUATERNARY (early Pleistocene)	Windsor Formation (Qw)	**Qw** contains clay-rich, fine- to coarse-grained sand that overlies fine- to coarse-grained, pebble-rich sand layers. **Qw** has a local maximum thickness of about 12 m (40 ft). The contact between **Qw** and overlying **Qsh** is disconformable. **Qw** is mapped along the Colonial Parkway and at Yorktown.	**Coastal Plain Sediments**—**Qw** is among the younger, fluvial-estuarine deposits with highly variable compositions. **Paleontological Resources**—Fossils are not common for this unit and none have been located within park boundaries to date. Elsewhere, **Qw** contains *in situ* vertical knobby burrows similar to those formed by *Calianassa major* (modern ghost shrimp). **Qw** also displays mollusk molds formed in goethite, hematite, and limonite minerals from reworked **Ty** mollusks. **Hydrogeologic System at Yorktown Battlefield**—**Qw** is part of the interlayered shallow system of aquifers and confining layers. Sandy sediments of **Qw** are part of the Columbia aquifer. **Qw** is also part of the Cornwallis Cave aquifer.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—**Qw** was part of a series of complex erosional surfaces, channel incisions, and sedimentary fill events during local sea level changes. **Qw** accumulated in fluvial, estuarine, tidal flat, and restricted marine settings. **Qw** was deposited approximately 1.5 million years ago.
	Moorings unit of Oaks and Coch (1973) (Qm)	**Qm** consists of massively bedded sand or clay.	None documented	None documented	**Building and Reshaping the Coastal Plain**—**Qm** was part of a series of complex erosional surfaces, channel incisions, and sedimentary fill events during local sea level changes.
	Bacons Castle Formation (Qbc)	**Qbc** is composed of massively bedded and lenticular to flaser-bedded layers of sand, silt, and clay. Basal layers commonly contain pebbles and coarser sand grains. **Qbc** ranges in thickness from 14 to 21 m (45 to 70 ft). **Qbc** crops out in Swanns Point and along the Colonial Parkway.	**Coastal Plain Sediments**—**Qbc** has flaser bedding in which mud streaks or lenses occur in ripple troughs, but not on the crests. **Paleontological Resources**—Fossils are not common for this unit and none have been located within park boundaries to date. **Qbc** may contain invertebrate burrows. **Subsurface Geologic Features and the Chesapeake Bay Impact Crater**—**Qbc** overlies regional faults that may affect shallow-aquifer dynamics. **Hydrogeologic System at Yorktown Battlefield**—**Qbc** is part of the interlayered shallow system of aquifers and confining layers. Clay-rich layers in **Qbc** form part of the Cornwallis Cave confining unit. **Qbc** is part of the Cornwallis Cave aquifer.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Geologic Hazards and Risks**—**Qbc** underlies local buildings with relatively elevated radon levels. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield.	**Building and Reshaping the Coastal Plain**—**Qbc** was part of a series of complex, shifting depositional environments resulting from climatic and sea level changes. **Qbc** accumulated in fluvial, estuarine, tidal flat, and possibly marine settings approximately 2.3 to 2.0 million years ago.
NEOGENE (late Pliocene)	Cold Harbor Formation (Tch)	**Tch** contains yellow to red, muddy, fine- to coarse-grained sand with rare granules. Some lenticular clay layers may reach 9.1 m (30 ft) in thickness. **Tch** also commonly includes a basal gravel layer with large pebbles. Total thickness of **Tch** ranges up to 24.2 m (80 ft). **Tch** unconformably overlies **Tymh** and **Tc**. **Tch** is mapped in creek drainages crossed by the Colonial Parkway.	**Paleontological Resources**—burrows such as *Ophiomorpha nodosa* are common for **Tch**.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan.	**Building and Reshaping the Coastal Plain**—**Tch** accumulated in marginal-marine, wave-dominated deltaic, shallow marine, and tidal flat/channel settings. **Tch** was deposited during a period of sea-level rise.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
NEOGENE (late Pliocene)	Yorktown Formation, Moore House Member (Tymh)	**Tymh** is one of four members of the Yorktown Formation (**Tc**) and consists of a shell hash of coquina layer and sandy, clayey silt that is yellowish to brown in color. The sand layers coarsen downward from very-fine sand to granules. **Tymh** is typically 2 to 3 m (7 to 10 ft) thick.	See descriptions for **Tc**	See descriptions for **Tc**	**Building and Reshaping the Coastal Plain**—**Tymh** accumulated in a fluvial-estuarine, and tidal channel settings.
NEOGENE (Pliocene and early Pliocene)	Chesapeake Group, Yorktown and Eastover formations, undivided (Tc)	**Tc** includes interlayered shell-rich, fine-grained sand, clay-rich fine-grained sand, and silty fine- to very fine-grained sand. The Yorktown Formation contains interlayered shell-rich sand and fine-grained sand with dark brown clay-rich sand and clay at the top of the unit. Locally, the Yorktown Formation ranges in thickness between 12 and 14 m (39 and 45 ft). Its maximum thickness at Yorktown is 16.8 m (55 ft). The contacts between the Yorktown and overlying and underlying units are disconformable. Recent mapping and drilling on the James-York Peninsula have revealed the previously used “Sedley Formation” to be a weathering layer within the Yorktown Formation. The Eastover Formation consists of sand with interlayers of fossiliferous sand. The Eastover Formation varies in thickness from 5 to 28 m (16 to 92 ft). The contacts between The Eastover Formation and underlying older units, as well as overlying units are disconformable. **Tc** is mapped at Swanns Point, Yorktown, and along the Colonial Parkway.	**Coastal Plain Sediments**—**Tc** is among the older, thin, tabular, fossiliferous marine deposits. **Paleontological Resources**—The Yorktown Formation contains shells and shell debris (coquina). The first figured and described fossil from North America (ca. 1687) may have come from this unit—*Chesapecten jeffersonius*, named the state fossil of Virginia in 1993. The Yorktown Formation is rich in mollusks (at least 600 molluscan species) and other species such as *Turritella* (gastropod), *Crepidula* (gastropod), *Striarca centenaria* (bivalve), *Tellina* (bivalve), *Balanus* (barnacles), *Scaphopoda* (tusk-shelled mollusks), *Yoldia limatula* (bivalve), bryozoans, brachiopods, sponges, corals, annelid worms, decapod burrows, foraminifera, ostracodes, and echinoids. Vertebrate fossils discovered in the Yorktown Formation include fish bones, shark teeth, walrus jaw (*Prorosmarus alleni*), whale (*Balaena*) vertebrae, and a whale tooth. The Eastover Formation contains fossil-bearing layers that may include foraminifera, diatoms, palynomorphs (pollen and spores), dinoflagellates, brachiopods, gastropods, bivalves, ostracodes barnacles, crabs, echinoids, sharks, bony fish, auks, whales, and burrows; mollusks from the Eastover Formation may also be reworked into the Yorktown Formation. **Subsurface Geologic Features and the Chesapeake Bay Impact Crater** —the deposition of **Tc** coincides with active Cenozoic faulting that may affect shallow-aquifer dynamics. **Hydrogeologic System at Yorktown Battlefield**—**Tc** is part of the interlayered shallow system of aquifers and confining layers. Clay-rich layers in **Tc** form part of the Cornwallis Cave confining unit. **Tc** is the part of the Cornwallis Cave aquifer. **Tc** is part of the Yorktown confining unit. The Yorktown Formation is the lowermost part of the interlayered shallow system of aquifers and confining layers. The Yorktown Formation is the primary portion of the Cornwallis Cave aquifer and part of the Yorktown-Eastover aquifer, both of which underlie nearly the entire battlefield.	**Paleontological Resource Inventory, Monitoring, and Protection**—the park does not yet have a site-specific paleontological resource management plan. **Geologic Hazards and Risks**—Lateral heave within layers of the Yorktown Formation lead to local slope instability. **Tc** underlies local buildings with relatively elevated radon levels. **Groundwater Quantity and Quality**—this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield. the Eastover Formation portion of this unit is part of the regional shallow aquifer and confining layer system at Yorktown Battlefield, but is located at depths that are not reached by local stream incision. **Karst Landscape Management**—dissolution of carbonate-rich layers within **Tc** causes sinkhole formation at Yorktown Battlefield. **Yorktown Formation Shrink-and-Swell Clays**—clays within the Yorktown Formation swell when water saturated and shrink upon drying. The resulting volume changes can cause damage to roads and overlying structures. **Abandoned Mineral and Disturbed Lands**—Cornwallis Cave was excavated into coquina layers of the Yorktown Formation. The roof of the cave is failing.	**Building and Reshaping the Coastal Plain**—the Yorktown Formation accumulated in a variety of shallow marine settings including open marine, lagoon or other restricted marine, and barrier environments. Climate was relatively warmer during the deposition of the Yorktown Formation resulting in subtropical species flourishing. Age dates for the Yorktown Formation range from 4.5 to 2.5 million years ago. The Eastover Formation accumulated in shallow marine depositional environments during the Late Miocene. The Eastover Formation contains a record of a climate shift from older, cooler, open marine phase, to a younger, subtropical, shallow marine phase. The Eastover Formation may be as old as 11 million years.