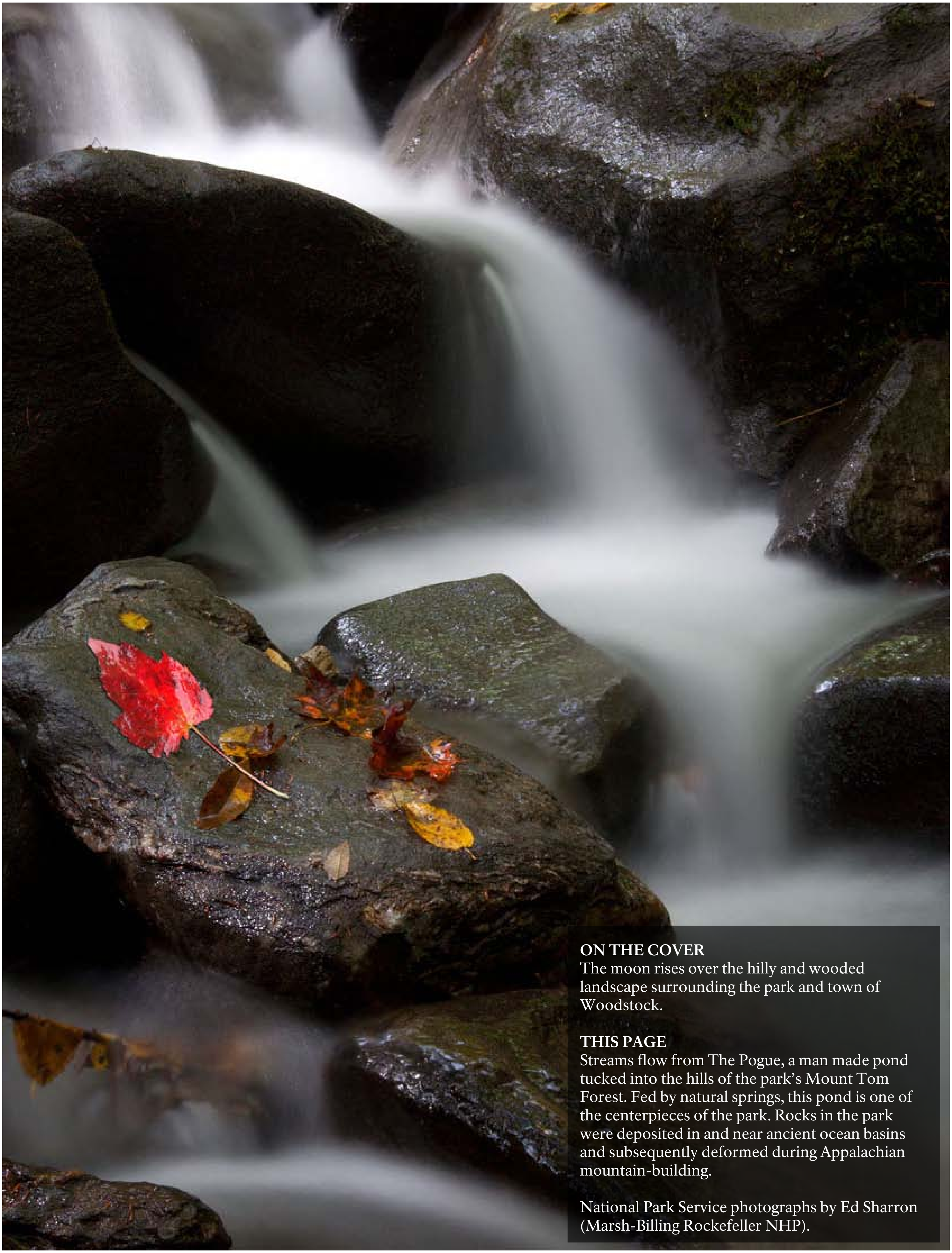
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Marsh-Billings-Rockefeller National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2011/454



ON THE COVER
The moon rises over the hilly and wooded landscape surrounding the park and town of Woodstock.

THIS PAGE
Streams flow from The Pogue, a man made pond tucked into the hills of the park's Mount Tom Forest. Fed by natural springs, this pond is one of the centerpieces of the park. Rocks in the park were deposited in and near ancient ocean basins and subsequently deformed during Appalachian mountain-building.

National Park Service photographs by Ed Sharron (Marsh-Billing Rockefeller NHP).

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National Park Service
Geologic Resources Division
PO Box 25287
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U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

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Executive Summary

This report accompanies the digital geologic map data for Marsh-Billings-Rockefeller National Historical Park in Vermont, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Marsh-Billings-Rockefeller National Historical Park portrays a landscape of degradation and loss recovered by innovation and conservation. The park commemorates four individuals and their families, who served as occupants, developers, and stewards of the rolling hill lands of eastern Vermont for nearly two centuries. George Perkins Marsh, Frederick Billings, and Laurance and Mary Rockefeller played important roles in the history of American conservation, leading by example. Marsh-Billings-Rockefeller National Historical Park interprets how humans strive to preserve and manage a sustainable environment for future generations.

In the late 1700s to early 1800s, much of eastern Vermont was deforested. George Perkins Marsh noticed the devastating effects that improper forest management had on the ecosystem including soil erosion, increased flooding, siltation of local streams and rivers, and decreased land fertility. In 1864, he published these ideas in *Man and Nature*. As the property was handed down from generation to generation, so were George Perkins Marsh's revolutionary ideas about man's long-lasting effects on the environment. In 1869, following Marsh's philosophies, Frederick Billings began a period of rapid improvements and experimental forest management strategies during his family's 60-year stewardship of the land. In 1951, Laurance and Mary Rockefeller continued to make the lessons of conservation available to the public through examples, outreach, and education opportunities.

Geology and geologic processes form the foundation for the ecosystem at Marsh-Billings-Rockefeller National Historical Park and continue to influence the evolution of the landscape. The park is located within the Connecticut Valley-Gaspé Province, which is east of the Green Mountains in east-central Vermont. This province contains Silurian and Devonian (approximately 444 to 359 million years ago), metamorphosed rocks originally deposited in an ancient ocean basin. The natural processes of weathering and erosion, acting on bedrock and geologic structures controls the geomorphology of the landscape. During the Pleistocene Epoch ice ages (the past 2 million years), glaciers beveled the mountains of Vermont, including the Taconic and Green mountains, and deposited thick mantles of sediment throughout the area.

Geologic issues such as changes in stream channel morphology, sediment load, wetland preservation, disturbed lands, mass wasting and erosion, and seismicity may be significant to the park's resource managers, as identified during a scoping meeting in July, 2007. Geologic knowledge contributes to understanding landscape evolution and anthropogenic impacts, such as the location of future facilities. Resource managers should understand how water is moving across, through, and under the park. Geologic processes such as erosion can impact the cultural landscape and natural systems in the park. Erosional processes distort the landscape and can increase sediment loads and meandering in local waterways, damaging the aquatic and riparian environments. Severe erosion in the past following deforestation has removed soil and carved steep valleys on the slopes of the park.

Distinctive geologic features within Marsh-Billings-Rockefeller National Historical Park include glaciated landforms, The Pogue, and paleontological resources. The park's museum collections also include a fossil fish from southwestern Wyoming. The geologic features and processes at the park are ideal for interpretive programs to educate the public about how geology and geologic processes affect the landscape and history of the park.

Bedrock units within Marsh-Billings-Rockefeller National Historical Park include the garnet-bearing metamorphic rocks (schist) of the Waits River and Gile Mountain Formations. These units were deformed by faults, folds, and shear zones developed over hundreds of millions of years of Appalachian mountain building and rifting events. On the surface at the park, units such as till, ground moraine, outwash, and kames record the presence of glaciers that once covered the landscape in thick lobes during the ice ages. Modern sediments of peat and muck, alluvium, and terrace gravels contain evidence of the impact of human activities throughout past centuries.

This report also provides a glossary, which contains explanations of technical, geologic terms, including terms on the map unit properties table. Additionally, a geologic timescale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top (fig. 11).

Acknowledgements

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

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Kyle Jones (Marsh-Billings-Rockefeller NHP) for providing feedback and photographs for the report. Peter Thompson (University of New Hampshire) provided information and feedback on early drafts of the report.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Marsh-Billings-Rockefeller National Historical Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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

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

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

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

Park Establishment and Setting

Established on August 26, 1992, and open to the public since 1998, Marsh-Billings-Rockefeller National Historical Park preserves the home and property of pioneer conservationist George Perkins Marsh and his successors Frederick Billings, Mary French Rockefeller, and Laurance Spelman Rockefeller. The park is located adjacent to the town of Woodstock in Windsor County, eastern Vermont (fig. 1) 21 km (13 mi) southwest of White Fiver Junction, which is situated on the eastern border of Vermont at the confluence of the White and Connecticut rivers. The park is the headquarters for the Conservation Study Institute and contains the oldest managed forest in the United States. Marsh-Billings-Rockefeller National Historical Park is devoted to demonstrating long-term conservation stewardship and responsible forest management practices. As John Elder, author and professor of environmental studies at Middlebury College, noted during the park's opening on June 5, 1998:

> "There is a mandate to invent an entirely new kind of park. It must be one where the human stories and the natural history are intertwined; where the relatively small acreage serves as an educational resource for the entire National Park Service and a seedbed for American environmental thought; and where the legacy of American conservation and its future enter into dialogue, generating a new environmental paradigm for our day."

Marsh-Billings-Rockefeller National Historical Park covers some 260 ha (643 ac) of hilly landscape in the Ottauquechee River drainage within the greater Connecticut River watershed. It is located on a ridgeline anchored on the east by Mount Tom, which rises to 409 m (1,342 ft) above sea level. A gently sloping saddle at the base of Mount Tom contains a large 5.7-ha (14-ac) man-made pond called The Pogue. The Ottauquechee River and its tributary Barnard Brook border the eastern portion of the park. Other streams in the area include Gulf Stream, Bridgewater Brook, and local unnamed streams. Notable highpoints in the area include Mount Ascutney, Dingleton Hill, Mount Tom, Tinkham Hill, Mount Peg, and Hurricane Hill. The Ottauquechee River runs through the village of Woodstock at an elevation of 229 m (750 ft). The highest point within the park rises to over 439 m (1,440 ft) just west of The Pogue.

Geologic Setting

The varying landscape of Vermont is divided into several elongate geo-physiographic provinces, from west to east: Champlain Lowlands and Vermont Valley provinces, Taconic Mountains Province, Green Mountain Province, Connecticut Valley-Gaspé Province, and Bronson Hill Province (fig. 2) (Doolan 1996). Marsh-Billings-Rockefeller National Historical Park is located within the Connecticut Valley-Gaspé Province, east of the Green Mountains. In the west, the low-lying Champlain Valley (also called Champlain Lowlands) contains rolling hills and gently tilted strata. A large mass of older rocks of the Taconic Mountains abruptly interrupts the Champlain Valley, roughly splitting it up the middle from the south. The Vermont Valley runs between the Taconic Mountains and the Green Mountain belt. Rocks of the Vermont Valley are similar to those of the Champlain Valley and host marble quarries. Farther east, the Green Mountains contain schists and phyllites which are metamorphosed equivalents of ancient sediments, lava flows, and slivers of oceanic crust. These rocks were deposited upon or pushed atop older (more than 1 billion years old) basement rocks that make up the spine of the Green Mountains. The eastern portion of Vermont contains Silurian and Devonian metamorphosed rocks, originally deposited in an ancient ocean basin and later intruded by magmas forming Vermont's famous granites (Doolan 1996).

Marsh-Billings-Rockefeller National Historical Park is on the east flank of the Green Mountain anticlinorium (a large, regional, convex-up fold). The park is within a region of domes and recumbent folds on a structural saddle that is located between the north-plunging end of the Chester Dome and the south-plunging end of the Pomfret Dome (fig. 3) (Chang et al. 1965; Thompson 2006; 2007). Just west of the park, Precambrian-aged rocks are exposed in the Green Mountains and Chester Dome (fig. 4). These ancient rocks were shoved and domed upward, deforming the overlying Paleozoic rocks creating complex folding patterns (Thompson 2007). East of Marsh-Billings-Rockefeller National Historical Park, a large regional fault, the Monroe thrust, separates the older Paleozoic rocks (such as those beneath the park) from the Bronson Hill and New Hampshire sequences to the east (fig. 4). North of the Ottauquechee Valley, the rocks are intensely folded while folding south of the river is less intense (Chang 1950). Repeated fold and faulting events associated with multiple Appalachian mountain-building events (orogenies; see the Geologic History section) are responsible for the complex structures underlying the park area.

Bedrock composition, geologic structures (such as faults and folds), glacial scouring, and differential erosion control the formation and evolution of the current topography in the area. The Connecticut River's course appears to follow the trace of the Monroe fault line (P. Thompson, geologist, Vermont and New Hampshire geological surveys, personal communication, 2007). This is likely due to the inherent weakness in the deformed bedrock associated with movement along the fault. During the last glacial advance of the Pleistocene Epoch, the Hudson-Champlain ice lobe descended south from Canada, scoured the area, beveling the mountains, and creating rounded hilltops. Upon glacial retreat, thick units of silt- and clay-rich till blanketed the landscape at Marsh-Billings-Rockefeller National Historical Park. More recently, streams and rivers incised through the glacial sediments, and are cutting into the underlying metamorphic bedrock. Steep slopes flank most local waterways.

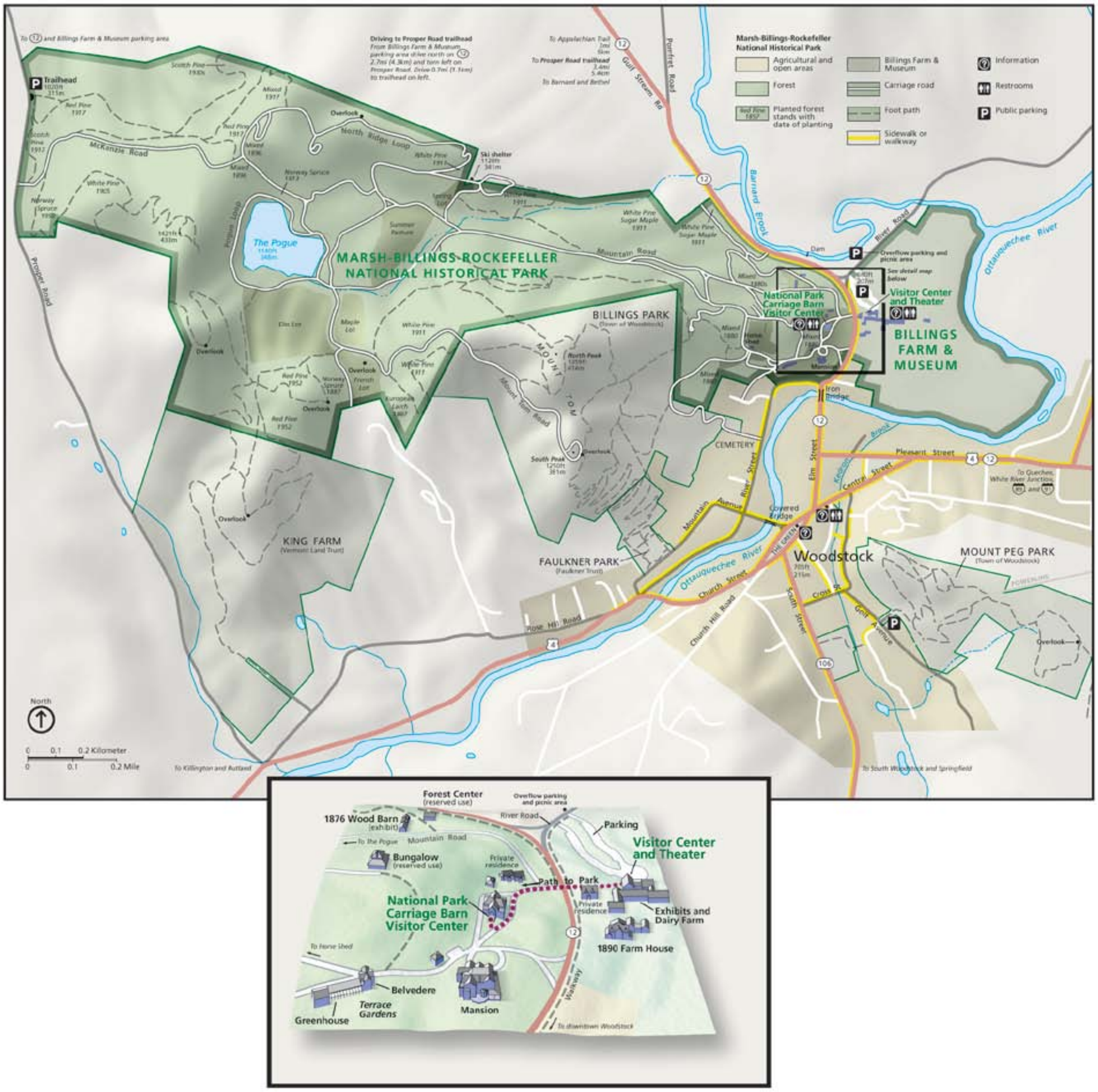


Figure 1. Maps of Marsh-Billing-Rockefeller National Historical Park. National Park Service maps available online: http://home.nps.gov/applications/hafe/hfc/carto-detail.cfm?Alpha=MABI, accessed 19 September 2011.

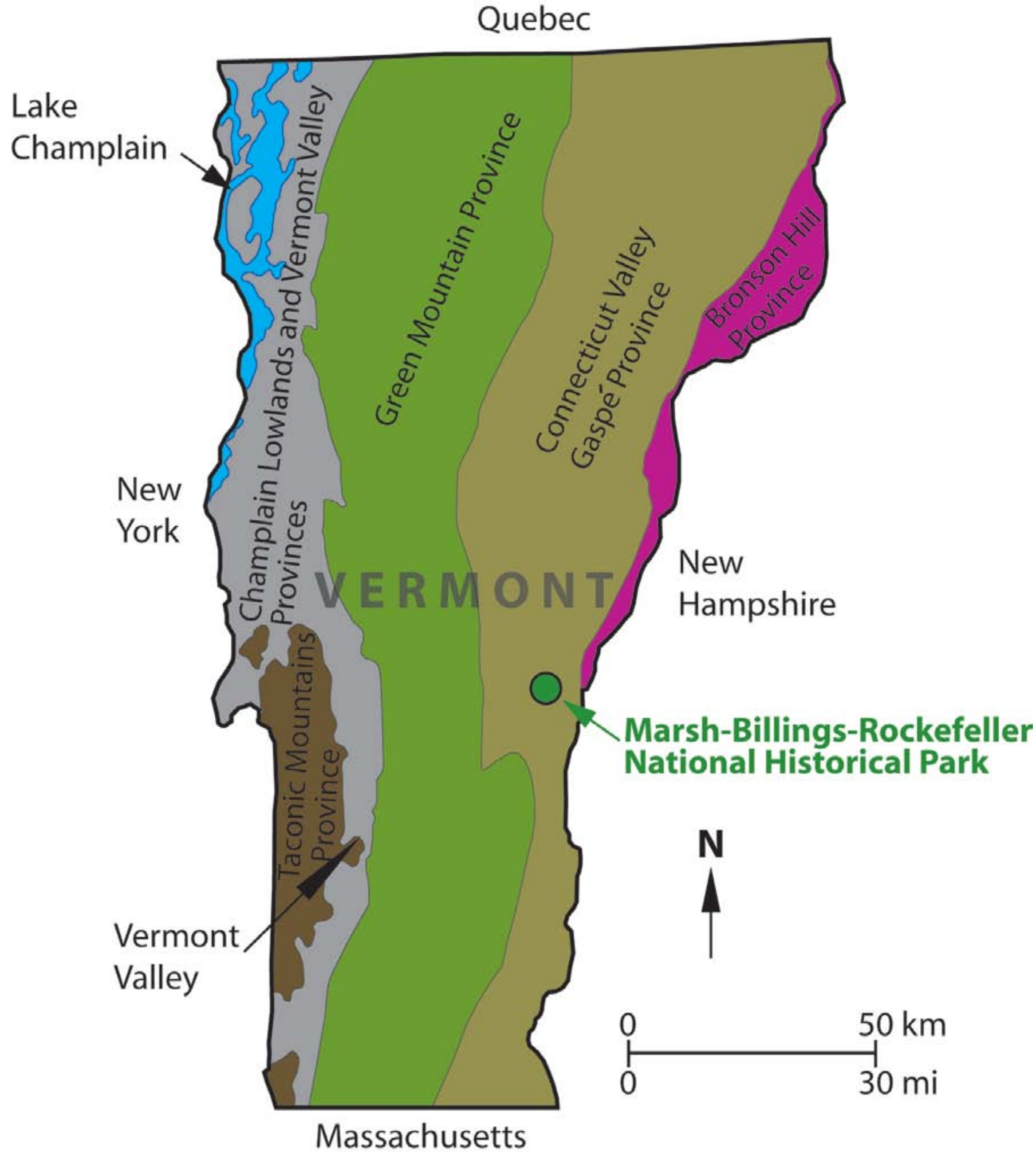


Figure 2. Map of the geo-physiographic provinces of Vermont and the location of Marsh-Billings-Rockefeller National Historical Park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 in Doolan (1996).

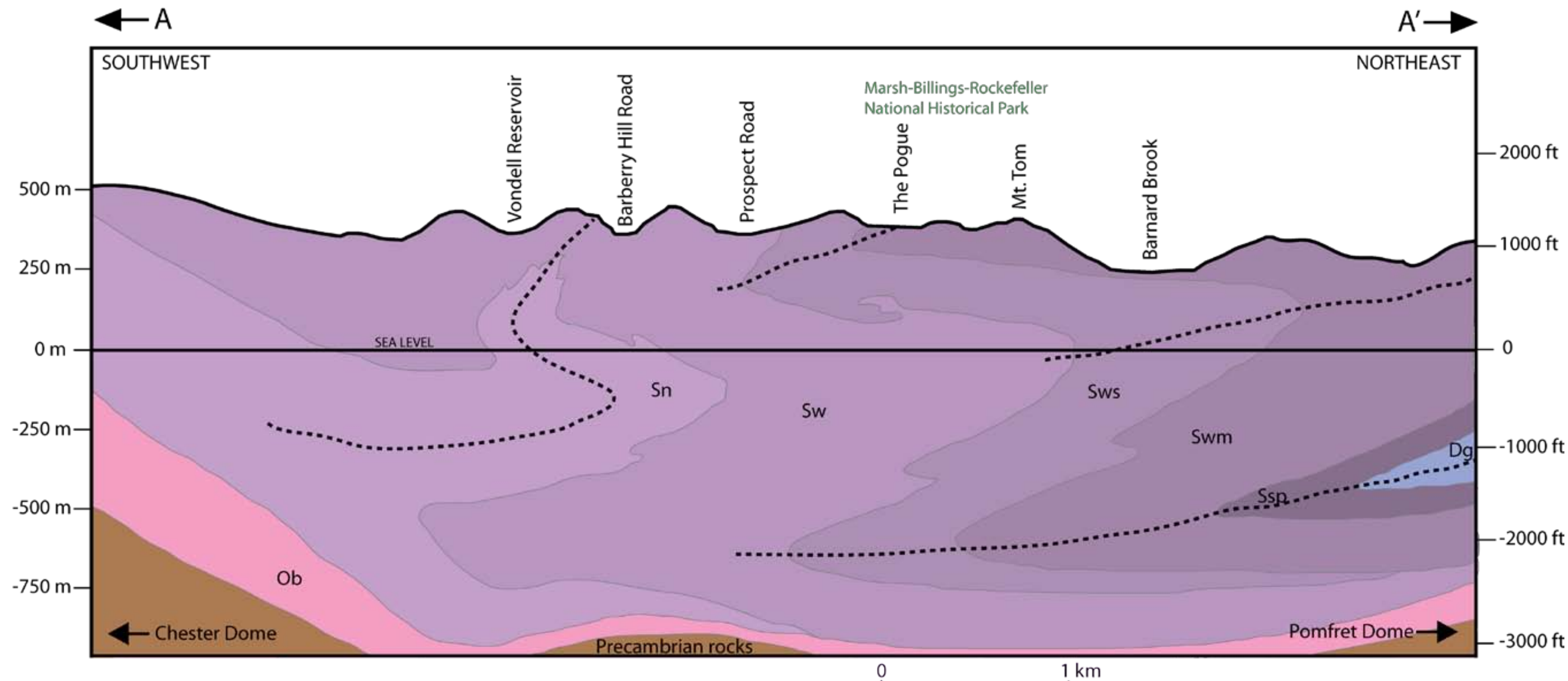


Figure 3. Cross section view through the Marsh-Billings-Rockefeller National Historical Park showing complex structural patterns resulting from folding and faulting during multiple Appalachian mountain-building events (orogenies). Note in particular the location of the park on a saddle-type structure between the Chester Dome and the Pomfret Dome. Dashed lines indicate fold axes. See figure 4 for location of cross-section. Ob is Barnard Gneiss; Sn is Northfield Formation; Sw is Waits River Formation; Sws is Waits River Formation, with between 10 to 50% calc-silicates; Swm is the Waits Formation, Mt. Tom Member; and Ssp is the Standing Pond Volcanics. Symbols and colors reflect those found in the Map Unit Properties Table. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after an excerpt from cross section A-A′ in Thompson (2006).

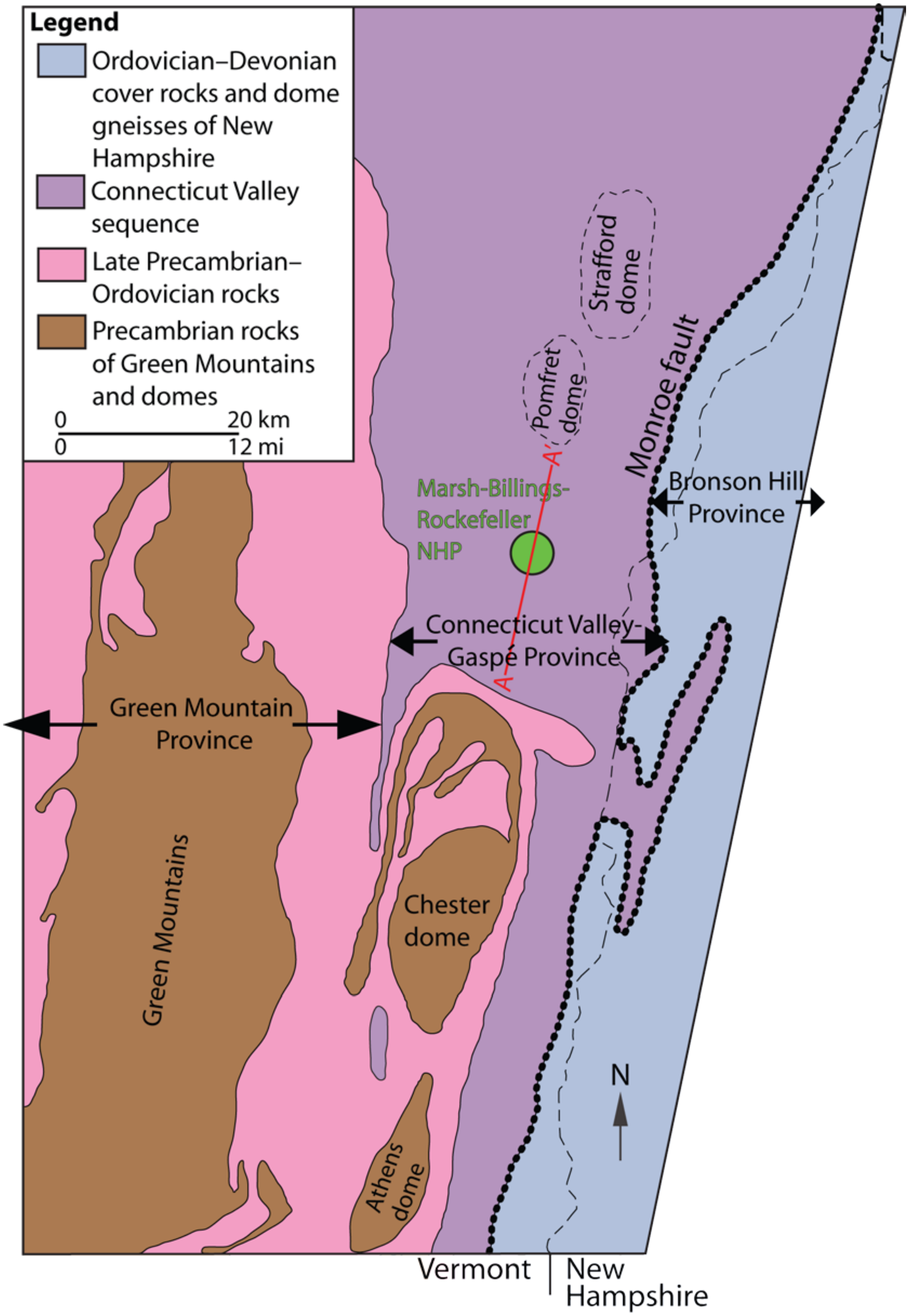


Figure 4. Generalized geologic map of the Marsh-Billings-Rockefeller National Historical Park showing the locations of the Chester and Pomfret domes, the Green Mountains, and the Monroe fault trace. General locations of relevant provinces from figure 2 are included. The cross section line of figure 3 is included in red. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 3 in Spear et al. (2002)

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Marsh-Billings-Rockefeller National Historical Park on July 10, 2007, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

Water Issues and Wetlands

The Ottauqhechee River and its tributaries, including Barnard Brook and several ephemeral streams, are significant factors contributing to the evolution of the landscape at Marsh-Billings-Rockefeller National Historical Park. Issues associated with this fluvial system include riverbank and headward erosion as identified during the July 2007 scoping meeting (Thornberry-Ehrlich 2007). Increased sedimentation can occur in some streams near high use or disturbed areas such as trails. Clearing of vegetation can accelerate runoff and erosion, locally increasing sediment load and changing stream channel morphology. Lord et al. (2009) provide an overview of fluvial geomorphology, and river and stream dynamics. They describe vital signs and stressors of fluvial systems, as well as methodologies for monitoring: 1) watershed landscape, 2) hydrology, 3) sediment transport, 4) channel-cross section, 5) channel-planform, and 6) channel-longitudinal profile.

At Marsh-Billings-Rockefeller National Historical Park, there are nearly 2 km (1 mi) of stream channels within park boundaries that, together with intermittent gullies, erode steep notches into the slopes of the landscape at the park. The Ottauquechee River and Barnard Brook are within the authorized boundary and seasonal flooding occurs along these waterways. Flooding occurs during seasonal thaws and following large storm events, such as nor'easters. Flooding threatens riparian habitats as well as buildings, roads, trails, and other infrastructure constructed along the floodplain zone flanking the waterways (Thornberry-Ehrlich 2007). Mass wasting, detailed below, is another issue associated with streams in the park.

Other surface water features present at the park include wetlands, swamps, and ponds. A large, 2-m (6-ft) deep man-made pond called The Pogue is a prominent feature perched between several topographic highs (fig. 5). However, it is prone to infilling by sedimentation and needs to be regularly maintained as a historic feature at the park. The Pogue was originally a natural wetland area whose location was influenced by geologic processes and structures. Glaciers scoured a shallow bedrock depression on an underlying saddle-like area between two domes, which formed a relatively flat basin for converging streams to create a natural wetland area (Thornberry-Ehrlich 2007). After its early impoundment (prior to 1869), it was enlarged in 1890 with a concrete dam (Foulds et al. 1994). While clearly not a glacial kettle pond (round ponds characterized by thick, surrounding mantles of glacial outwash or till deposits), the actual genesis of the original wetland remains unclear.

Wetlands act as floodwater retention areas, filter sediments and nutrients (improving surface water quality), provide wildlife habitat, preserve sediment (thus provide an important deposition record), and provide recreation and educational opportunities. As such, they are important features in any landscape. In 2004, The Woodstock Conservation Commission organized a wetlands inventory for the Township of Woodstock. This inventory was accomplished via remote sensing using color-infrared aerial photographs, digital orthophotographs, Natural Resources Conservation Service soil survey maps, topographic maps, and Vermont Significant Wetlands Inventory maps (Arrowhead Environmental 2004). It identified 365 different wetlands and potential wetlands. According to their definition, a site must meet the following criteria to be considered a wetland: 1) hydrophytic (wetland) vegetation, 2) hydric soils, and 3) wetland hydrology. In upland areas, the inventory identified seeps, fens, and northern hardwood seepage forests (Arrowhead Environmental 2004). The Township of Woodstock has a wealth of diverse wetland resources ranging in size from a 0.004 ha (0.01 ac) seep to a 9 ha (23 ac) alder-willow shrub swamp.

Detailed inventories of the wetlands at Marsh-Billings-Rockefeller National Historical Park would be a valuable dataset for resource managers for gaining insight into: 1) flood control, 2) water quality, 3) sediment retention, 4) wildlife habitat, 5) fisheries habitat, 6) erosion control (sediment stabilization), 7) open space, 8) recreation and education opportunities, 9) hydrophytic vegetation, and 10) rare, threatened and endangered species (Arrowhead Environmental 2004). These considerations are important for determining overall ecosystem health, protecting infrastructure integrity and visitor safety, and promoting informed natural resource management. As part of the Northeast Temperate Network, the park has access to Google Earth layers of spatial data, including water quality sites, vegetation maps, and lakes and ponds within 8 km (5 mi) of the park (http://science.nature.nps.gov/im/units/NETN/googleMaps/parkMaps_GoogleEarth_flash.cfm). For more information or support contact the National Park Service Water Resources Division.

Disturbed Lands

Historical land use practices factored strongly into the creation of Marsh-Billings-Rockefeller National Historical Park. At Marsh-Billings-Rockefeller National Historical Park, there was cut-and-fill activity around the mansion and other historic structures. Approximately 19 km (12 mi) of carriage roads carried guests and visitors along the slopes of Mount Tom (fig. 6). Forest maintenance at the park includes logging access roads (skid roads). These may be decommissioned and have to be created elsewhere for renewed access (Thornberry-Ehrlich 2007). Grazing by cattle and other livestock was also traditionally associated with the agrarian history of the area. To recreate the past landscape, the park is considering the re-introduction of grazing animals.

Regional mining interest has undoubtedly influenced the development of the community of Woodstock as well as Marsh-Billings-Rockefeller National Historical Park. Regional mines and quarries (located east of the park in Plymouth) extracted granite (granodiorite), dolomite, talc, and soapstone (Chang et al. 1965). Minor hematite and magnetite associated with the dolomite quarried from the Tyson Formation sparked some iron ore interest in the nineteenth century (Hitchcock et al. 1861). These units are not present on the digital geologic map for the park. Some bog ores in the same general area also provided iron.

Mass Wasting

Mass wasting refers to the dislodging and downslope movement of soil and rock material, such as during a rockfall, slump, or landslide. Local streams throughout the park area cut through unconsolidated glacial deposits creating steep slopes and terraces. Gravity, frost and plant root wedging, differential erosion, and minor karst dissolution are primary natural causes of slope instability. As such, hillslope processes such as landslides, slumping, and minor rockfall are a prevalent issue at the park (Thornberry-Ehrlich 2007). For example, the Pogue Stream ravine has active slope creep and slumping into the channel. Anthropogenic changes to the hill slopes such as road and trail construction, mining (e.g. gravel pits and regional quarries), undercutting, and deforestation are the most common causes of local mass wasting (Thornberry-Ehrlich 2007).

Intersecting joints in units such as the Barnard Gneiss (geologic map unit Ob) result in rectangular blocks that break away from the outcrop. Regional joint sets in the park area mostly trend northeast-southwest and roughly east-west (Thompson 2006). Through-going joints are also preferred conduits for groundwater flow and can have marked effects on the productivity of bedrock wells throughout the area (Thompson 2006).

At Marsh-Billings-Rockefeller National Historical Park, slope creep occurs along the Pogue Stream ravine that runs through the park. After high precipitation events, higher flow can erode banks, undercutting the overlying geologic units, leaving them prone to mass wasting. Park resource managers may want to consider monitoring stream corridors for slope creep, particularly since excessive erosion may lead to increased sediment load and aquatic environment degradation. Also in the park area, mass wasting and erosion may also expose attractive almandine garnets and amphibole clusters from bedrock geologic units (such as the Standing Pond Volcanics, geologic map unit Ssp) that could be targets for mineral collectors (Thornberry-Ehrlich 2007).

Wieczorek and Snyder (2009) described the various types of slope movements and mass wasting triggers, and suggested methodologies and five vital signs for monitoring slope movements: 1) types of landslides, 2) landslide triggers and causes, 3) geologic materials in landslides, 4) measurement of landslide movement, and 5) assessing landslide hazards and risks. Their publication provides guidance using vital signs and monitoring methodology.

Seismicity

In brief, New England consists of fragments of crust (terranes) accreted onto the ancient North American margin during Appalachian mountain-building events hundreds of millions of years ago as the supercontinent Pangaea was being assembled. There are also extensional basins formed later when Pangaea pulled (rifted) apart. These accreted blocks and rift basins are typically separated or bounded by faults or sutures that are often zones of weakness. These ancient zones of weakness may be reactivated and responsible for the seemingly enigmatic earthquake events throughout New England in modern times (Kafka 2004). According to this model, preexisting faults, suture zones (regional-scale features along which two or more bodies of rock were joined), and other geological fault features formed in the ancient past persist within the interior of the North American tectonic plate and these features may fail periodically under applied stress (Kafka 2004).

Marsh-Billings-Rockefeller National Historical Park is not located near a currently active seismic zone and has not been since the end of Appalachian Mountain building. However, small earthquakes do happen locally. Most of these earthquakes are too minor to be felt at the surface, ranging between magnitude 2.5 and 4 on the Richter scale. They may arise from residual tectonic stresses caused by the Jurassic (approximately 200 to 145 million years ago) Ascutney intrusive event. This event involved the emplacement of molten material (magma) that formed the White Mountain volcanic-plutonic series along the Connecticut River, just southwest of the town of Windsor (Thornberry-Ehrlich 2007; Nielson 1973). Determining which structures are likely to shift and cause an earthquake is very difficult (Kafka 2004). An ambiguous relationship between geological features and seismic events is typical of intraplate areas (areas far from plate boundaries) such as New England. It is nearly impossible to predict the time and location of future earthquakes (Kafka 2004). The formation of New England and mountain-building events are described in the Geologic History section of this report.

The largest, most recent earthquake to significantly impact Vermont was a magnitude 5.2 event on June 14, 1973. The epicenter of this event was in western Maine; however, the shock was felt over an area of about 250,000 sq. km (97,000 sq. mi). Local effects from this event included cracked plaster, chimney displacement, and road surface cracks (U.S. Geological Survey 2009). On October 2, 2006, a 3.8 magnitude earthquake off the southern coast of Maine triggered landslides and rockfalls in Acadia National Park forcing trail closures, road repairs, and groundwater level drops in monitoring wells (Graham 2010).

Moderate to large seismic events may trigger debris flows, landslides, and rockfall threatening to damage park infrastructure. Based on patterns of past seismicity and known geologic features, the U.S. Geological Survey has produced a series of earthquake hazard maps for the United States. According to the U.S. Geological Survey's national seismic hazard map of 2008, Marsh-Billings-Rockefeller National Historical Park sits in an area of moderately low hazard that trends throughout much of New England. These maps indicate that in most parts of New England, there is about a 10% probability that, in any given 50 year period of time, potentially damaging earthquakes will occur (Kafka 2004). The nearest seismic station is at the Weston Observatory, Boston College, Weston, Massachusetts (http://quake.bc.edu:8000/).

The U.S. Geological Survey monitors seismic activity throughout the region. The U.S. Geological Survey maintains an earthquake monitoring website: http://earthquake.usgs.gov/eqcenter/recenteqsus/ as well as an earthquake hazards site: http://earthquake.usgs.gov/hazards/. Braile (2009) provides an overview of earthquakes and provides six suggestions for seismic monitoring: 1) monitoring earthquake activity, 2) analysis and statistics of earthquake activity, 3) analysis of historical and prehistoric earthquake activity; 4) earthquake risk estimation, 5) geodetic monitoring and ground deformation, and 6) geomorphic and geologic indications of active tectonics.

Figure 5. The Pogue. This man-made pond was once a natural wetland area prior to its impoundment. The Geologic Features and Processes section further describes the geologic influences on the location of The Pogue. National Park Service photograph by Ed Sharron (Marsh-Billings-Rockefeller NHP).

Figure 6. Carriage trails, such as this one, criss-cross the park. Such disturbed features are considered cultural resources and provide access to remote areas of the park. National Park Service photograph by Nora Mitchell (Marsh-Billings-Rockefeller NHP).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Marsh-Billings-Rockefeller National Historical Park.

Glacial Features

During the last glacial maximum between 26,000 and 19,000 years ago (Pleistocene ice ages), continental ice sheets covered the landscape of the Connecticut River Valley, after descending south from Canada (see fig. 16 in Geologic History section). Glaciers are extremely effective agents of landscape change, beveling hills and mountains while transporting vast amounts of sediments entrained en route. Glaciers that covered the area of Marsh-Billings-Rockefeller National Historical Park during the Pleistocene left lasting influences on the landscape. Glacial features found in the park include drumlins, rock-cored drumlins (west and north of the Pogue), plucked cliffs, a mantle of glacial till, and a roche moutonnée. A drumlin is an elongated, whale-shaped hill of glacial deposits such as till, formed by glacial action with a long axis that is parallel with the movement of the glacier, and a blunter end facing into the direction of glacial movement. A roche moutonnée is a knob of bedrock whose long axis is oriented in the direction of ice movement. The side profile of a roche moutonnée and its relation to glacial ice movement is opposite to that of a drumlin (fig. 7). The stoss (or upstream side) is gently inclined and rounded whereas the lee (downstream) side is steep and rough.

While traveling over the landscape, glaciers pick up and carry vast amounts of sediment. When the glacial ice melts and the ice sheets retreat, the entrained sediment is dropped, covering the underlying landscape (fig. 8). Glacial deposits at Marsh-Billings-Rockefeller National Historical Park include glacial till, outwash, kame, kame terrace, and ground moraine deposits (geologic map units ti and tt, ow, ka, kt, and gm, respectively—see Geologic Map Data section) (DeSimone 2006). The nature of the glacial deposits depends on numerous factors, including rate of retreat, deposition mechanism, and bedrock lithology and morphology. If glacial retreat is rapid, the sediments previously carried in the glacial ice are released all at once, forming glacial till (geologic map units ti and tt). As a result of such rapid deposition, glacial till is relatively unsorted and contains rock fragments of various sizes ranging from the smallest clay to boulders. Outwash streams typically accompany glacial melting and form downslope away from the melting ice front. These sediment-choked streams leave behind sorted channel, delta (into temporally ephemeral lakes), and floodplain deposits (geologic map unit ow). A glacial feature called a kame is deposited on the land surface when the underlying glacial ice melts completely. Kames (geologic map unit ka) form irregularly shaped hills or mounds typically composed of sand, gravel, and glacial till that accumulate in a depression on the surface of a retreating glacier. Kame terraces (geologic map unit kt) frequently form along the side of a valley filled with glacial ice, deposited by meltwater streams flowing between the ice and the adjacent valley wall. Kame terraces typically appear as long, flat benches. Ground moraines (geologic map unit gm) are glacial till-covered areas that exhibit irregular topography with no definitive ridges (fig. 8). Ground moraines often form gently rolling hills. They accumulate under the glacier by lodgment, which is the plastering beneath a glacier of successive layers of basal till upon bedrock or other deposits. Ground moraines are locally deposited as the ice melts and the glacier retreats.

The Pogue

Remnant glacial ice may also have contributed to the early formation of the original Pogue wetland. The Pogue is a large anthropogenic pond at the base of Mount Tom. Originally a boggy wetland area, The Pogue is located in a shallow depression on the lee side of a roche moutonnée. This depression, scoured by glacial ice, likely through a combination of plucking and abrasion, formed when glaciers modified the horseshoe-shaped ridge north and west of the pond (P. Thompson, geologist, Vermont and New Hampshire geological surveys, written communication, 2007). Streams draining the surrounding ridges converged in the small basin. This was a natural place to build a pond. Richardson (1927) mentions The Pogue as being a natural lake, the only one worthy of mention in Woodstock, on private property known as the Billings Estate. In 1890, in accordance with plans laid out by Frederick Billings, construction of a concrete dam on Pogue Brook (located before its confluence with Barnard Brook), enlarged The Pogue (Wilke et al. 2002). This historic feature provided fertile soil from dredging, ice, and drinking water for the various inhabitants of the settlement (Thornberry-Ehrlich 2007).

Geology and History Connections

The rich natural resources of the greater Connecticut River Valley have attracted human interest for thousands of years. The geology and landforms of the Woodstock, Vermont area focused the location of settlements along the river corridor and its tributaries. The floodplains of the Ottaquechee River and its major tributaries are among the most fertile in Vermont (Richardson 1927). Humans first arrived in New England more than ten thousand years ago and left behind artifacts such as carved stones and campsites (Curran and Dincauze 1977; Thornberry-Ehrlich 2007). Over time, humans altered the landscape to suit their needs. Deforestation, damming of waterways, and draining of swamps impacted ecosystems through increased runoff, soil loss, erosion, flash-flooding, and siltation (Foulds et al. 1994; Thornberry-Ehrlich 2007).

Prior to European settlement, tribes of the Abenaki Confederation supplemented their hunting and gathering with small-scale agriculture, growing limited crops in the fertile floodplains along the larger river valleys (Foulds et al. 1994). The Township of Woodstock was chartered in 1761; settlers were attracted by the abundance of forests, fertile lowlands and swamps, gentle slopes, and an abundant supply of water (Foulds et al. 1994). Marble and limestone, quarried from the Waits River Formation (geologic map unit Sw), were used in the construction of many early buildings in the township of Woodstock including the J. P. Benedict house (ca. 1848), the Alonzo S. Mack house (ca. 1852 in the Beaver Brook Valley), and the school house at Prosper (ca. 1867) (Richardson 1927).

Vast tracts of heavily forested wilderness containing spruce, white pine, and hardwoods once covered the entire region. By the late 1700s, nearly all of this forest cover had been cleared by logging for lumber, potash and pearlash (potassium carbonate-potassium hydroxide recovered in iron pots from washings of wood ashes), and for pasture and fields (Foulds et al. 1994; Searls 1994; Thornberry-Ehrlich 2007).

Charles Marsh, Sr. built a brick house (possibly from locally sourced clay) on the Marsh farm site in 1805-07 that would be the boyhood home of George Perkins Marsh (National Park Service 2006). During Marsh's childhood, Mount Tom was a bare upland pasture capped by a pair of exposed rock peaks (Foulds et al. 1994). George Perkins Marsh was among the first to notice that the local deforestation of Mount Tom for sheep pasture had resulted in uncontrolled runoff, increased erosion, steady loss of topsoil, and subsequent siltation and flash flooding in local streams (fig. 9) (Foulds et al. 1994; Thornberry-Ehrlich 2007). He also noticed the transformation of the Ottauquechee River as it became very erratic, flooding frequently during the spring and often drying entirely during the summer (Foulds et al. 1994). Fields lost their fertility, fish habitats were lost, and mill sites silted up or washed away during floods (Foulds et al. 1994). His observations regarding interrelationships among natural factors forming an ecosystem would have profound effects on forest management practices for future generations; especially when he published *Man and Nature* in 1864. Marsh set the standard for later owners of the farm to continue his forest management work and preserve his conservation legacy.

In 1869, continuing George Perkins Marsh's forward-thinking conservationism, Frederick Billings (a Vermont native, lawyer, conservationist, and businessman closely associated with the railroad expansion of the American west) purchased and enlarged the original brick structure into the Mansion (Foulds et al. 1994; National Park Service 2006). Under Billings, the adjacent agricultural lands and buildings were developed into a progressive and award-winning farm—the farm won top honors at the 1893 World's Columbian Exposition in Chicago (National Park Service 2006). New techniques in forest management were used, and carriage roads were designed and constructed along ridges underlain by resistant rock layers to take advantage of natural topography for optimal drainage. In addition to native species, Billings planted Norway spruce, European larch, and Scotch pines to renew the forest and attempt to baffle and capture eroding soil (Thornberry-Ehrlich 2007). Buildings were set on terraces to take advantage of scenic views.

In 1951, the property was purchased by Mary French Rockefeller and Laurance S. Rockefeller. Under their care, the Mansion, Belvedere, and Bungalow were restored, and the estate was expanded to encompass the Woodstock Inn, an adjacent golf course, and the Mount Tom and Suicide Six ski areas developed on slopes rounded by Pleistocene glaciers (National Park Service 2006). Their forest management priorities shifted from ideas of efficiency in forest production towards building forest viability and the avoidance of stagnation through selective thinning (Foulds et al. 1994).

The geology of the area has piqued geologists' interest for more than a century. E. Hitchcock, E. Hitchcock, Jr., A. D. Hager, and C. H. Hitchcock (1861), C.H. Richardson (Syracuse University, 1903, 1927, and 1929), and E. L. Perry (1927, 1929) were among the first to describe the Lower Paleozoic metasedimentary and metavolcanic units that dominate the bedrock geology of eastern Vermont.

Ecological Relationships

Important correlations exist between flora, fauna, and geologic features and processes at Marsh-Billings-Rockefeller National Historical Park. Forest management and conservation stewardship can be enhanced by understanding the interrelationships between geology, soil science, biology, climatology, and hydrology. There are many examples of geology influencing vegetation patterns, hydrology, and surficial drainage. For example, underlying geology controls soil composition in the case of the limey soils west of The Pogue as they support specific forest assemblages (Thornberry-Ehrlich 2007). Dredged material, including peat and limey marl from The Pogue, provided fertilizer for local fields (DeSimone 2006). Deep, clay rich glacial till substrates generally have poor drainage and inhibit some species such as hemlocks and beech from growing successfully, whereas others, such as red maple and willow, thrive. Layering vegetation maps over soils, and surficial and bedrock geologic maps illuminates correlations between flora and underlying substrate. Some of these data sets are available as Google Earth layers from the NPS Northeast Temperate Network (http://science.nature.nps.gov/im/units/netn/). A soils database was completed for the park in 2005 (National Park Service 2005).

Groundwater Potential

Groundwater studies conducted by the Vermont Geological Survey demonstrate the value of combining bedrock and surficial geologic mapping to help identify areas where groundwater resource potential may exist.

Derivative products of such work include groundwater resource maps and recharge area maps (Becker et al. 2007). The GIS data produced for the park contains aquifer boundaries and recharge areas (see Geologic Map Data section). Cracks in bedrock, including faults, fractures, and joints may serve as conduits for groundwater. For a crack to be optimally transmissive, it must be long and cross-cutting, connected to shorter joints that abut or cross bedding planes or other textures within the bedrock (Thompson 2006). In the park area many joints strike perpendicular to bedding and parallel to the maximum dip direction of the bedrock (fig. 10). This orientation causes the groundwater flow direction to be either in the down-dip or up-dip directions (approximately east-west) (Thompson 2006).

Weathering and intersecting joints in the Barnard Gneiss (geologic map unit Ob) result in rectangular blocks that slough away from the outcrop. These joints are generally widely spaced (outcrop scale) and continuous through large exposures of bedrock permitting groundwater to flow easily. Some of the highest yielding bedrock wells in the Woodstock, Vermont area are dug through Barnard Gneiss; generally southwest of town and outside of the park boundary (Thompson 2006). Within the park and surrounding area, nearly every outcrop contains at least one joint oriented roughly east-west, reflecting a strong preferred regional orientation. Long, continuous (through-going), planar joints in schists of the Waits River Formation (geologic map unit Swm) tend to be in that orientation, whereas joints in calc-silicate rocks (geologic map unit Sws) and curved joints show more variation in orientation patterns. Another set of joints, trending northeast-southwest, is apparent in many outcrops, approximately parallel to the trend of the Ottauquechee River (Thompson 2006). This relationship may indicate significant influence of joint orientation to the development of the river valley (Thornberry-Ehrlich 2007; Becker et al. 2007). Understanding the orientation of joints within the subsurface lends understanding to the hydrogeologic system and to more productive predictions of potential groundwater well locations.

Bedrock features such as bedding, dip, and cleavage also contribute to the permeability of a particular unit. Permeability is a measure of the ease with which a liquid can move through porous rock; porosity is a measure of the open space (between mineral grains or fractures), no matter how connected within a rock. The Waits River Formation (geologic map unit Sw), which underlies much of the park area, consists of interbedded garnet schist and sandy marble. The marble layers are more permeable than the schists. In places where the layers are gently to moderately inclined, vertical bedrock wells penetrate multiple, alternating rock types and are more likely to encounter fractures, bedding planes, and other permeable layers that yield more water (Becker et al. 2007). Where layering (or bedding) is more vertical, well yields can be highly variable between high and low (Becker et al. 2007).

Much of the surface in the park area is covered by glacial deposits including thin till (geologic map unit tt), ice contact deposits (sand and gravel of geologic map units ow and ka), and, along the major valleys, minor kame terraces (geologic map unit kt) which appear as a terrace-like ridge of stratified sand and gravel formed as a deposit between a melting glacier and a higher valley wall or moraine. Unconfined aquifers formed in surficial fluvial terrace or floodplain units of sand and gravel are also present in the park area (Becker et al. 2007). These types of aquifers tend to recharge rapidly and are particularly vulnerable to contamination due to surficial land use of such wastes as fertilizers, pesticides, manure, oil and gas from roadways, etc.

Paleontological Resources

Fossil resources present opportunities for education, interpretation, and scientific research in the park. As part of a compiled report for all Northeast Temperate Network parks, Tweet et al. (2010) summarized the paleontological resources present within the park as well as those units that may potentially contain fossils. The unconsolidated Quaternary sediments of Marsh-Billings-Rockefeller National Historical Park include Pleistocene glacial deposits (geologic map units ow, ka, kt, gm, ti, and tt) and Holocene river, floodplain, and wetland deposits (geologic map units al, af, ft, and pm) (DeSimone 2006). Of these, the peat and muck deposits (geologic map unit pm) from wetlands and swamps contain organic material and may contain important fossil resources (Tweet et al. 2010). Deposits associated with The Pogue, including marl (lime-rich mudstone), are known to be fossiliferous. Fossiliferous Holocene-age marl in Vermont is often called shell marl, as it is composed of the remains of freshwater bivalves and gastropods (Tweet et al. 2010). Historically, it was valued as a fertilizer (Thompson 1853). Marl beds often form under peat. The location that would eventually become The Pogue contained rich marl and overlying peat deposits (Hitchcock et al. 1861). Marl pieces containing plant remains were collected by a seasonal ranger from the vicinity of The Pogue (K. Jones, park ecologist, and C. Marts, park resource manager, personal communication, January and February 2010 [from Tweet et al. 2010]). These specimens are currently part of the park's collections (MABI 4331) and include imprints of veined leaves, twigs, and grass stems (L. Anderson, park museum curator, personal communication, September 2009 [from Tweet et al. 2010]).

According to Tweet et al. (2010), potential exists for the discovery of additional Quaternary fossils at the park. These fossils would likely be associated with glacial deposits and postglacial ponds and may include spores, plants, snails, crustaceans, and fish, as well as large mammals. Some 30 km (18 mi) southwest of the park, Louis Agassiz discovered the remains of a mammoth or mastodon in 1848 (Johnson 1998; Tweet et al. 2010). There is also some slight potential for the metamorphosed Silurian Waits River Formation and Devonian Gile Mountain Formation to contain fossils. Elsewhere, the Waits River Formation (localities near Newport, Berlin Corners, and Woodbury, Vermont) contains sparse cephalopods, graptolites, and plants, whereas the Gile Mountain Formation (Westmore, Vermont area) contains corals, trilobites, and crinoids (Doll 1984; Tweet et al. 2010).

The different families that inhabited the settlement at the park were noteworthy collectors of natural specimens from all over the country. Among their collections is a specimen of the perch-like fish *Priscacara liops* (MABI 3940) in a piece of limestone from the approximately 50 million-year-old (Eocene) Green River Formation of Wyoming (L. Anderson, personal communication, September 2009 [from Tweet et al. 2010]). Fossil Butte National Monument (Kemmerer, Wyoming; http://www.nps.gov/fobu) interprets the geology and paleontology of the Green River Formation. According to A. Aase (Fossil Butte National Monument museum specialist, personal communication to Marsh-Billings-Rockefeller National Historical Park, October 2008 [from Tweet et al. 2010]), the style of fossil preparation indicates the fossil was prepared sometime between the late 1800s and early 1900s, suggesting it was obtained by the Billings or Rockefeller families.

Santucci et al. (2009) present more information on paleontological resource management and monitoring strategies including five vital signs: 1) erosion (geologic factors), 2) erosion (climatic factors), 3) geohazards, 4) hydrology/bathymetry, and 5) human access/public use.

Karst Dissolution

Karst processes act, to a minor degree, on the landscape at Marsh-Billings-Rockefeller National Historical Park. Karstification involves the processes of chemical erosion and weathering of soluble limestone or dolomite (carbonate rocks) (Palmer, 1981). Limestones readily dissolve in acidic solutions (carbonic acid). The carbon dioxide necessary to naturally form carbonic acid comes from the atmosphere. However, it is concentrated in the soil due to microbial degradation of organic material increasing the carbon dioxide pressures and therefore the solubility in pure water (White 1988). The more saturated the water is with carbon dioxide, the more ability the groundwater will have to dissolve limestone (White 1988). Karst features have not developed to any appreciable extent, but there are local solution pits (Thornberry-Ehrlich 2007). Solution most likely occurs in the punky-weathering (semi-indurated, friable) sandy marble of the Silurian Waits River Formation, and some minor limestone beds in the Gile Mountain Formation. These formations underlie most of the park area as indicated by Dg and Sw geologic map units (Thompson 2006; 2007).

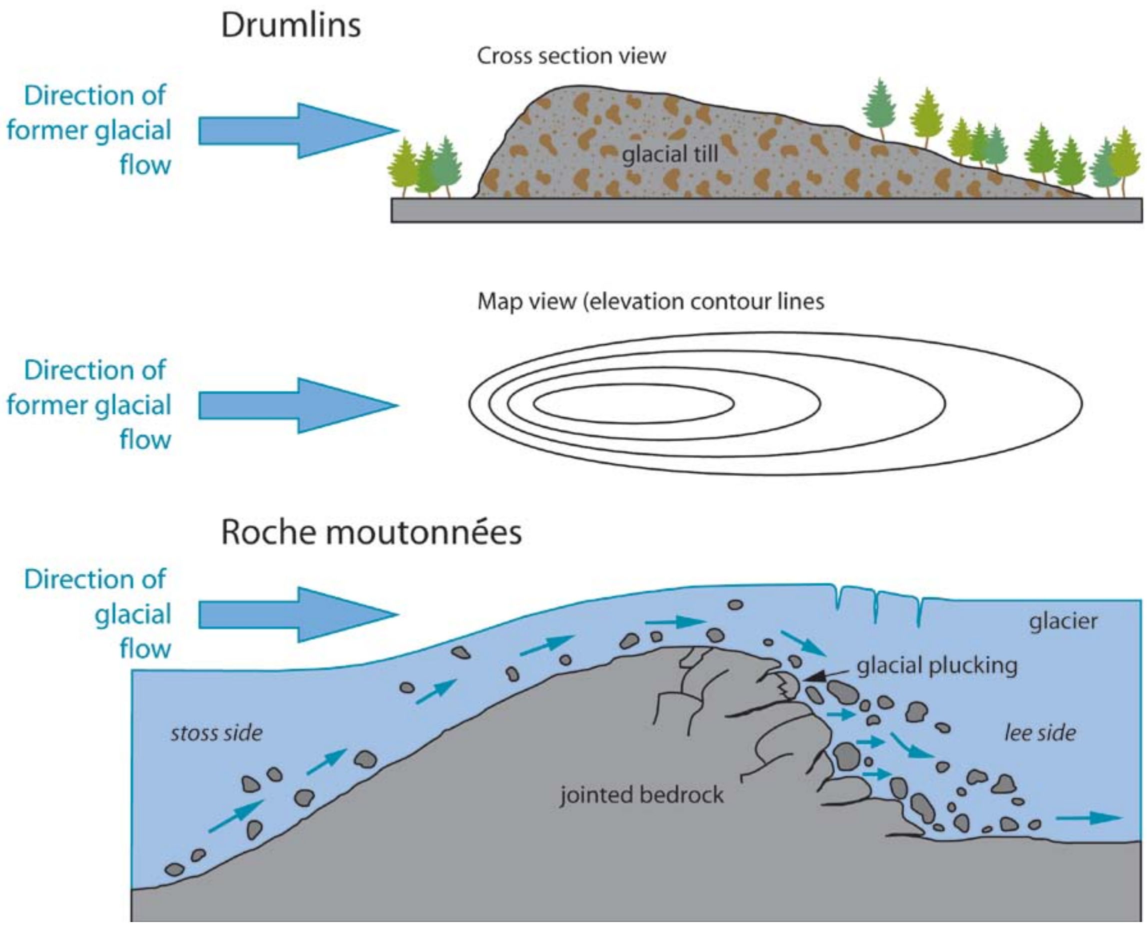


Figure 7. Drumlin and roche moutonnée formation. Note the difference in resulting topography versus glacial flow direction. Glacial plucking that forms a steep lee side of the roche moutonnée. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Brooklyn College (http://depthome.brooklyn.cuny.edu/geology/core332/central.htm). Accessed 17 January 2011.

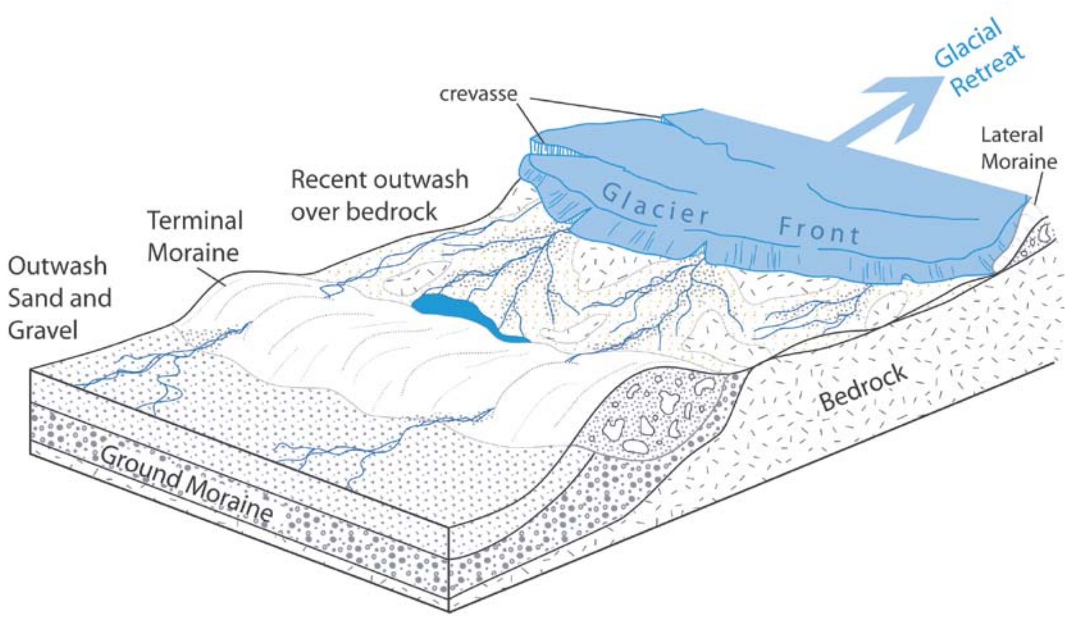


Figure 8. Diagrammatic view of a retreating glacier with a recent terminal moraine and a broad space between the moraine and the glacier front. Note the variety of glacial deposits including the layers of till, ground moraine, and outwash (geologic map units tt, gm, and ow, respectively). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

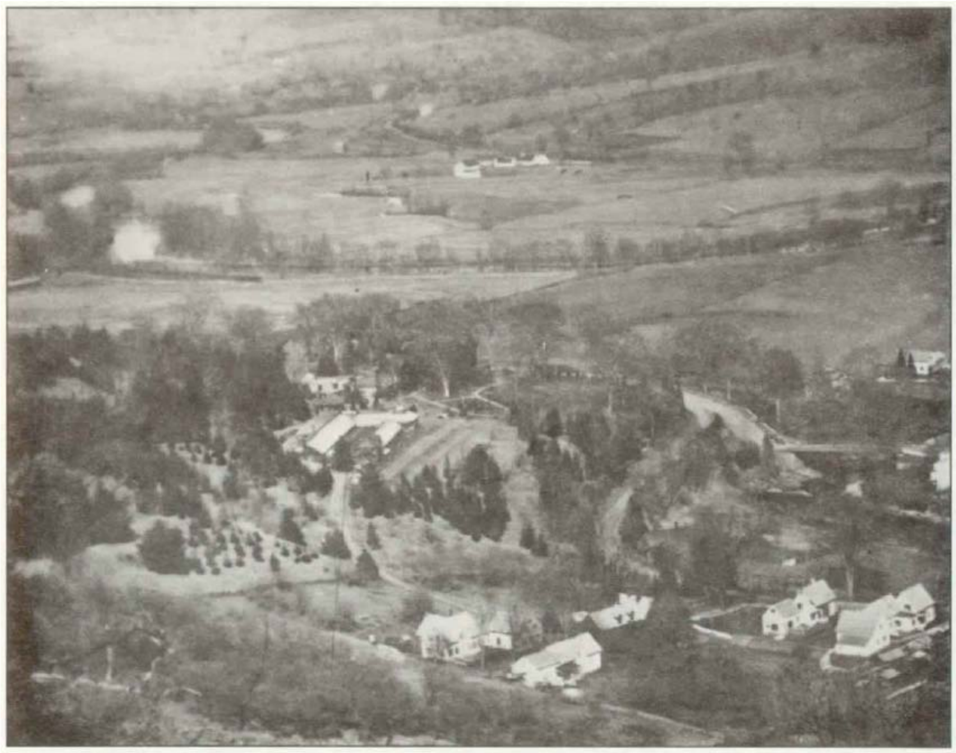


Figure 9. Historic photograph of the Mansion, grounds, and floodplain meadow from the heights of Mount Tom ca. 1886. Note the presence of newly planted trees on the flanks of the mountain. Photograph is figure 20 from Foulds et al. (1994) obtained from the Woodstock Historical Society.

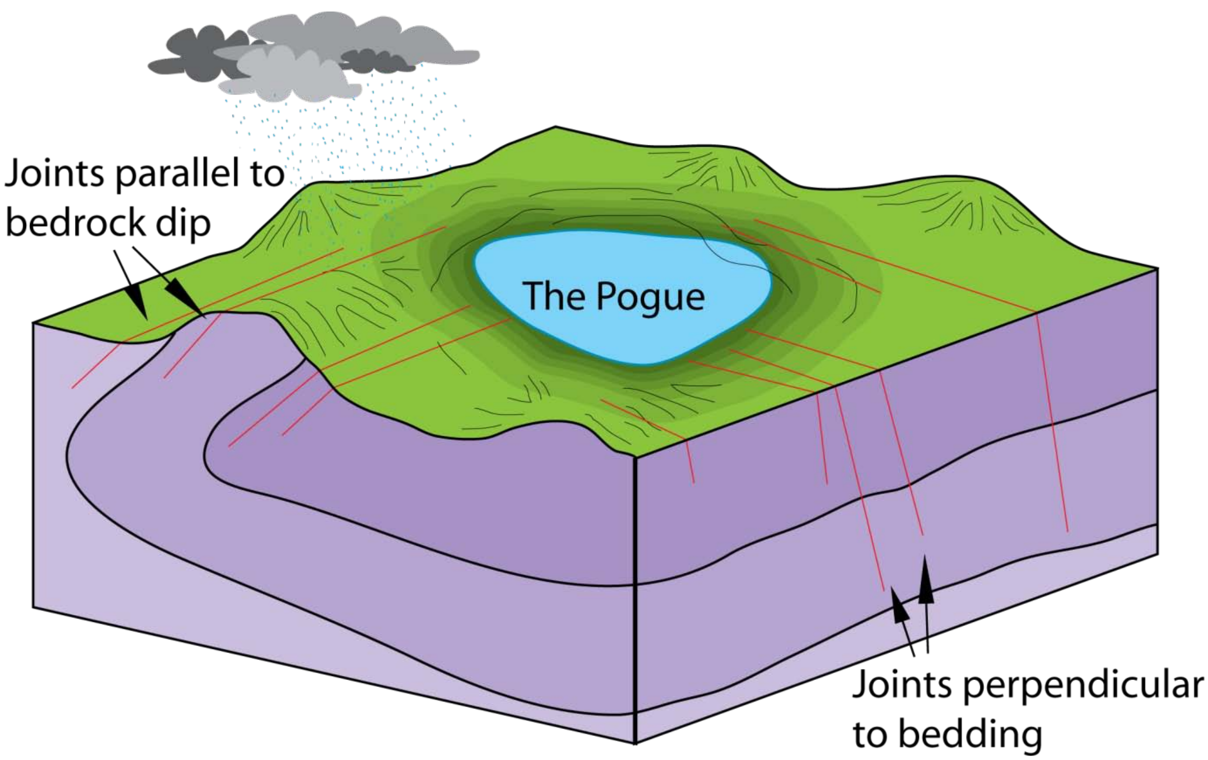


Figure 10. Diagrammatic view of joints orientations through the bedrock beneath the park. Note the location of The Pogue where the joints intersect. Such jointed bedrock was plucked by glaciers on the lee side of a roche moutonnée forming a shallow depression that would later be filled in to form The Pogue. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Marsh-Billings-Rockefeller National Historical Park, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The geologic history of Marsh-Billings-Rockefeller National Historical Park includes several major mountain-building events (orogenies) that led to the formation of the Appalachian Mountains and the assembly of the supercontinent Pangaea hundreds of millions of years ago. Much more recently, during the ice ages (within the past 2 million years), glacial ice sculpted the landscape. The geologic history reflected in rocks in and around the park spans from the Ordovician (approximately 480 million years ago) to the present (fig. 11).

Proterozoic Eon (2,500–542 million years ago): Ancient Mountain Building and Iapetus Ocean Formation

The Green Mountain massif (now a regional topographic and structural feature) refers to the rigid 1.1–1.4 billion year old rocks in the core of the Green Mountains in the southern half of Vermont (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). These and other rocks of the Grenville Province, more than 20 km (12 mi) west of the park (figs. 2 and 4), form an area deformed and metamorphosed during the Grenville Orogeny, over one billion years ago (Karabinos et al. 1999). These ancient rocks were progressively shifted, deformed, and metamorphosed by the tectonic forces responsible for the formation of the younger Appalachian Mountains, described below (Doolan 1996). As an illustration of just how much rock from this time period is now missing, rocks metamorphosed during the Grenville Orogeny—now exposed at the surface—may have been buried beneath 35 km (22 mi) of rock (Doolan 1996).

Approximately 590 million years ago, continental rifting in the area began to break up a supercontinent called Rodinia. This left behind a subcontinent called Laurentia on the west side of the rift (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). This rifting caused the rocks of the Grenville Province to become the eastern margin of the ancient North American continent for nearly 100 million years (Kim and Wunsch 2009). Between 580 and 560 million years ago, rifting in northern Vermont thinned the lithosphere and was accompanied by volcanic eruptions. In central Vermont, volcanism was relatively minor and synchronous with large amounts of coarse-grained sediments being shed into rift basins as alluvial fans along the edges of steep-sided valley walls; these sediments eroded from highland areas east and west of central Vermont (Doolan 1996). As rifting progressed, an ocean basin opened that eventually became the Iapetus Ocean (figs. 12A and 13).

Paleozoic Era (542–251 million years ago): Building the Appalachians and Assembling Pangaea

At the dawn of the Paleozoic Era, continued rifting, subsidence and marine incursion established a basin where marine sediments were deposited, persisting for approximately 100 million years (fig. 12B) (Doolan 1996). The ancient coastline of Vermont was blanketed with deposits of beach and tidal-flat sands (later metamorphosed into quartzite), which are sporadically exposed along the full length of Vermont although not within the park area. Their deposition coincided with the opening of the Iapetus Ocean (fig. 13) (Doll et al. 1961; Doolan 1996). Other marine deposits included carbonates deposited in shallow marine tidal-flats and later deposition of sandstones (Mehrtens 1985; Doolan 1996). The deposition of carbonates continued into the Ordovician Period as part of a well-developed Cambrian-Ordovician shallow ocean platform adjacent to the continent. These deposits are exposed in western Vermont (Doolan 1996).

The ancient Grenville continental margin persisted until approximately 510 million years ago, when geologic forces changed from extension and spreading to convergence (Kim and Wunsch 2009). The Iapetus Ocean basin began to shrink. Convergence and subduction within the basin created volcanic island arcs. The oldest volcanic arc rocks in New England are approximately 500 million years old. Sedimentation on the Laurentian margin continued (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011).

Rocks east of the Green Mountain province formed after the development of the eastern continental margin of ancient North America (Doolan 1996). This margin was inundated by rising sea level and then destroyed by the onset of the Taconic Orogeny. The Taconic Orogeny began during the Ordovician Period (approximately 488 to 440 million years ago). It involved the collision of numerous volcanic island arcs with the eastern Laurentian margin. The timing, extent, and exact nature of collisions between numerous volcanic arcs and the North American continent during the Taconic Orogeny is actively debated and the subject of much study. In general, the Taconic Orogeny involved the collision of one or more volcanic arcs with the North American continent, subduction of oceanic crust, and the eventual closing of the Iapetus Ocean (fig. 13). Ocean basin sediments were disrupted and in some cases transported long distances (tens of kilometers) to the west by thrust faults. Deep water sediments (now slates in the western-central Vermont Taconic Mountains) were transported by thrust faults onto the Cambrian-Ordovician carbonate platform that formed on the continental margin (Doolan 1996). Volcanic arcs formed above subduction zones and fragments of crust that formed elsewhere (terranes) were accreted to the North American craton (Laurentia). As a result of accretion the eastern margin of the continent shifted further eastward and a mountain range developed (figs. 12C and 12D) (Doolan 1996; Kim and Wunsch 2009). The Ordovician Barnard volcanic member of the Missisquoi Formation, or Barnard Gneiss (geologic map unit Ob) from Thompson (2006), is the oldest unit that is exposed in rocks adjacent to Marsh-Billings-Rockefeller National Historical Park. This unit primarily contains interbedded light- and dark-colored metamorphosed volcanic rocks, probably associated with volcanic arcs that were active as they collided with the continent (see below) with minor metamorphosed sedimentary rocks such as schist and phyllite (see Map Unit Properties Table) (Chang et al. 1965).

Among the volcanic arcs that formed within the Iapetus Ocean were the Shelburne Falls and Bronson Hill arcs. The Shelburne Falls volcanic arc formed above an subduction zone between approximately 500 and 470 million years ago off the eastern margin of North America (fig. 14A). It collided with the Laurentian margin approximately 470–460 million years ago during the Taconic Orogeny. Later, The Bronson Hill Arc formed above a new subduction zone. Volcanism was active between approximately 455 and 440 million years ago (fig. 14B) (Karabinos et al. 2003). The Bronson Hill arc collided with the Laurentian margin and Shelburne Falls arc in the Silurian Period (figs. 12C, 12D, 14C, and 14D) (Kim and Wunsch 2009; J. Kim, geologist, Vermont Geological Survey, written communication, May 2011).

After the Taconic Orogeny ended around 440 million years ago, the majority of Vermont was situated on the western shore of the Iapetus Ocean basin. At this time, lands east of the Green Mountains began to stretch and subside (Doolan 1996; J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). One major geologic feature of the Connecticut River Valley in New Hampshire and Vermont is the Connecticut Valley-Gaspé Trough between the Shelburne Falls volcanic arc on the west and the Bronson Hill Arc on the east (fig. 12C) (Karabinos et al. 2003; Rankin et al. 2007). The Connecticut Valley-Gaspé Trough formed between the accreted Shelburne Falls and Bronson Hill arcs (fig. 14C) during the Silurian Period (approximately 444 to 416 million years ago) as a result of temporary rifting or extensional episodes between periods of collisions or compressional events (fig. 12E) (Doolan 1996; Karabinos et al. 2003). This elongate basin extended from New England and Quebec as far north as the Gaspé Peninsula (Doolan 1996). A regional unconformity developed as a result of the opening of the trough (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). The basin filled with sediments shed from the western highlands that eventually became shale, limestone, and sandstone (Doolan 1996). Overlying the Barnard Gneiss, the Silurian Shaw Mountain Formation (geologic map unit Ss) contains quartz conglomerate, quartzite and quartz-mica schists. This unit commonly occurs as loose blocks of distinctive quartz conglomerate. The Silurian Northfield Formation (geologic map units Sn and Snc) contains black phyllite, impure quartzite, and impure meta-limestone and grades upwards into the Waits River Formation (geologic map units Sw, Swm, Swmc, Sws, and Swr) (Chang et al. 1965).

Much of the bedrock exposed in the park area was deposited in the rifted Connecticut Valley-Gaspé Trough including the Mt. Tom member of the Waits River Formation (geologic map unit Swm) (Thompson 2006). A seaway intermittently filled the trough. Sedimentary rocks deposited within the trough began as turbidites, formed as underwater debris flows (Naylor 1989). Thick-bedded, impure, metamorphosed limestone is the primary constituent of the Waits River Formation (Chang et al. 1965). Located between the lithologically similar Waits River and younger Gile Mountain formations (geologic map unit Dg), the interbedded amphibolite and schist of the Standing Pond Volcanics (geologic map units Ssp and Sspc) form an important, regional horizon marker bed, correlative over long distances. The Standing Pond Volcanics, exposed in the eastern portion of the park date back to the Silurian and were deposited during intermittent volcanic episodes within the trough (Thompson 2006). The intricate loops of the map pattern of the Standing Pond Volcanics provide excellent evidence for interpreting fold structures. The narrow band of volcanics to the northeast outline (map view) the traces of two large recumbent folds whose axial surfaces (areas of maximum bending) arch over the Pomfret dome located east of the park (Chang et al. 1965).

By the early Devonian Period, about 375 million years ago, landmasses were converging again along the eastern seaboard of ancient North America and the oceanic basin was rapidly disappearing (Doolan 1996). This marked the onset of the Acadian Orogeny (fig. 12F) (Karabinos et al. 1999). This is the most important Paleozoic orogenic event affecting rocks in eastern Vermont with accompanying metamorphism and igneous intrusions (Chang 1950). During this mountain building event intense deformation and metamorphism created the mineral assemblages and fabrics found in the park rocks (see Map Unit Properties Table). The Green Mountains were arched into an anticlinorium and domes such as the Chester and Athens domes, just west of Marsh-Billings-Rockefeller National Historical Park, formed during the Acadian Orogeny (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011).

During the Acadian Orogeny, the final assembly of the various small continental blocks (terranes) occurred (Doolan 1996). In Vermont, following Early Devonian sedimentation, the earliest stages of the Acadian Orogeny produced west-directed folds with tens of kilometers of transport (Thompson et al. 1968; Robinson 2008). Molten material produced during the Acadian Orogeny later cooled into large quantities of granite Vermont is now famous for. The metamorphic rocks, schist and quartzite, of the Gile Mountain Formation (geologic map unit Dg), exposed in the eastern portions of the park, dates back to the Devonian as does some local granitic sills (geologic map unit Dbg) intruded in layers parallel to the fabric of the surrounding bedrock (Thompson 2006). The strong north to south orientation of primary bedding (strike), fold axes, metamorphic foliation, schistosity, cleavage, and lineations visible in the rocks of the park area (Chang et al. 1965) formed during the Acadian Orogeny.

Also during the Acadian Orogeny, compressional forces deformed and folded the sediments deposited in the Connecticut Valley-Gaspé Trough into "nappes." A nappe is a large, sheetlike body of rock that has been moved more than a few kilometers from its original position during continental plate collisions (fig. 15). During the formation of a nappe, large folds are sheared so much that they fold back over on themselves and typically break apart forming a large-scale, over-turned or recumbent (pushed over on its side) fold structure. Later, Acadian events may have locally involved further deformation manifested as backfolding. Late Acadian doming then deformed all older structures in the area (Thompson 2007). Marsh-Billings-Rockefeller National Historical Park sits between two such domes—the northeastern flank of the Chester dome and the southwestern flank of the Pomfret dome (figs. 2, 3, and 4).

Later in the Paleozoic, approximately 315 to 295 million years ago, the African continent collided with the North American continent during the Alleghany Orogeny. Although some associated metamorphism occurred in southeastern Vermont, New Hampshire, Massachusetts, Maine, and Connecticut, most of the effects of this collisional event were focused elsewhere, generally in the central and southern Appalachian Mountains (Doolan 1996; J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). At this time, Vermont was located in the core of the assembled supercontinent, Pangaea, until extensional forces began to pull the continent apart at the dawn of the Mesozoic Era (fig. 13).

Mesozoic Era (251–65.5 million years ago): Pangaea Separation, Atlantic Ocean Formation, and Appalachian Mountain Erosion

Rifting began pulling Pangaea apart during the Triassic and Jurassic periods, forming the Atlantic Ocean and separating the modern continents of Africa and North and South America (fig. 13) (Thompson et al. 1993). The Connecticut Valley of Massachusetts and Connecticut is a vestige (a failed rift arm) of this rifting event (J. Kim, geologist, Vermont Geological Survey, written communication, May 2011). This rifting formed many normal fault-bounded extensional basins along eastern North America. Steeply dipping normal faults formed the boundaries of these basins, which quickly filled with sediment eroded from the surrounding highlands. In the park area, several normal faults and Mesozoic basaltic dikes (geologic map unit MZb) reflect this extensional tectonic setting (Thompson et al. 1993; Thompson 2006). Following the Mesozoic rifting, the area including Vermont became relatively passive. One exception was the intrusion of igneous rocks around 122 million years ago. These rocks were later exposed by erosion on Mount Ascutney, located 20 km (12 mi) south of the park (Schniederman 1989; Thompson et al. 1993). Locally, dark gray basalt dikes cut through adjacent metamorphosed bedrock. Intruded during the Mesozoic; they are among the youngest bedrock units in the park area (Chang et al. 1965). Erosion caused by the incision of local rivers began to wear away the mountains formed during the Paleozoic orogenic events. Weathering and erosion dominate the geologic history of the park area throughout the Mesozoic and most of the following Cenozoic Era.

Cenozoic Era (the past 65.5 million years): Appalachian Mountain Erosion and Ice Age Glaciation

Repeated glaciations (ice ages) over approximately the last 2 million years scoured and reshaped the preexisting topography of most of New England. Thick sheets of ice repeatedly advanced and retreated over the Vermont landscape (Doolan 1996). Evidence of glaciation and ice movement are present as striations crossing the bedrock. Striations in the park area (often on hard, white vein quartz units) indicate glacier movement directions ranging from 160° (south south-east) to 210° (south west) (Richardson 1927). Although glaciers advanced repeatedly over the area during the ice ages, the most recent glacial advance of the area was by the Hudson-Champlain lobe of the Laurentide Ice Sheet which reached its maximum extent between about 26,000 and 18,000 years ago (fig. 16) (Dyke and Prest 1987; Thornberry-Ehrlich 2007). It obscured and overprinted previous glacial signatures, including striations and moraine deposits, and deposited widespread glacial sediments up to tens of meters thick. The interbedded schist and marble of the Waits Formation (geologic map unit Sw) underlying much of the park, was easily abraded by glacier ice and sculpted into rounded hills (Becker 2007).

As the glacial ice sheets retreated, vast glacial lakes of meltwater formed in valleys impounded by ice and sediment. The largest of these in New England was Glacial Lake Hitchcock, which inundated what is now the Connecticut River Valley and adjoining tributary valleys (fig. 17). Glacial Lake Hitchcock first formed about 17,900 years ago in the lower valley. Its impoundment was located south of Marsh-Billings-Rockefeller National Historical Park in southern Massachusetts near Middletown. As the lake filled, it extended northward as the glacial ice sheets continued melting and retreating. The slopes of Marsh-Billings-Rockefeller National Historical Park were not free of glacial ice (deglaciated) until after 14,700 years ago, at which time Glacial Lake Hitchcock occupied the nearby section of the Connecticut River Valley. It persisted there until about 12,600 years ago, when it drained (Benner et al. 2009). The lake itself never inundated the park area, but might have had some influence on the development of the Ottauquechee River and its tributaries, which would have drained into the lake.

After the glaciers melted away from eastern Vermont, local rivers incised channels through the glacial sediments. Erosion is continually subduing the topography. Throughout the Holocene, deposits of peat, muck, fossiliferous marl, alluvium, river terrace, and floodplain deposits (geologic map units pm, al, and ft) accumulated on the park's landscape (DeSimone 2006).

Soils continued to develop on the landscape. The town of Woodstock lends its name to a characteristic soil type found throughout the area that is loamy, shallow (between 20 and 50 cm [8 and 20 in.] deep) and relatively rich in iron, aluminum, and organic carbon (Villars 1990). As an integral component of forest management, forest soils are a vital sign monitored within the park (National Park Service 2011). The geologic history and framework at the park in concert with the climate and soils contribute to the history of forest management and the park's continuing legacy of conservation.

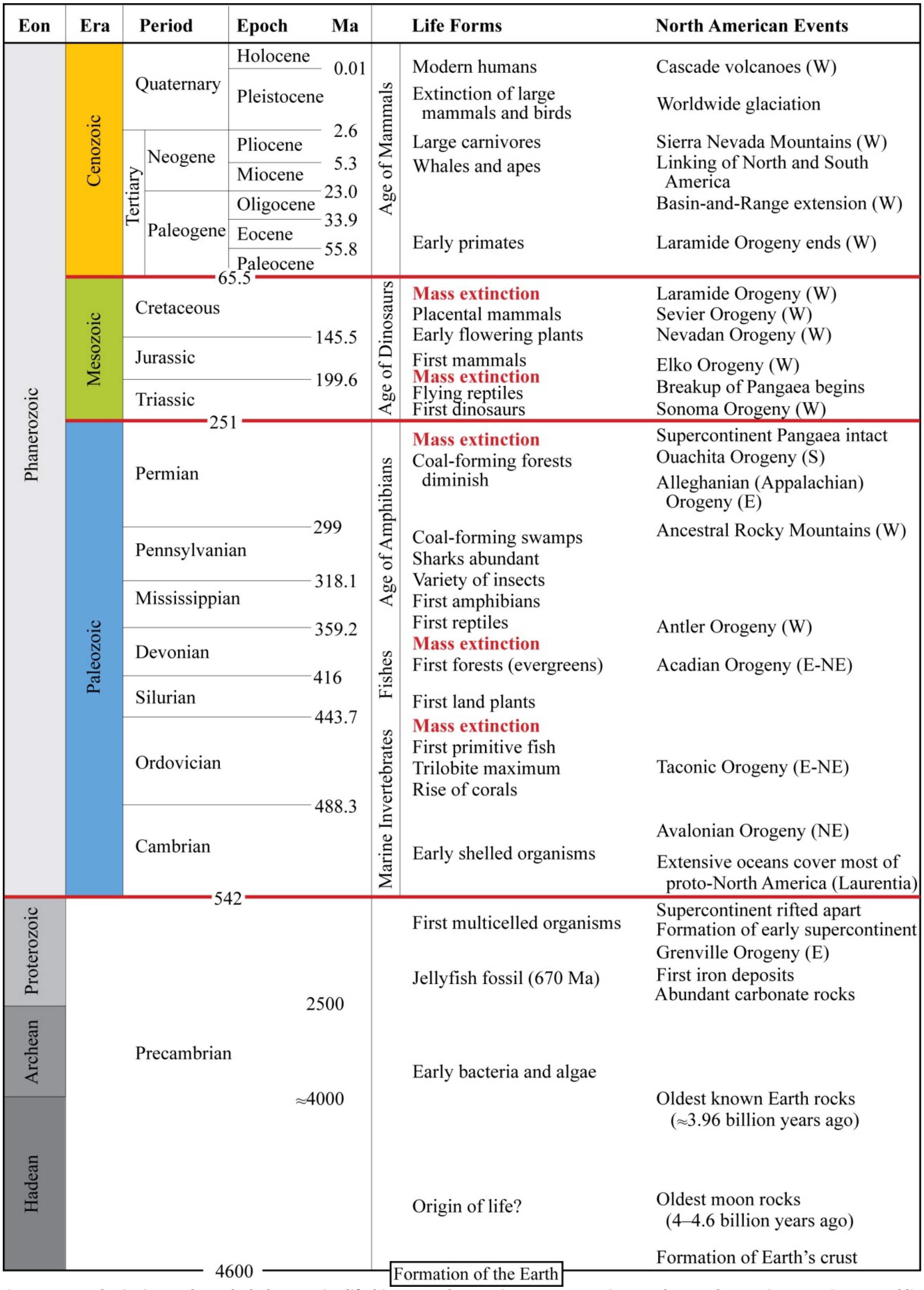


Figure 11. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Graphic by Trista L. Thornberry-Erhlich (Colorado State University) with information from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/view.php?id=25).

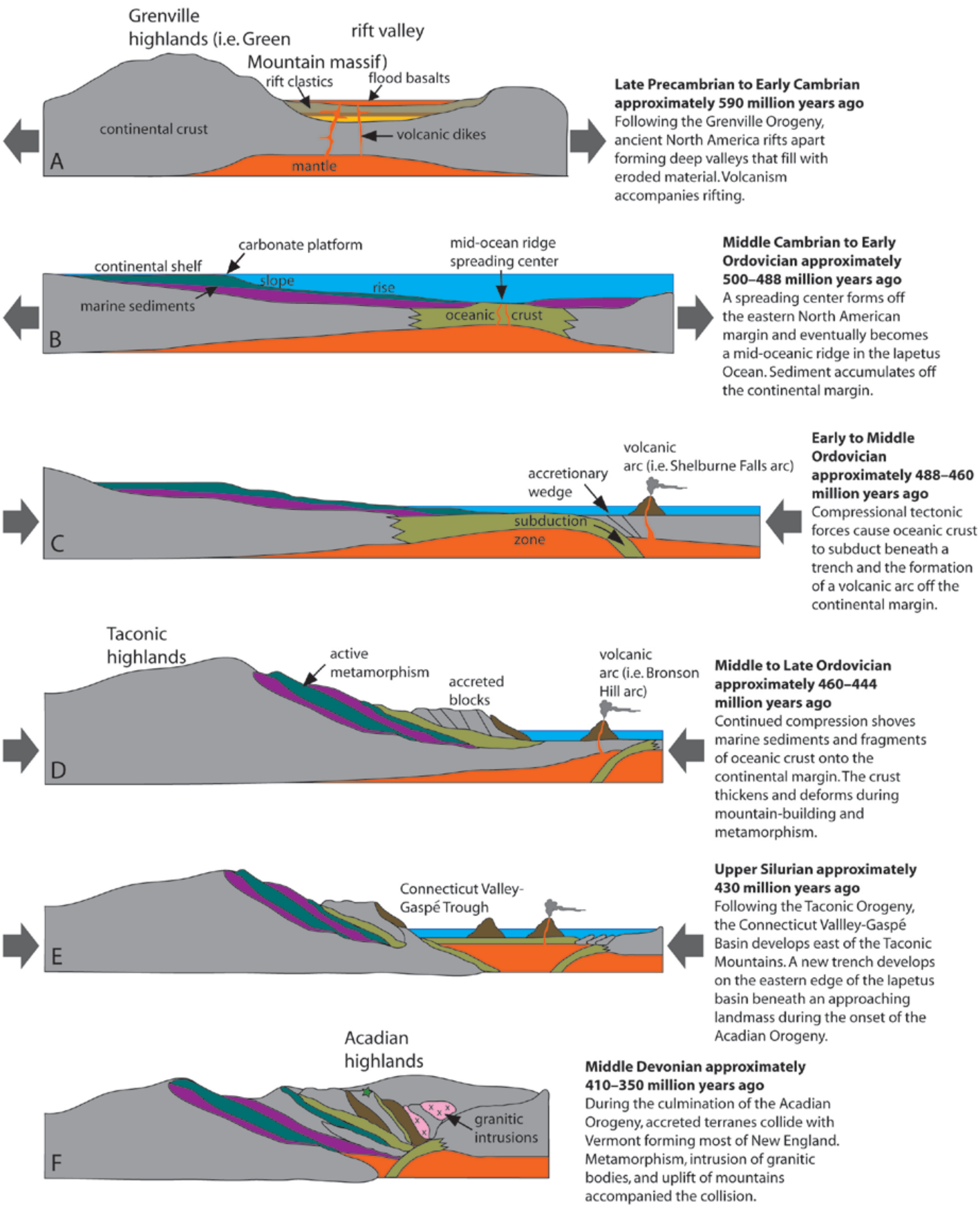


Figure 12. Tectonic evolution of the Vermont area of New England throughout the Paleozoic. Green star on panel F indicates the approximate location of Marsh-Billings-Rockefeller National Historical Park. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from figure 4 in Doolan (1996).

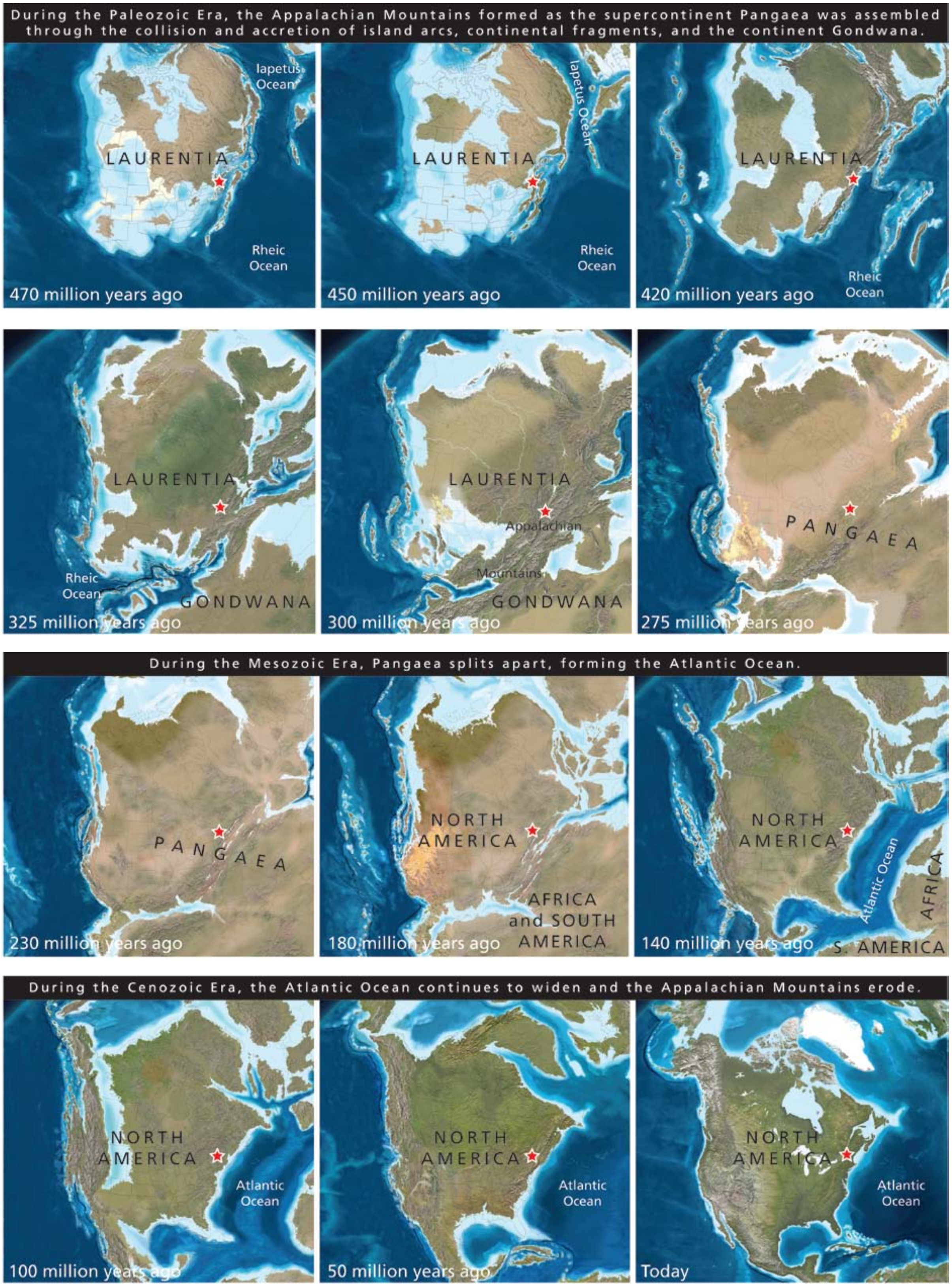


Figure 13. Paleogeography of North America. The bedrock geologic units of Marsh-Billings-Rockefeller are tied to the intense deformation and intrusion of molten material during the formation of the Appalachian Mountains during several Paleozoic orogenies that lead to the assembly of Pangaea. Pangaea began to split apart during the Mesozoic and the Appalachian Mountains began to erode. Today, the Atlantic Ocean continues to widen and erosion has exposed the core of the Appalachian Mountains. Red stars indicate approximate location of Marsh-Billings-Rockefeller National Historical Park. Graphic compiled and annotated by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.) and available online: http://cpgeosystems.com/paleomaps.html.

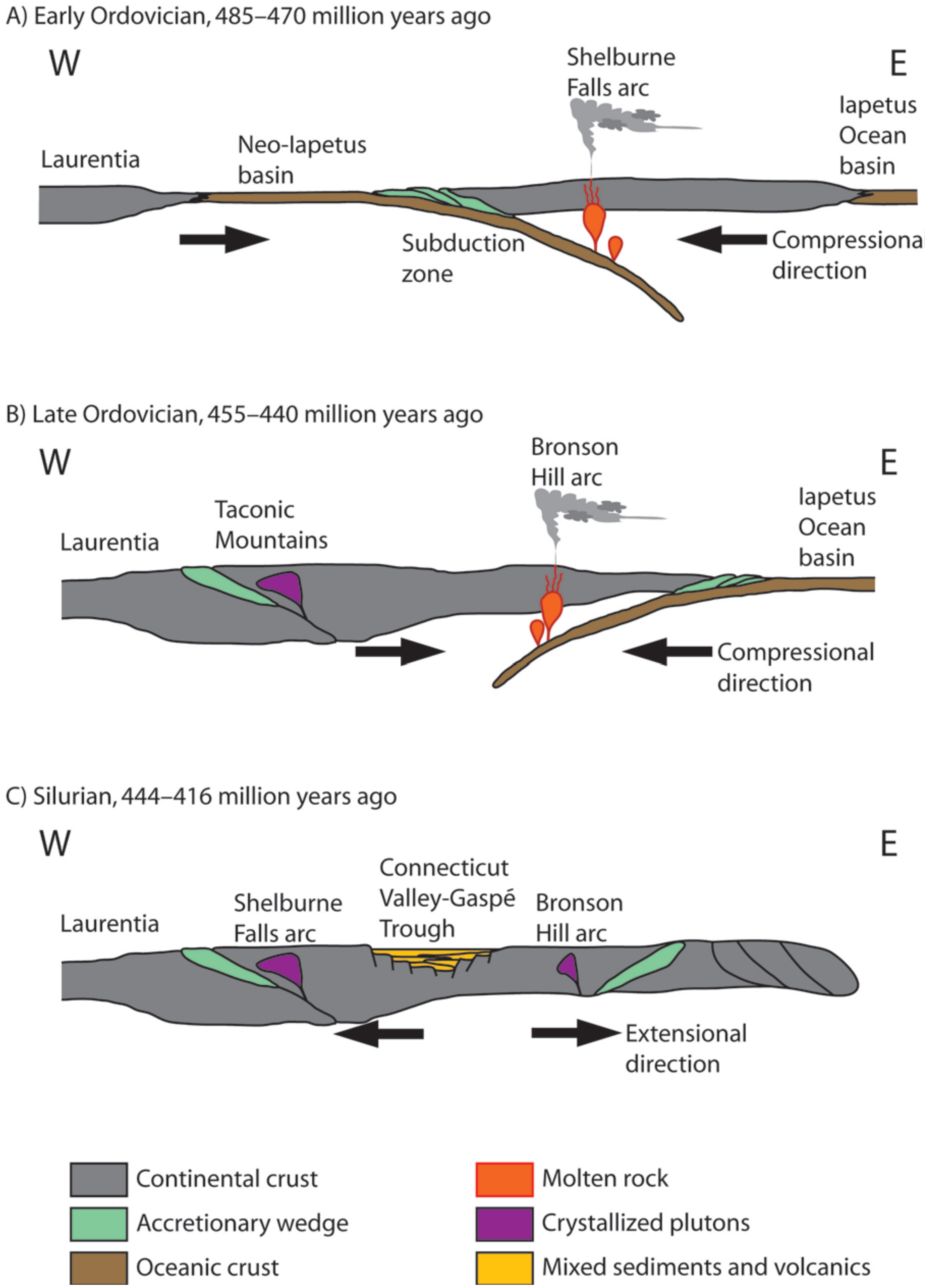


Figure 14. Evolution of the Connecticut Valley-Gaspe Trough between the Shelburne Falls and Bronson Hill arc. E = East; W = West. Marsh-Billings-Rockefeller National Historical Park is located within the trough. Graphic by Trista L. Thornberry-Ehrlich, adapted from figure 5 in Karabinos et al. (1998).

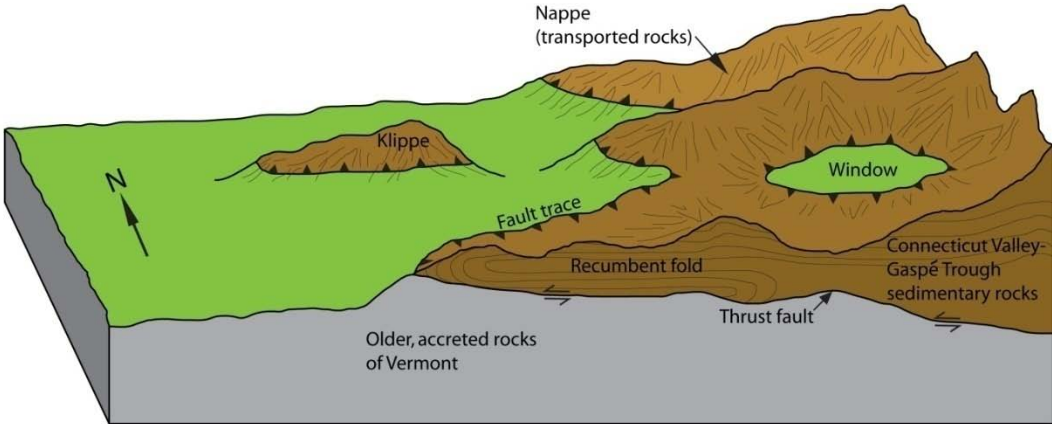


Figure 15. Schematic, cross-sectional view of an eroded nappe structure and recumbent folding at the front of a large thrust sheet. Teeth along faults are on the overriding block. A "nappe" represents rocks transported by a thrust fault over previously accreted rocks. A "window" is an eroded area of thrusted rocks that displays the rocks beneath the thrust sheet. A "klippe" is an erosional remnant or outlier of a nappe. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) adapted from a figure posted to Wikimedia Commons.

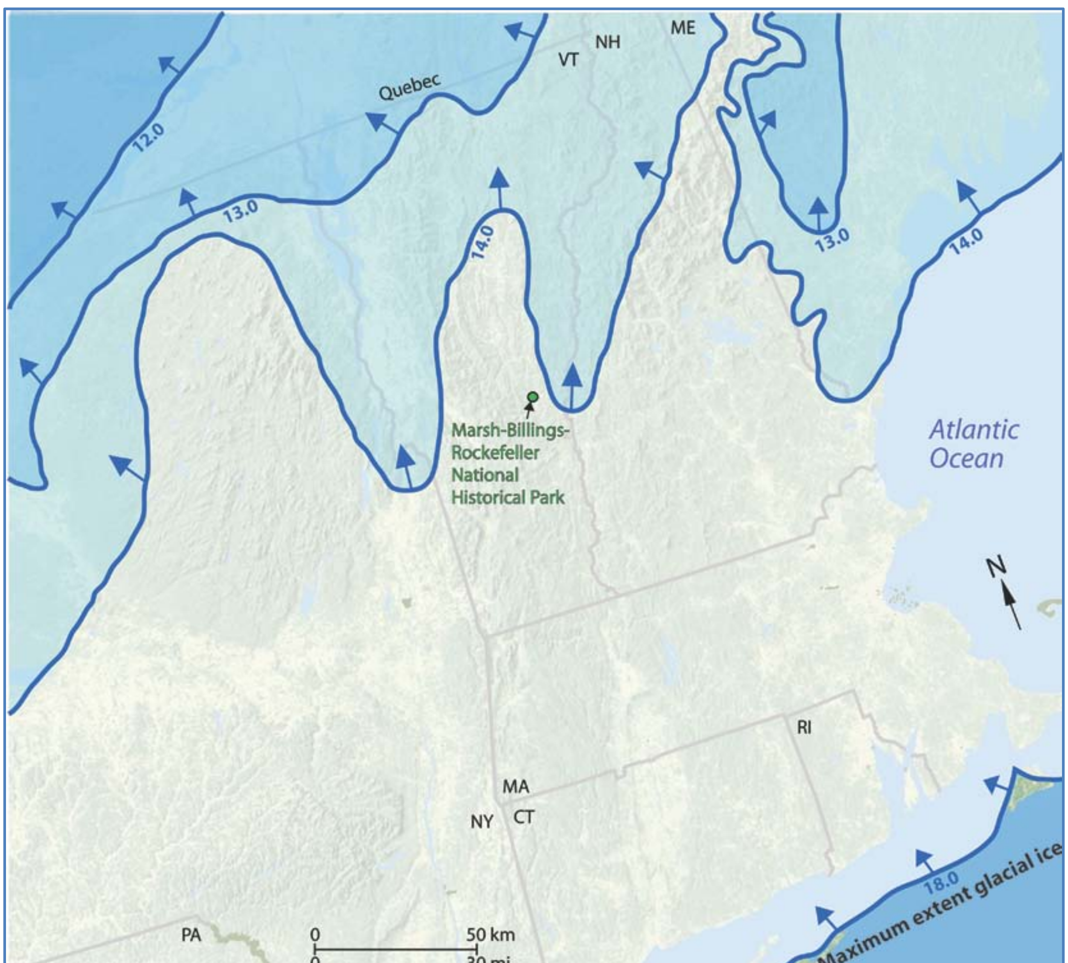


Figure 16. Timing of glacial retreat. This map shows the Wisconsinan and Holocene retreat of the Laurentide Ice Sheet from New England. Blue contours indicate the subsequent ice margins with age in thousands of years. Note the deglaciation of the Marsh-Billings-Rockefeller National Historical Park area (green dot) approximately 14,000 years ago. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) based on information from Dyke and Prest (1987).

Figure 17. Map showing the extent of Glacial Lake Hitchcock drowning the present Connecticut River Valley as the glacial ice sheet melted northward. Marsh-Billings-Rockefeller National Historical Park area (green dot) was just beyond the lake shore. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after Ridge and Larson (1990).

Geologic Map Data

This section summarizes the geologic map data available for Marsh-Billings-Rockefeller National Historical Park. It includes a fold-out geologic map overview and a summary table that lists each map unit displayed on the digital geologic map for the park. Complete GIS data are included on the accompanying CD and are also available at the Geologic Resources Inventory (GRI) publications website: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into the GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to create the digital geologic data for Marsh-Billings-Rockefeller National Historical Park:

Thompson, P. J. 2006. Bedrock Geologic Map of Woodstock, Vermont (scale 1:24,000). (Digital data–Gale, M. and G. Farrugia). Open-File Report VG06-4. Vermont Geological Survey, Waterbury, Vermont, USA.

DeSimone, D. 2006. Surficial Geologic Map of Woodstock, Vermont (scale 1:24,000). (Digital data–Gale, M.). Open-File Report VG06-5. Vermont Geological Survey, Waterbury, Vermont, USA.

These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Marsh-Billings-Rockefeller National Historical Park using data model version 2.0.

GRI digital geologic data for Marsh-Billings-Rockefeller National Historical Park are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select Marsh-Billings-Rockefeller National Historical Park from the unit list. Note that as of September 2011, IRMA is only compatible with the Internet Explorer browser. The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.hlp) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables and map unit descriptions, legends, and other information captured from source maps.
- An ESRI map document file (.mxd) that displays the digital geologic data

Geology data layers in the Marsh-Billings-Rockefeller National Historical Park GIS data.

Data Layer	Code	On Geologic Map Overviews?
Geologic Cross Section and Profile Lines	SEC	No
Aquifers:		
Aquifer Lines	AQL	No
Aquifer Boundaries	AQUA	No
Aquifers	AQU	No
Recharge Potential for Unconfined Aquifers Boundaries	AR1A	No
Recharge Potential for Unconfined Aquifers	AR1	No
Recharge Potential for Bedrock Aquifers Boundaries	AR2A	No
Recharge Potential for Bedrock Aquifers	AR2	No
Surficial Geology:		
Glacial Feature Lines	GFL	No
Depth to Bedrock Contours	CN1	No
Surficial Contacts	SURA	Yes
Surficial Units	SUR	Yes
Bedrock Geology:		
Geologic Observation Localities	GOL	No
Geologic Attitude and Observation Point	ATD	No
Mine Point Features	MIN	No
Linear Geologic Units	GLN	No
Deformation Areas		
Geologic Line Features	GLF	No
Deformation Area Contacts	DEFA	No
Deformation Areas	DEF	No
Geologic Contacts	GLGA	Yes
Geologic Units	GLG	Yes

Note: All data layers may not be visible on the geologic map overview graphic.

Geologic Map Overview

The fold-out geologic map overview displays the GRI digital geologic data draped over aerial imagery of Marsh-Billings-Rockefeller National Historical Park and includes basic geographic information. For graphic clarity and legibility, not all GIS feature classes are included on the overview. The aerial imagery and geographic information are not included with the GRI digital geologic GIS data for the park, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the fold-out map unit properties table correspond to the accompanying digital geologic data. Following overall structure of the report, the table highlights the geologic issues, features, and processes associated with each map unit. The units, their relationships, and the series of events the created them are highlighted in the "Geologic History" section. Please refer to the geologic timescale (fig. 11) for the geologic period and age associated with each unit.

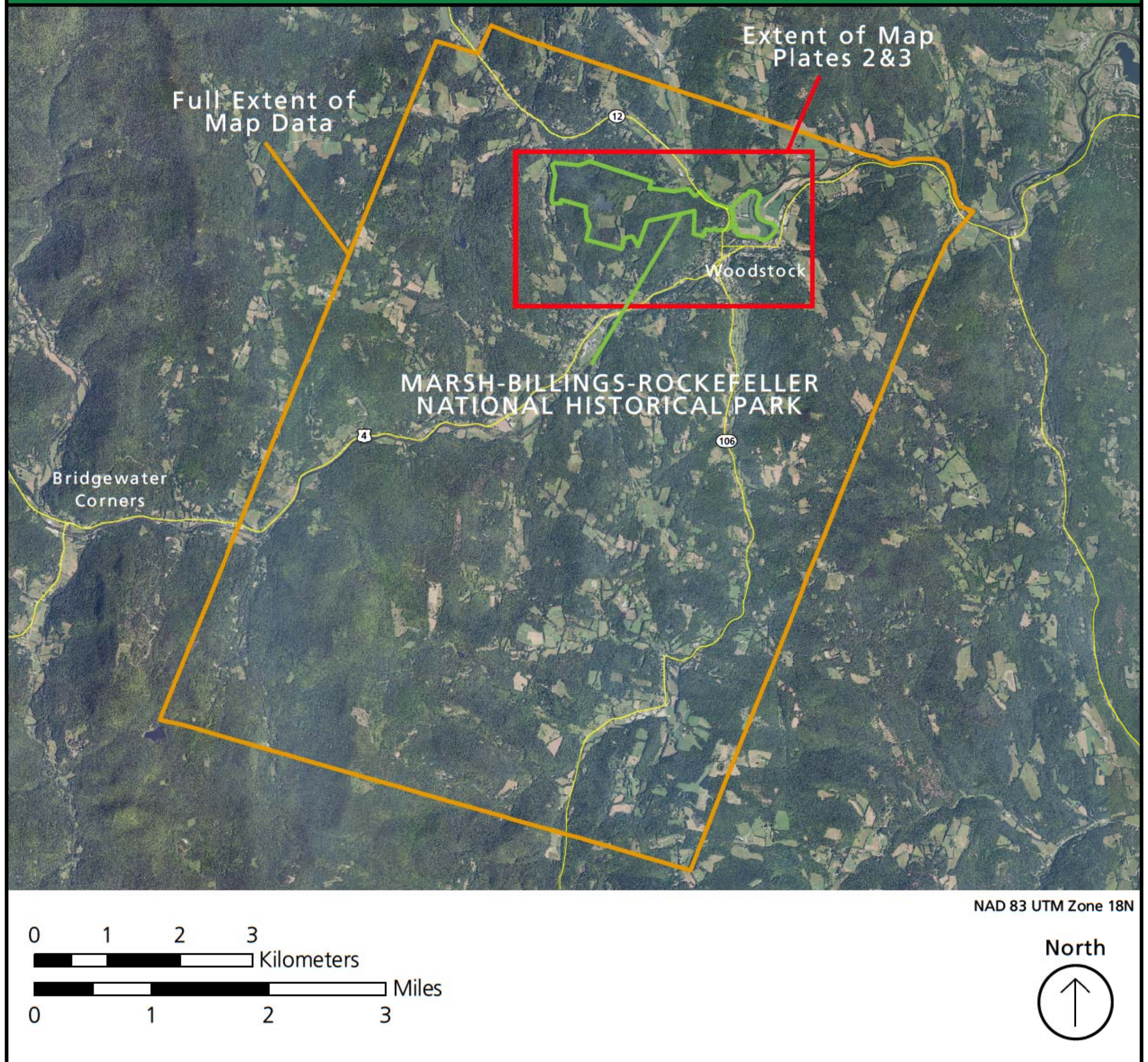
Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations, and ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters /40 feet (horizontally) of their true location.

Please contact GRI with any questions.

Overview of Digital Geologic Data for Marsh-Billings-Rockefeller NHP

Map Plate 1: Extent of Data and Map Plates



NPS Boundary

Surficial Contacts

- known or certain
- map boundary

Surficial Units

- fi - fill
- pm - peat and muck
- al - alluvium
- af - alluvial fan
- ft - fluvial terrace
- ow - outwash
- ka - kame
- kt - kame terrace
- gm - ground moraine
- ti - till
- tt - thin till
- ro - rock outcrop

Geologic Contacts

- concealed
- map boundary

Linear Geologic Units

- qv - Thick quartz vein
- MZb - Basalt dike
- Dbg - Granite sill

Geologic Units

- Dg - Gile Mountain Formation
- Dgc - Gile Mountain Formation, calc-silicates horizon
- Dgh - Gile Mountain Formation, horneblende fascicle schist
- Ssp - Standing Pond Volcanics
- Sspc - Standing Pond Volcanics, calc-silicates horizon
- Sw - Waits River Formation, > 50% calc-silicates
- Swm - Waits River Formation, Mt Tom Member
- Swmc - Waits River Formation, Mt Tom Member, calc-silicates horizon
- Sws - Waits River Formation, 10 to 50% calc-silicates
- Swr - Waits River Formation, rusty schist
- Sn - Northfield Formation
- Snc - Northfield Formation, calc-silicates horizon
- Ss - Shaw Mountain Formation
- Ob - Barnard Gneiss

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters /40 feet (horizontally) of their true location.

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

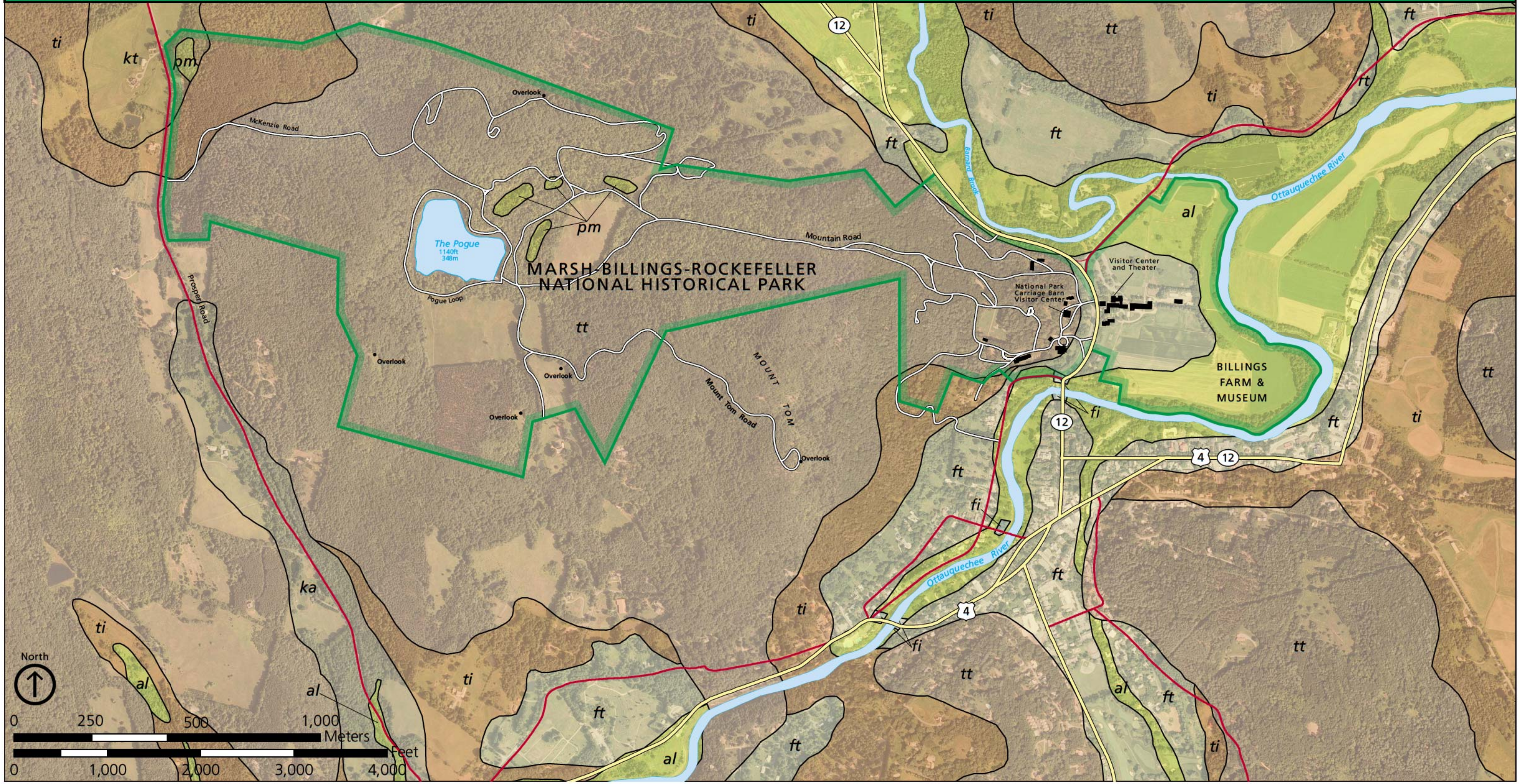
DeSimone, David. 2006. Surficial Geologic Map of Woodstock, Vermont (scale 1:24,000). [Digital data - M. Gale]. Open-File Report VG06-5. Vermont Geological Survey.

Thompson, Peter J. 2006. Bedrock Geologic Map of Woodstock, Vermont (scale 1:24,000). [Digital data M. Gale and G. Farrugia]. Open-File Report VG06-4. Vermont Geological Survey.

Digital geologic data and cross sections for Marsh-Billings-Rockefeller National Historical Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. (Enter "GRI" as the search text and select Marsh- Billings-Rockefeller National Historical Park from the unit list.)

Overview of Digital Geologic Data for Marsh-Billings-Rockefeller NHP

Map Plate 2: Surficial Geology

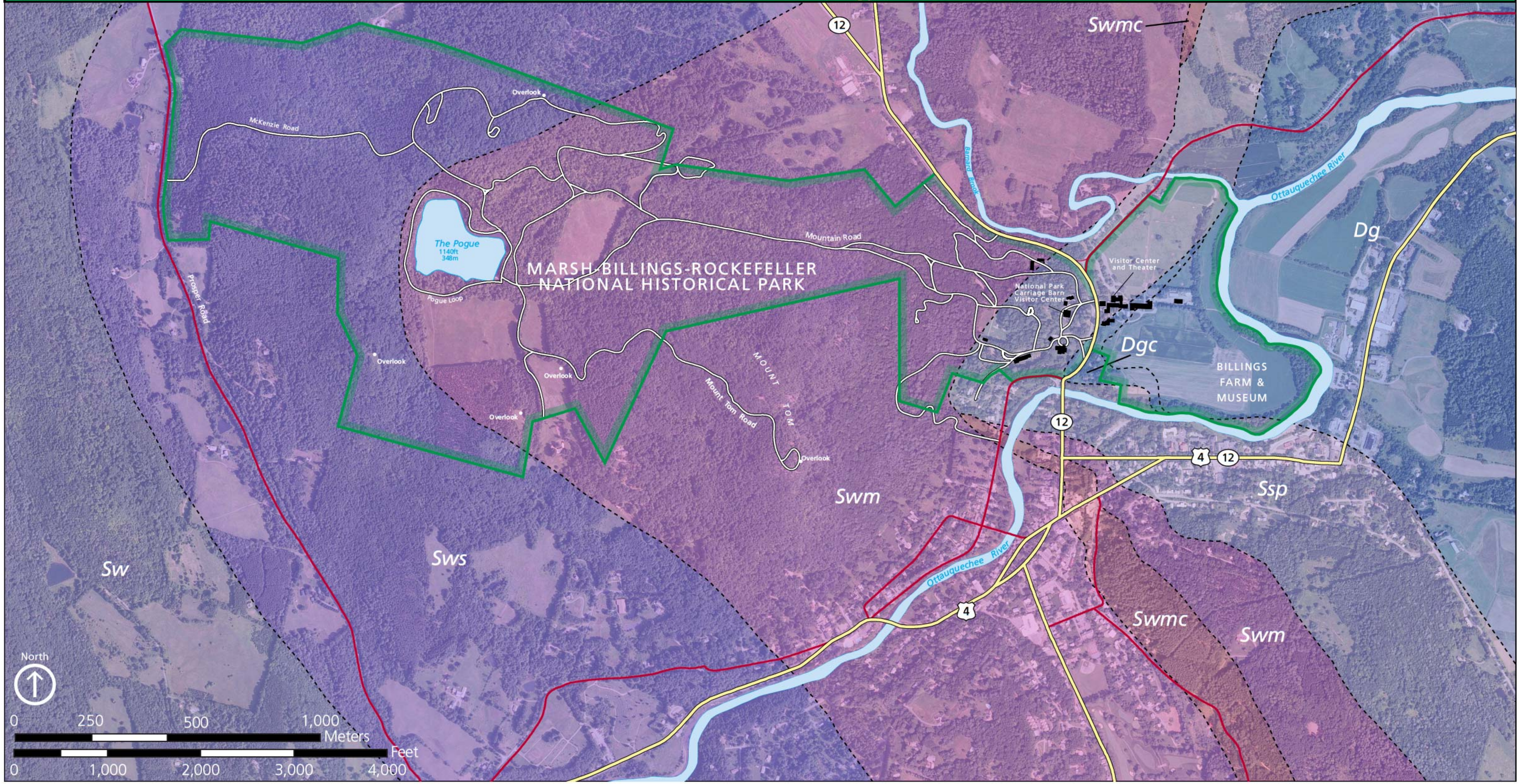


Produced by the Geologic Resources Inventory

September 2011

Overview of Digital Geologic Data for Marsh-Billings-Rockefeller NHP

Map Plate 3: Bedrock Geology



Produced by the Geologic Resources Inventory

September 2011

Map Unit Properties Table: Marsh-Billings-Rockefeller National Historical Park

Gray-shaded rows indicate geologic map units included within the digital geologic data but are not mapped within the park. Colors in the age column are U.S. Geological Survey standard colors.

Age	Unit Name (Symbol)		Features and Description	Erosion Resistance	Suitability for Infrastructure and Potential Geologic Hazards	Cultural Resources	Paleontological Resources	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
HOLOCENE	Surficial Geologic Units	Fill (*fi*) peat and muck (*pm*) alluvium (*al*) alluvial fan (*af*) fluvial terrace (*ft*)	Unit ***fi*** contains various materials used to form rail beds and embankments, fill low-lying areas and provide foundation for road beds. Unit ***pm*** contains organic sediments, silt, and clay primarily in wetlands and swamps. Unit ***al*** consists of fine sand, silt, and gravel associated with riverways. Unit ***af*** is composed of gravel, sand, and silt in poorly sorted, gently to moderately sloping deposits along the base of steep slopes and at stream junctions. Unit ***ft*** consists of fine sand, silt, gravel, and cobbles on perched terraces above the modern stream floodplains. Unit is generally less than 5 m (15 ft) thick and forms flat to gently sloping lands. Units ***pm***, ***al***, and ***ft*** are mapped within the park.	Very low to moderate for ***fi***	Units ***pm*** and ***al*** are associated with low-lying areas prone to flooding and aquifer discharge areas like seeps and springs and should be avoided for infrastructure. Units ***af***, ***ft***, and ***al*** can be a fair to good aquifer if sufficiently thick. Permeability varies in ***af***. Unit ***af*** occurs along the base of steep slopes and is associated with some slumping (mass movement). Unit ***ft*** may be prone to failure on banks above streams. Unit ***ft*** can be sufficiently thick to support conventional septic systems; however, percolation rates are locally variable and ephemerally wet areas are not uncommon.	Forms modern surface and may contain cultural remains associated with the history of the site.	Marl associated with the Pogue is fossiliferous, containing veined leaves, twigs, grass stems; may also contain bivalves and gastropods. Peat and muck may be fossiliferous.	Sand, gravel, silt, clay, cobbles	Units ***pm*** and ***al*** are associated with wetland and riparian habitats. Unit ft supports deep soils (well drained loams suitable for agriculture)	Units record the modern history of land use and landform evolution throughout the Holocene in the park area. Marsh and swamp deposits contain a detailed environmental record of paleoclimate and sedimentation conditions.
PLEISTOCENE		Outwash (*ow*) kame (*ka*) kame terrace (*kt*) ground moraine (*gm*) till (*ti*) thin till (*tt*)	Unit ***ow*** consists of well-sorted gravels and sands forming gently sloping to flat lands with deposits typically greater than 5 m (15 ft) thick. These deposits collected at the front of melting glacial ice. Unit ***ka*** contains stratified and unstratified sand, gravel, and boulders with variable silt contents. These deposits collected in depressions within melting glacial ice. Units ***ka*** and ***gm*** imperceptibly grade into each other. Unit ***kt*** consists of stratified and unstratified gravel, sand, boulders, and some silt in flat to nearly flat landforms and deposits typically greater than 10 m (33 ft) thick. Kame terraces accumulated at 262 m (860 ft) and 274 m (900 ft) elevation locally; they formed in flowing water at the margin of glacial ice. Unit ***gm*** contains a wide range of deposits from stratified and well-sorted sand and gravel to unstratified and poorly sorted silt, sand, gravel, and boulders. These deposits fall out as glacial ice melts. Unit ***ti*** contains hardpan silt, boulders, gravel, and sand in unsorted, unstratified deposits. Thickness of this unit is generally greater than 3 m (10 ft) and outcrops of boulders and glacial erratics are common. Unit ***tt*** consists of hardpan silt, boulders, gravel, and sand with thicknesses of less than 3 m (10 ft). Units ***kt***, ***ti***, and ***tt*** are mapped within the park.	Low to moderately low	Units ***ow*** and ***kt*** have intermediate to high permeability. Unit ***ka*** can be a fair aquifer if thick enough and of sufficient areal extent. Slopes at the edges of ***kt*** and ***gm*** may pose mass wasting issues and stability concerns. Percolation rates associated with ***kt*** are suitable for conventional septic systems. ***kt*** is a good local aquifer; however, aquifer recharge areas are prone to contamination from infiltration. Unit ***gm*** has low to high permeability and can be a fair aquifer limited by variable thickness, sediment types, and sedimentary structures. Units ***ti*** and ***tt*** have low permeability and ***ti*** forms unstable slopes for excavations. Unit ***ti*** is prone to significant slope failure along streams and can act as an aquitard to groundwater flow. Unit ***tt*** is also prone to instability and sliding, especially where in contact with the bedrock.	Where units are exposed at the surface, may contain historical or American Indian artifacts.	Plant fossils may exist in postglacial ponds.	Units ***ow***, ***kt***, and ***ka*** have high gravel and sand resource potential. Glacial erratics may contain minerals of interest from Canada.	Units ***ka*** and ***gm*** form rolling, hilly lands with variable drainage to support upland forests. Loose and uncompacted ***gm*** forms a veneer over the underlying compacted till and bedrock. Unit ***ti*** tends to support poorly drained soils and perched water tables. Units ***tt*** and ***ti*** have rock outcrops commonly and ***tt*** forms ledges.	Units record Pleistocene Ice Age glacial advances and retreats across the landscape. Unit ***ow*** forms as glacial melt water deposits. Unit ***ka*** forms as glacial deposits in streams, slumps, and deposition from ice. Unit ***kt*** forms along the ice contact as melt water and sediment flow deposits. Unit ***gm*** forms as ice contact sediment flow, melt water, and ice deposited sediments. Units ***tt*** and ***ti*** formed as a variety of ice-derived deposits beneath the glacier.
UNKNOWN	Linear Geologic Units	Thick quartz vein (*qv*)	Unit contains localized veins of coarsely crystalline quartz.	Moderate to moderately high	Unit is too localized to impact infrastructure development.	Unit may have provided tool or trade material.	None	Quartz	Unit forms coarse-grained residuum.	Quartz veins originally deposited during percolation of super-heated fluids through fractures in the bedrock.
MESOZOIC ERA		Basalt dike (*MZb*)	Unit consists of dark gray basalt, an igneous rock. A dike is a discrete intrusion that cuts across preexisting bedrock fabrics such as bedding. In outcrop, the unit appears tan-colored and dikes cut across the fabric of surrounding bedrock.	Moderately high	Unit is probably too localized to impact infrastructure development, but may act as an aquitard at depth.	Unit may have provided tool or trade material.	None	Basalt, feldspar phenocrysts	Unit may weather to produce iron, magnesium, and/or calcium rich soils.	Unit records intrusive igneous activity in the area during the Mesozoic as Pangaea rifted apart.
DEVONIAN		Granite sill (*Dbg*)	Unit contains two-mica granite (igneous rock) that appears light-colored in outcrop. Unit forms a sill that intruded parallel to the fabric of the surrounding bedrock.	Moderately high to high	Unit may contain enough potassium to produce radon-rich regolith during weathering processes. Such regolith should be avoided for basements and foundations.	None documented	None	Granite, mica	Unit may weather to produce calcium-rich soils.	Unit records igneous intrusive activity in the Devonian Period during Appalachian mountain building.

Gray-shaded rows indicate geologic map units included within the digital geologic data but are not mapped within the park. Colors in the age column are U.S. Geological Survey standard colors.

Age		Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure and Potential Geologic Hazards	Cultural Resources	Paleontological Resources	Mineral Occurrence	Habitat	Geologic Significance and Miscellaneous Notes
DEVONIAN	Bedrock Geologic Units	Gile Mountain Formation: (*Dg*) calc-silicates horizon (*Dgc*) hornblende fascicle schist (*Dgh*)	Unit ***Dg*** contains metamorphosed rocks including garnet schist with individual quartzite beds that can reach more than 1 m (3 ft) thick. Unit contains calc-silicate (***Dgc***) and hornblende-fascicle schist (***Dgh***) horizons. Units ***Dg*** and ***Dgc*** are mapped within the park.	Moderately high	Not enough carbonate present to pose any karst-related hazards. In areas where schistosity is pronounced, unit may be prone to sliding where the slope is parallel with the foliation (schistosity).	Crystals may have provided trade material.	None documented.	Staurolite, kyanite, garnet, quartzite	Units may weather to form calcium-rich soils.	Units record mixed depositional environments during the Devonian, and deformation and metamorphism throughout the late Paleozoic.
SILURIAN	Bedrock Geologic Units	Standing Pond Volcanics: (*Ssp*) calc-silicates horizon (*Sspc*)	Unit ***Ssp*** consists of metamorphosed rocks, including dark, blackish-green amphibolite, feldspar-amphibole gneiss, quartzose granofels, and localized calc-silicate (***Sspc***) horizons and schist. This unit forms a prominent marker bed in the area, whose ropy map pattern demonstrates the remarkable amount of deformation these rocks sustained throughout mountain-building events. Unit ***Ssp*** is mapped within the park.	Moderately high	Heterogeneous nature of units may render then unstable on exposed slopes. Not enough carbonate present to pose any karst-related hazards.	Crystals may have provided trade material.	None documented.	Unit contains giant amphibolite fascicles and garnets up to 5 cm (2 in.) across called garbenschiefer.	Units may weather to form calcium-rich soils.	Units record mixed depositional environments during the Silurian, and deformation and metamorphism throughout the late Paleozoic. Granofels (with little to no foliation) may represent metamorphism only from heating, in the absence of directed stress.
SILURIAN	Bedrock Geologic Units	Waits River Formation: >50% calc-silicates (*Sw*) Mt Tom Member (*Swm*) Mt Tom Member, calc-silicates horizon (*Swmc*) 10 to 50% calc-silicates (*Sws*) rusty schist (*Swr*)	Unit ***Sw*** contains metamorphosed rocks, including garnet-bearing schist interlayered with >50% (of the whole unit composition) blocky, brown-weathering calc-silicate (a metamorphic rock that contains calcite and calcium-bearing silicate minerals) sandy marble. ***Swm*** consists of schist with less than 10% calc-silicate-bearing layers and relatively common graded beds near the top of the formation. ***Swmc*** contains more abundant blue gray calc-silicate-bearing interlayers than ***Swm***. ***Swmc*** weathers to blocky, brown-colored outcrops. ***Sws*** is schist with less than 50% blue gray sandy marble (calc-silicates). ***Swr*** consists of fine-grained schist, which weathers to a rusty-colored outcrop. Units ***Swm*** and ***Sws*** are mapped within the park.	Moderate	Calc-silicate members may be prone to dissolution and cause some weakness in the rock column. Units may be prone to sliding if exposed (weathered) on a slope and schistosity fabric is parallel to the slope. Marble layers (calc-silicates) are more permeable than schists. Well production depends on orientation of layering (vertical layers can be less productive than horizontal layers).	Crystals may have provided trade material.	None documented.	***Sw*** contains sandy marble, garnet, staurolite, and kyanite.	Units may weather to form calcium-rich soils.	Units record mixed depositional environments during the Silurian, and deformation and metamorphism throughout the late Paleozoic. Units were easily abraded by glaciers during the Pleistocene forming rounded hills veneered with till.
SILURIAN	Bedrock Geologic Units	Northfield Formation: (*Sn*) calc-silicates horizon (*Snc*)	Unit ***Sn*** contains metamorphosed sedimentary rocks, including phyllite and schist that appears dark gray to black and is garnetiferous (porphyroblasts). Rare thin quartzite and calc-silicate beds (***Snc***) occur locally. ***Sn*** exhibits a foliation defined by the biotite crystals, which lay across the trend. ***Snc*** consists of sandy, calc-silicate blue-gray-colored marble. ***Snc*** contains distinctive garnet "carbuncles" in blocky, brown-weathered outcrops.	Moderately high	Not enough carbonate present to pose any karst-related hazards. Inherent foliation in phyllites and schists may render the units prone to rockfall and sliding when units are undercut or exposed on moderate to steep slopes.	Crystals may have provided trade material.	None documented.	Quartzite, sericite, biotite, garnet (in porphyroblasts up to 3 mm [0.25 in.] across), graphite, marble, and iron sulfides.	Units may weather to form calcium-rich soils.	Units record mixed depositional environments during the Silurian, and deformation and metamorphism throughout the late Paleozoic.
SILURIAN	Bedrock Geologic Units	Shaw Mountain Formation (*Ss*)	Unit occurs as isolated outcrops of quartz conglomerate.	High	Unit may be prone to blockfall and sliding when undercut on moderate to steep slopes. Fractures in unit may provide groundwater conduits for the bedrock aquifer.	None documented.	None documented.	Quartz conglomerate	Unit may form ledges and steep slope habitats.	***Ss*** occurs on the west slopes of Long Hill.
ORDOVICIAN	Bedrock Geologic Units	Barnard Gneiss (*Ob*)	Unit contains metamorphic rocks, such as felsic gneiss interlayered with dark-colored amphibole and biotite gneiss.	Moderately high	Unit may be prone to block fall if undercut or exposed on moderate to steep slopes. Unit is suitable for most forms of infrastructure development unless heavily weathered or fractured. Investigate for radon potential. Well-jointed portions of this unit can make good aquifers.	None documented.	None	Gneiss, amphibole, biotite	Unit may weather to form iron, and calcium-rich soils	Unit records a history of volcanism, deformation, and metamorphism since the Ordovician. Orientation of jointing (two dominant sets oriented east-west and northeast) possibly controlled the orientation of the Ottauqhechee River and the location of glacially scoured pockets in bedrock.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

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

accretionary prism. A wedge-shaped body of deformed rock consisting of material scraped off of subducting oceanic crust at a subduction zone. Accretionary prisms form in the same manner as a pile of snow in front of a snowplow.

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

allochthonous. Describes rocks or materials formed elsewhere and subsequently transported to their present location. Accreted terranes are one example.

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

alluvium. Stream-deposited sediment.

alpine glacier. A glacier occurring in a mountainous region;

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

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

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

anticlinorium. A large, regional feature with an overall shape of an anticline. Composed of many smaller folds.

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

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

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

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

authigenic. Describes rocks or minerals that have not been transported from where they formed.

autochthon. A body of rocks in the footwall (underlying side) of a fault that has not moved substantially from its site of origin. Although not moved, the rocks may be mildly to considerably deformed.

authochthonous. Formed or produced in the place where now found. Similar to "authigenic," which refers to constituents rather than whole formations.

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

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

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

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

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

bedding. Depositional layering or stratification of sediments.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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).

conjugate set (of joints). A pair of intersecting joints usually formed during compression. Commonly described on the basis of the angle of intersection.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

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

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

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

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

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

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

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

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

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

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

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

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

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

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

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

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

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

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

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

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

greenschist. A metamorphic rock, whose green color is due to the presence of the minerals chlorite, epidote, or actinolite, corresponds with metamorphism at temperatures in the 300–500°C (570–930°F) range.

hanging wall. The mass of rock above a fault surface (also see “footwall”).

hinge line. A line or boundary between a stable region and one undergoing upward or downward movement.

horst. Areas of relative “up” between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see “graben”).

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

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

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

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

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

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

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

limb. Either side of a structural fold.

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

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.

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

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to “felsic.”

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

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

marine terrace. A narrow coastal strip of deposited material, sloping gently seaward.

marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

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

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with “physical weathering.”

mélange. A mappable body of jumbled rock that includes fragments and blocks of all sizes, both formed in place and those formed elsewhere, embedded in a fragmented and generally sheared matrix.

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

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

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

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

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

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

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

nappe. A sheetlike, allochthonous (manufactured elsewhere) rock unit that has moved along a predominantly horizontal surface. The mechanism may be thrust faulting, recumbent folding, or gravity sliding.

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

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

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

orogeny. A mountain-building event.

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

outwash. Glacial sediment transported and deposited by meltwater streams.

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

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

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

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

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

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

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

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

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

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

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

quartzite. Metamorphosed quartz sandstone.

recharge. Infiltration processes that replenish groundwater.

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

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

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

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

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

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

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

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

sapping. The undercutting of a cliff by erosion of softer

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

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

schistose. A rock displaying schistosity, or foliation.

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

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

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

shoreface. The zone between the seaward limit of the shore and the more nearly horizontal surface of the offshore zone; typically extends seaward to storm wave depth or about 10 m (32 ft).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

suture. The linear zone where two continental landmasses become joined via obduction.

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

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

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

tectonic. Relating 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.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

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

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

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

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

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

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

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

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

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

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

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

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

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

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

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

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

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of September 2011.

Geology of National Park Service Areas

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

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

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

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

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

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

Geological Survey and Society Websites

Vermont Geological Survey: http://www.anr.state.vt.us/dec/geo/vgs.htm

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

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

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

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

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

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

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

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

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

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

U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix: Scoping Session Participants

The following is a list of participants from the GRI scoping session for Marsh-Billings-Rockefeller National Historical Park, held on July 10, 2007. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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