National Park Service
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Natural Resource Stewardship and Science

Minute Man National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1523

ON THE COVER
Assabet Quartz Diorite is exposed in the garden of the North Bridge Visitor Center overlooking North Bridge and the Minute Man statue. Photograph by Chris Hepburn (Boston College) taken in summer 2016.

THIS PAGE
The Bloody Bluff—type locality of the Bloody Bluff Fault Zone—was a scene of intense fighting during the initial conflict of the American Revolution. Photograph by Chris Hepburn (Boston College) taken in summer 2016.

Minute Man National Historical Park

Geologic Resources Inventory Report

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

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

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

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Contents

Figures

Page

Tables

Page

Executive Summary

The Geologic Resources Inventory (GRI) program provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This report synthesizes discussions from a scoping meeting held in 2007 and a follow-up conference call in 2016 (Appendix A). Sections of this report discuss the geologic setting, distinctive geologic features and processes within Minute Man National Historical Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Posters (in pocket) illustrate these data.

The "shot heard 'round the world" on April 19, 1775 was likely fired by a colonial farmer, or group of farmers, standing on floodplain alluvial deposits and sandy deposits of ancient glacial Lake Concord. They were confronting British soldiers at the North Bridge, over a narrow reach of the Concord River, just upstream of the Great Meadow, a great flanking wetland area. During the British retreat from the bridge, colonial militia hunkered behind stone walls made from glacial erratic boulders and outwash gravel, and outcrops of the Nashoba and Avalon bedrock terranes. The long human history of Minute Man National Historical Park played out on a glaciated landscape whose geologic features strongly influenced the early settlement of the area, the attraction of literary luminaries, as well as the tactics and ultimate outcome of the first battle of the American Revolution.

The bedrock units in Minute Man National Historical Park reflect the assembly of eastern Massachusetts during Appalachian mountain-building orogenies hundreds of millions of years ago that eventually lead to the creation of the supercontinent Pangaea. A major boundary—the Bloody Bluff Fault (named after the battle fought nearby)— between two such rock "pieces," or geologic terranes, which accreted to the edge of North America about 425 million years ago, runs through the eastern end of the Battle Road unit. This northeast-to-southwest trending fault separates metamorphic and igneous rocks of the Avalon terrane (geologic map units **Zwm** and **ZSfhg**) on the east from the Nashoba terrane (**COm**, **Sgrm**, **DSag**, **DSaqd**, and **COnu**) on the west. Nearly 200 million years of weathering and erosion whittled away the massive Appalachian mountain range to expose its core in New England.

The most recent ice age glaciations over the past few hundreds of thousands of years then carved the bedrock landscape and left behind glacial till (**Qt**), outwash and glacial lake deposits (**Qsdc** and **Qsdf**), alluvium (**Qal**), and swamp deposits (**Qsw**) across the region. At Minute Man, the glacial outwash and lake deposits are related to glacial Lake Sudbury along Battle Road and Barretts Farm, as well as two levels of Lake Concord in the environs of North Bridge, Mill Brook, The Wayside, and the town of Concord. Rivers. Wind, and weather continue to rework these sediments today. Throughout more recent history, humans significantly modified the landscape by clearing forests, draining or filling wetlands, channeling streams, building roads, plowing fields, and other suburban development.

One of the park goals is to reveal the battle-era landscape appearance while protecting and preserving this valuable natural area in the greater Boston area. The geologic foundation of the park is a major factor to these efforts because it played such a prominent role in the history and geologic processes can alter historic context. Geologic features, processes, and resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- **Fluvial Features and Processes**. Fluvial features are those which are formed by flowing stream and river water. Fluvial processes construct and erode landforms. The Assabet River flows by the Barrett's Farm Unit and converges with the Sudbury River to form the Concord River, which flows through the North Bridge Unit. Many small streams and brooks flow through the Battle Road Unit, including Mill Brook, which flows by The Wayside Unit.

- **Wetlands**. Wetlands are transitional areas between land and water bodies where water frequently floods the land or saturates the soil. Geologic controls of wetland locations include substrate nature (e.g., drainage capacity), local topography, and geologic history. Large areas of the park are wetlands, including flanking areas of most streams, Folly Pond and other small ponds, kettle hole wet meadows, a red maple-black gum swamp, Elm Brook wetland, and vernal pools. These wetlands provide several significant functions, including (1) bird and other wildlife habitat, (2) surface water detention, (3) nutrient transformation, and (4) retention of sediments.
- **Glacial Features**. Glaciations affected the landscape in two major ways; they (1) created erosional features on top of the bedrock landscape, and (2) deposited mantles of sediment over the eroded bedrock surface. Locally, two distinct till deposits (**Qtt** and **Qt**) record at least two separate glacial advances. Glacial deposits in the park are of two types: (1) those deposited directly by moving ice such as sand and gravel-rich glacial till, and (2) those deposited by meltwater in rivers (glaciofluvial; **Qsdc**) or lakes (glaciolacustrine; **Qsdf**). A prominent feature on the park landscape is Authors Ridge-Revolutionary Ridge, which formed as a kame delta from glacial rivers flowing into Glacial Lake Concord.
- **Eolian Features**. Eolian features include dunes and loess sheets. These form from wind-blown erosion, transportation, and deposition of sediment. Stratified glacial deposits (**Qsdf**) were a likely source for ice age dunes at Minute Man National Historical Park. Surficial mapping revealed ventifacts, or "sandblasted" rocks, at the park. They formed after the glacial ice retreated and wind blew fine grained materials across the barren landscape. Two examples of ventifacts are present in the area.
- **Bedrock Exposures**. Bedrock is the solid, ancient rock that underlies the younger unconsolidated surficial and glacial deposits of the park. Igneous and metamorphic bedrock units are exposed within park boundaries. Park and regional features have lent their names to geologic units, including Fiske Hill, Hubbard Hill, Balls Hill, and Jupiter Ridge.
- **Faults and Shear Zones**. Faults are fractures along which rocks have moved. Shear zones are wider areas of intense, commonly more ductile, deformation that resulted from movements deep in Earth's crust. The Burlington Mylonite Zone-Bloody Bluff Fault (sheared zone), Assabet River Fault, and Sedge Meadows Fault run through and adjacent to park areas. These and myriad other smaller-scale faults attest to the structural complexity within the Avalon and Nashoba terranes and the long geologic history of the local rocks.
- **Flooding and Wetlands Restoration**. Flooding occurs along the Assabet and Concord rivers, as well as local streams in the park area. Wetlands, most near streams, are a significant natural resource in the park. Many wetlands have historical significance and, at the time of this report, the park is in the midst of restoring certain areas. Beaver activity has contributed to flooding and increases in park wetland areas.
- **Erosion and Slope Movement Hazards, and Risks**. Slope movements are the downslope transfer of earth materials under the influence of gravity. Vegetation disturbances on slopes or near streams cause local erosion. Trails on slopes in several park areas are eroding. The terraced slope at The Wayside is in poor condition.
- **Aquifers and Groundwater Availability**. The park's battle-era appearance includes farmed fields and orchards. A regional drought has prompted discussion about the use of water sources for irrigation. Local aquifers include limited thick glacial deposits and fractured bedrock. A keen understanding of the local hydrogeologic system would provide additional information for understanding impacts of groundwater extraction to surficial wetlands and fluvial systems, as well as overall groundwater supply.
- **Disturbed Lands and Mineral Extraction**. Humans have altered the landscape of the Lexington and Concord area for hundreds of years by terracing, clearing, farming, and development. Artificial fill (**Qaf**) underlies dams, road grades, and other infrastructure. Small quarries and pits within the park, now overgrown with vegetation, function as wetlands. The park has removed more than 200 structures (e.g., houses and stores) since the 1960s. Urban landcover still makes up 17% of the park land.

- **Seismic Activity Hazards and Risks**. Hundreds of millions of years ago the park area was in a tectonically active area. Today, Minute Man National Historical Park is not located near a known active seismic zone; however, the potential for moderate earthquakes exists. There is a 4% to 6% probability of a magnitude-5.0 or greater earthquake within 100 years. In such a suburban setting, should a moderate earthquake occur, damage to infrastructure could be significant.
- **Paleontological Resource Inventory, Monitoring, and Protection**. Fossils are evidence of life preserved in a geologic context. The ancient bedrock at the park is unlikely to yield any fossils, but the more recent, surficial deposits may contain fossils. These fossils are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. The report presents the geologic setting of the park and geologic connections to park resources and stories. Tables and figures in the report summarize geologic features, processes, and resource management issues.

This GRI report is supported by two GRI GIS geologic maps of the park. These maps were developed from source maps produced by Boston College and the US Geological Survey. The Boston College map is a bedrock map and details the ancient rocks and bedrock structures such as the Bloody Bluff Fault. The US Geological Survey map is a surficial map that shows the glacial and postglacial deposits that mantle the bedrock. A previous surficial map by Koteff (1964) includes additional details of the glacial history but is not part of the GRI GIS data. The “Geologic Map Data” section in this report summarizes those maps and data layers. Posters (in pocket) illustrate these data and include the Koteff (1964) map. Google Earth compatible versions of GRI GIS data are also available.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. Geologists from Boston College and the US Geological Survey developed the source maps and reviewed GRI content.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

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

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

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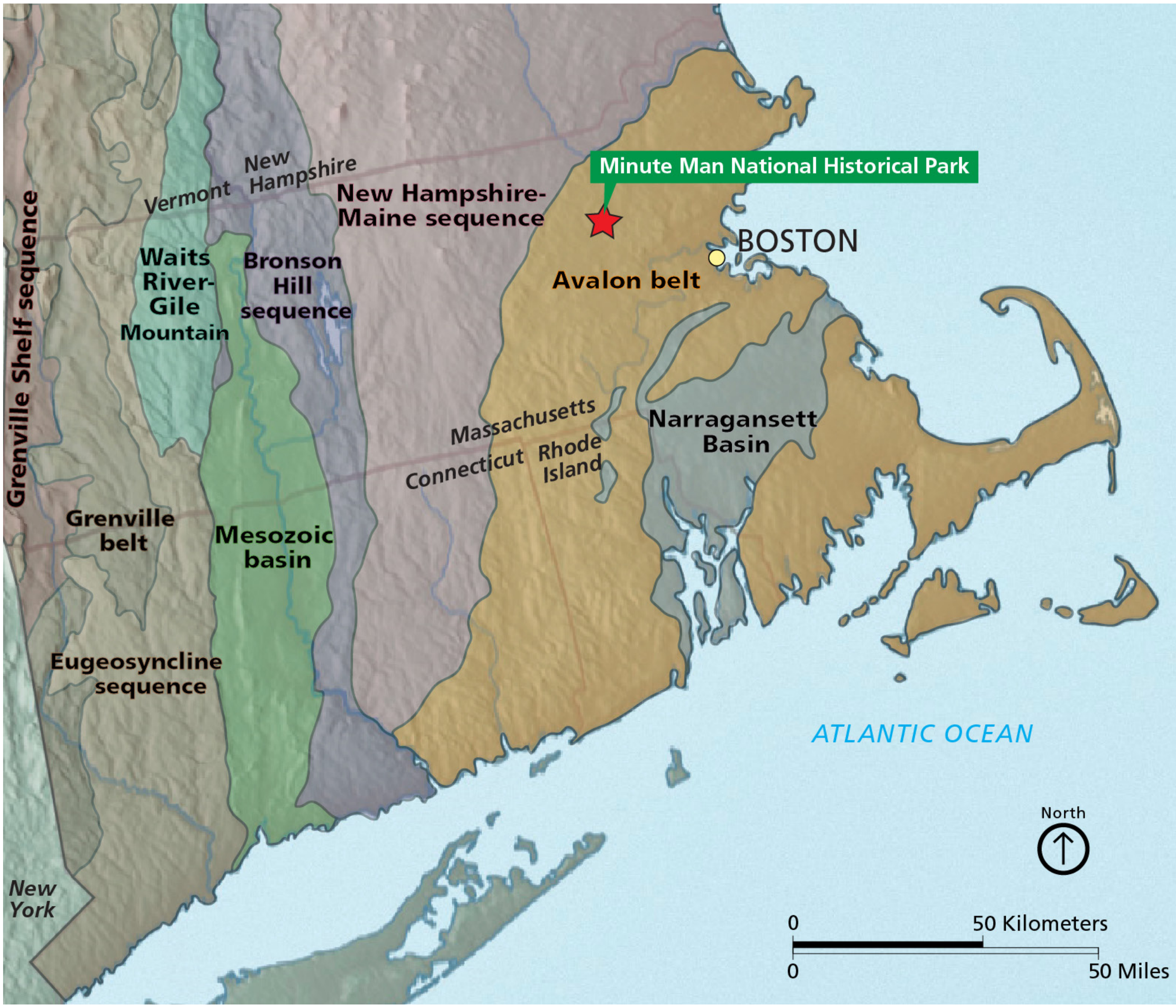


Figure 1. Map of geologic provinces of Massachusetts, Rhode Island, and Connecticut. Minute Man National Historical Park (red star) is part of the Avalon belt—a series of accreted terranes added over millions of years to the eastern edge of North America. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after information from Robinson and Kapo (2003). Shaded relief base map by Tom Patterson (National Park Service), available at http://www.shadedrelief.com/physical/index.html.

Geologic Setting, History, and Significance

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

Park Setting

Minute Man National Historical Park commemorates the "shot heard 'round the world" on April 19, 1775 and the beginning of the American Revolution. It also preserves local contributions to the American literary tradition and attracts more than one million visitors annually (National Park Service 2015). Encompassing more than 420 ha (1,038 ac) in Middlesex County, eastern Massachusetts, the park was first designated a national historic site on April 14, 1959 and then redesignated as a national historical park on September 21, 1959 (P.L. 86-321; National Park Service 2015). The latest addition, Barrett House and Farm, officially became part of the park in 2012. The park consists of four units: North Bridge, Barrett's Farm, The Wayside, and Battle Road—the largest unit within the park (plate 1, in pocket). The history of how Minute Man National Historical Park came to be is well described and summarized in Herbster (2005) and Zenzen (2010).

Rolling hills, muted ridges, broad stream valleys, kettle ponds, and bucolic views of meadows and fields characterize the landscape of Minute Man National Historical Park. The Sudbury and Assabet rivers converge to form the Concord River, which flows through the North Bridge unit. Other park streams include Mill and Elm brooks. Stretches of Battle Road straddle the divide between stream drainages (Herbster 2005).

The communities of Lexington and Concord were established in 1713 and 1635, respectively, and were part of an expansive agricultural economy. As colonial unrest against England escalated, communities established minute companies who stockpiled arms and prepared for conflict. In the evening of April 18, 1775, British soldiers marched westward from Boston to confiscate and destroy munitions cached by the colonists. Men, such as Paul Revere and William Dawes, rode horses ahead to warn colonists of their approach. At dawn the next day, an initial skirmish at Lexington left eight colonists dead. Later that morning, at the bridge over the Concord River northeast of Concord, the colonists fought back and released the fateful shots which killed British soldiers. The soldiers engaged again at Meriam's Corner where the colonists ambushed the British and continued the skirmish for nearly 32 km (20 mi) as the British retreated to Boston along Battle Road. The geologic foundation of Minute Man National Historical Park is strongly connected with the park's history—influencing the area's settlement, road patterns, river and stream crossings, and battle strategies and outcomes.

Geologic Setting and History

Early Construction of North America

Minute Man National Historical Park straddles a major bedrock boundary between two accreted terranes that form part of eastern Massachusetts. The park is underlain by rocks of the Avalon and Nashoba terranes which make up part of the Avalon belt of Robinson and Kapo (2003) (fig. 1). These terranes accreted to the growing edge of Laurentia (ancient North America) by about 425 million years ago (figs. 1 and 2, table 1; Zen et al. 1983; Robinson and Kapo 2003). A terrane is a group of rocks with similar characteristics and geologic history that differ from those around it, and commonly formed somewhere other than its present location. Terranes are associated with continent-scale plate tectonic forces that displace, squeeze, or rip apart large bodies of rock across distances ranging from a few to thousands of kilometers. Examples of terranes may include fragments of continents, volcanic arcs, and oceanic basins. Hundreds of millions of years ago (table 1), the rocks that make up eastern North America gradually pushed onto (accreted to) the eastern edge of the growing continent. Over some 200 million years, mountain-building events (orogenies) ultimately created the Appalachian Mountains. In the park area, from west to east, the terranes are called the Merrimack, Nashoba, and Avalon terranes (fig. 2; Hepburn et al. 1987; Zen et al., 1983). The park actually straddles the boundary between the Avalon terrane (home to Lexington) and the Nashoba terrane (home to Concord) (fig. 2). The boundary between the two today is the Burlington Mylonite Zone-Bloody Bluff Fault.

Terrane Histories

Each terrane has its own distinct history and geologic

Table 1. Geologic time scale. Table continues on next page.

Era	Period	Epoch	MYA	Geologic Map Units	Eastern Massachusetts Events
Cenozoic (CZ) "Age of Mammals"	Quaternary (Q)	Holocene (H)	0.01–today	Qaf emplaced, Qal and Qsw accumulating	Human history. Erosion, development of wetlands, river meandering
Cenozoic (CZ) "Age of Mammals"	Quaternary (Q)	Pleistocene (PE)	2.6–0.01	Qscd, Qsdf deposited Qt deposited Qtt deposited and eroded	Worldwide glaciations (ice ages). Ice sheets covered New England (fig 10); periglacial conditions
Cenozoic (CZ) "Age of Mammals"	Tertiary (T): Neogene (N)	Pliocene (PL)	5.3–2.6	Throughout Tertiary: all units are weathered and eroded.	Throughout Tertiary (Paleogene and Neogene): continued erosion and slope movements.
Cenozoic (CZ) "Age of Mammals"	Tertiary (T): Neogene (N)	Miocene (MI)	23.0–5.3		
Cenozoic (CZ) "Age of Mammals"	Tertiary (T): Paleogene (PG)	Oligocene (OL)	33.9–23.0		
Cenozoic (CZ) "Age of Mammals"	Tertiary (T): Paleogene (PG)	Eocene (E)	56.0–33.9		
Cenozoic (CZ) "Age of Mammals"	Tertiary (T): Paleogene (PG)	Paleocene (EP)	66.0–56.0		
Mesozoic (MZ) "Age of Reptiles"	Cretaceous Period (K)		145.0–66.0	Throughout Mesozoic: all units are weathered and eroded.	Erosion of Appalachian Mountains; deposition on Coastal Plain (continues throughout Cenozoic Era)
Mesozoic (MZ) "Age of Reptiles"	Jurassic Period (J)		201.3–145.0		~200 MYA, breakup of Pangaea began; possible movement along Bloody Bluff Fault; Atlantic Ocean opens (and continues today)
Mesozoic (MZ) "Age of Reptiles"	Triassic Period (TR)		252.2–201.3		
Paleozoic (PZ) (Amphibians common during late Paleozoic)	Permian Period (P)		298.9–252.2	During orogenies in Paleozoic, units are deformed.	Supercontinent Pangaea intact
Paleozoic (PZ) (Amphibians common during late Paleozoic)	Pennsylvanian Period (PN)		323.2–298.9		Alleghany (Appalachian) Orogeny; extensive faulting and metamorphism; Rheic Ocean closed; all terranes accreted.
Paleozoic (PZ) (Amphibians common during late Paleozoic)	Mississippian Period (M)		358.9–323.2		Late Devonian and/or Early Mississippian: possible movement along Bloody Bluff Fault.
Paleozoic (PZ) (Fishes diversify during Devonian)	Devonian Period (D)		419.2–358.9		Acadian Orogeny during Late Silurian and Devonian; extensive deformation and metamorphism throughout New England.
Paleozoic (PZ) (Marine invertebrates diversify greatly during early Paleozoic)	Silurian Period (S)		443.7–419.2	Sgrm, DSag, DSaqd intrude Nashoba terrane (~420 MYA); youngest possible age of ZSfhg	~420 MYA, Avalon accreted to/subducted beneath Nashoba terrane/Laurentia; Burlington Mylonite Zone formed ~425 MYA, Nashoba terrane accreted to Laurentia, Iapetus Ocean closed; subduction below Nashoba terrane began as Avalon terrane neared

Table 1, continued. Geologic time scale.

Era	Period	Epoch	MYA	Geologic Map Units	Eastern Massachusetts Events
Paleozoic (PZ) (Marine invertebrates diversify greatly during early Paleozoic)	Ordovician Period (O)		485.4–443.7	none	~450 MYA, Taconic Orogeny; terrane accretions began onto Laurentia ~460 MYA, Rheic ocean expanded; Nashoba and Avalon terranes move toward Laurentia ~485 MYA, Avalon terrane separated from Gondwana; Rheic Ocean opened
Paleozoic (PZ) (Marine invertebrates diversify greatly during early Paleozoic)	Cambrian Period (C)		541.0–485.4	COnu and COm formed	~500 MYA, Nashoba terrane separated from Gondwana and advanced into Iapetus Ocean; back-arc basin formed ~525 MYA, Nashoba terrane forms as volcanic arc on or near edge of Gondwana.
Neoproterozoic Era (Z) "Precambrian"			1,000–541.0	Zwm formed (may be older); oldest possible age of ZSfhg.	~600 MYA, Avalon terrane formed as volcanic arc along edge of Gondwana in high southern latitudes; volcanism and plutonism. ~700 MYA, Iapetus Ocean formed, separating Laurentia from Gondwana Early supercontinent rifted apart.
Mesoproterozoic Era (Y) "Precambrian"			1,600–1,000	none	Formation of early supercontinent.
Paleoproterozoic Era (X) "Precambrian"			2,500–1,600	none	none
Archean Eon "Precambrian"			~4,000–2,500	none	none
Hadean Eon "Precambrian"			4,600–4,000	none	Formation of the Earth approximately 4,600 million years ago.

The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Boundary ages are millions of years ago (MYA). Geologic units mapped within the park are included in the "Geologic Map Units" column. Chris Hepburn (geologist, Boston College, written communication, 5 August 2016) provided information for the "Eastern Massachusetts Events" column. Dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale). Colors are US Geological Survey standard colors for geologic time scale.

record. The sedimentary and igneous rocks that would become the Avalon terrane (see figs. 2 and 3) formed during the Neoproterozoic, more than 600 million years ago on the north coast of a massive southern continent called Gondwana. Gondwana included today's Antarctica, South America, Africa, Madagascar, Australia, and other smaller landmasses. At that time, in a setting that was similar to the modern Andes Mountains of South America, a subduction zone was fueling an arc of volcanoes and creating an immense amount of molten material that would later cool deep underground into plutonic rocks. (fig. 4A; Hepburn et al. 1993; Skehan 2001; Linnemann et al. 2007; Tweet et al. 2010). The rocks of the Avalon terrane, including the Fiske Hill Granite and Westboro Formation (geologic map units **ZSfhg** and **Zwm**, respectively), which are exposed inside park boundaries, were part of this late Proterozoic continental volcanic arc that formed in the high southern latitudes (Hepburn et al. 1993; Langford and Hepburn 2007). By about 520 million years ago (early Paleozoic Era), the rocks of the Nashoba terrane, including the Marlboro Formation (**COm**) and Nashoba Formation (**COnu**) exposed at the park (see figs. 3 and 4B), were also forming on or near the edge of the Gondwanan continent as part of another volcanic arc and backarc complex (fig. 5; Hepburn et al. 1993; 1995; Langford and Hepburn 2007; Kay et al. 2009; Dabrowski 2014).

In the late Neoproterozoic and earliest Paleozoic eras, Gondwana was separated from the more equatorial Laurentia (proto-North America) by the Iapetus Ocean—named for Iapetus, who in Greek mythology was the father of Atlas, the namesake of the Atlantic Ocean (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). By about

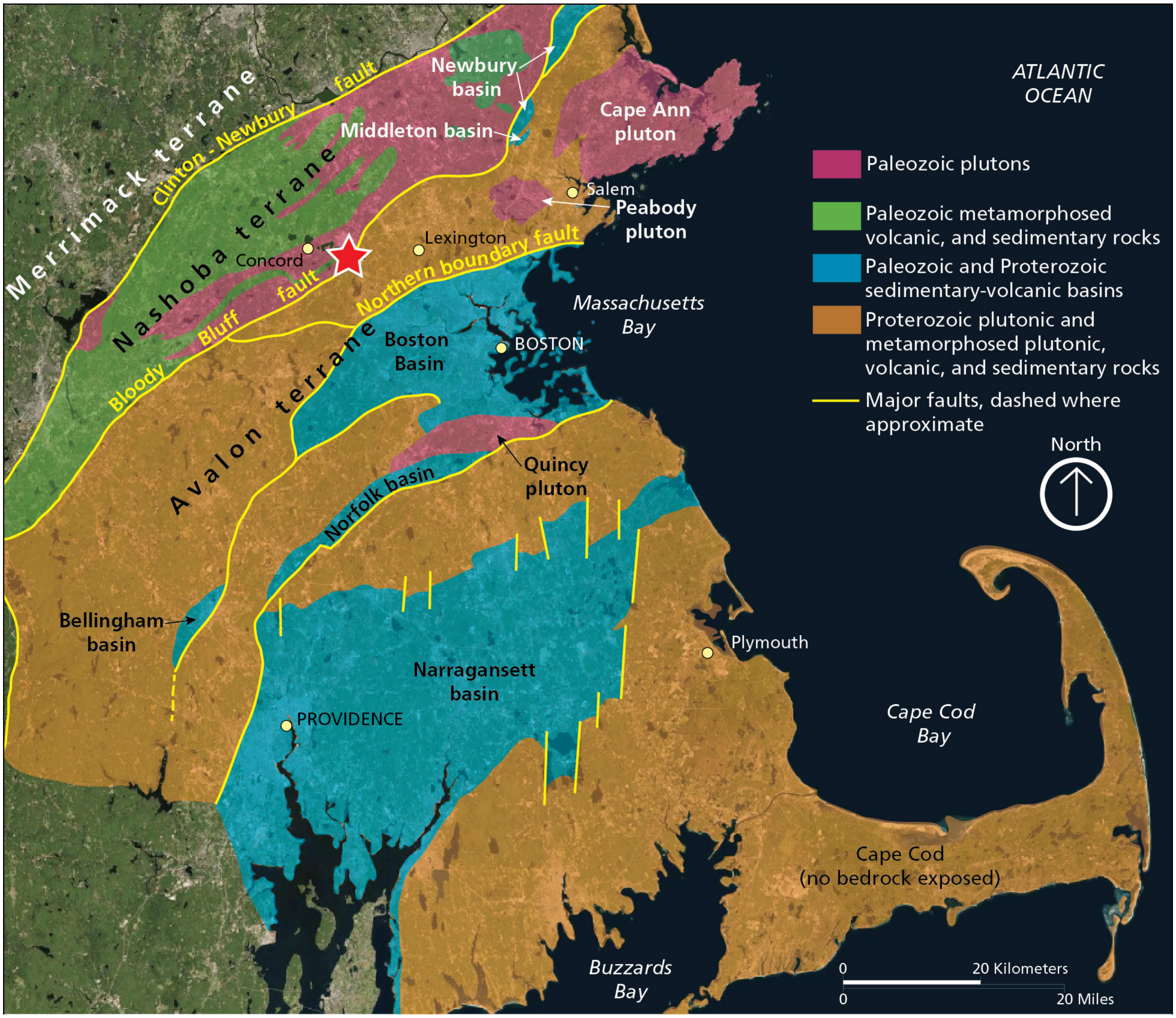
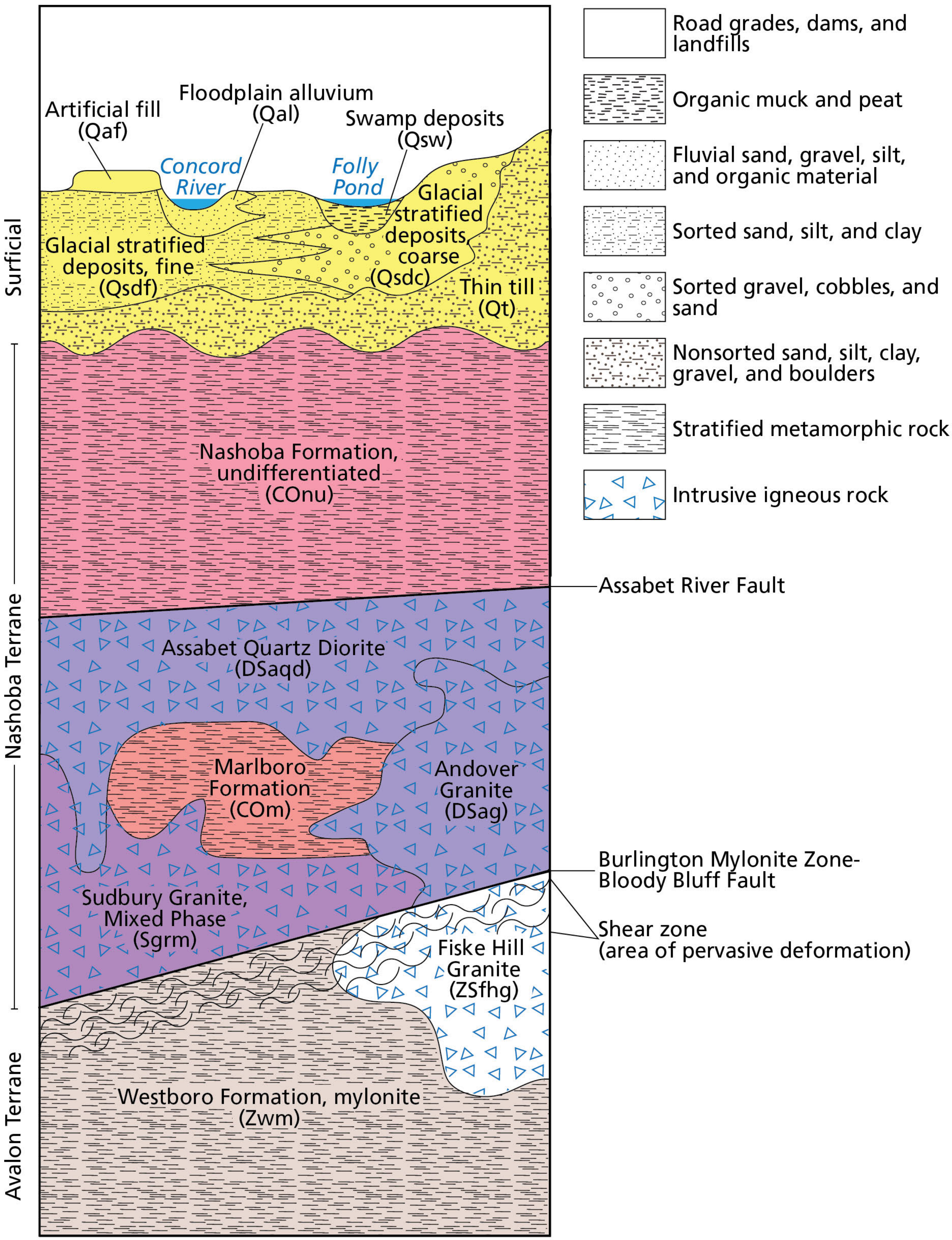
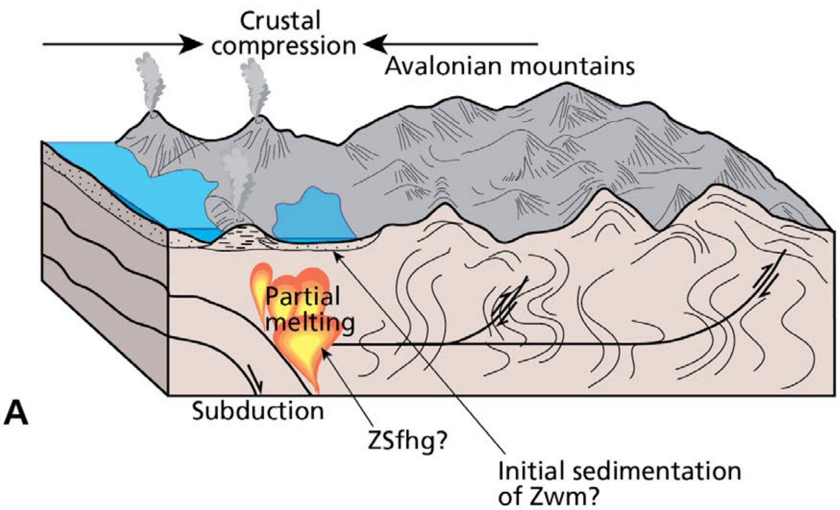


Figure 2 (above). Map of major bedrock features of eastern Massachusetts. Minute Man National Historical Park (red star) stretches between the Avalon and Nashoba terranes—two of a series of accreted terranes added over millions of years to the eastern edge of North America hundreds of millions of years ago. Major faults (bold yellow lines) denote the boundaries of terranes and prominent bedrock basins. The Bloody Bluff Fault was named for a feature within the park and is represented on the GRI GIS data (see poster, in pocket, and "Geologic Map Data" section). Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 1 from Goldsmith (1991a) and information from Zen et al. (1983), Arvin (2010), and Chris Hepburn, Boston College, geologist, written communication, 5 August 2016, using ESRI World Imagery basemap (accessed 28 April 2014).

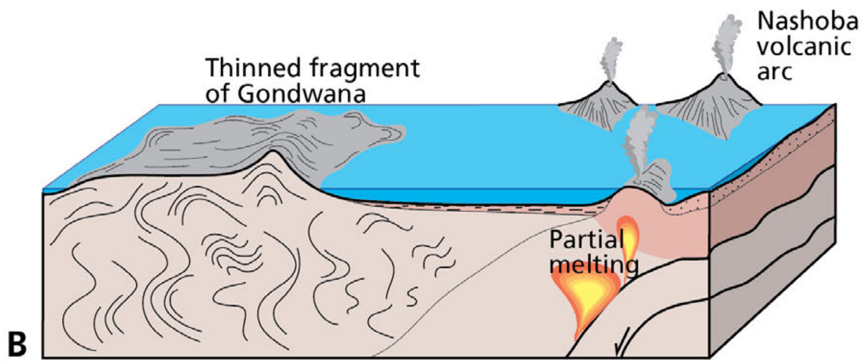
Figure 3 (facing page). Simplified stratigraphic column representing map units within the GRI GIS data. Neoproterozoic and Paleozoic bedrock underlie Quaternary surficial deposits. Bedrock is exposed in areas where the surficial materials either eroded away or were never deposited. Only units that are mapped within the park in the GRI GIS data are included. Unit colors are according to US Geological Survey standards for geologic time periods. Section is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Stone and Stone (2006) and Langford and Hepburn (2007).



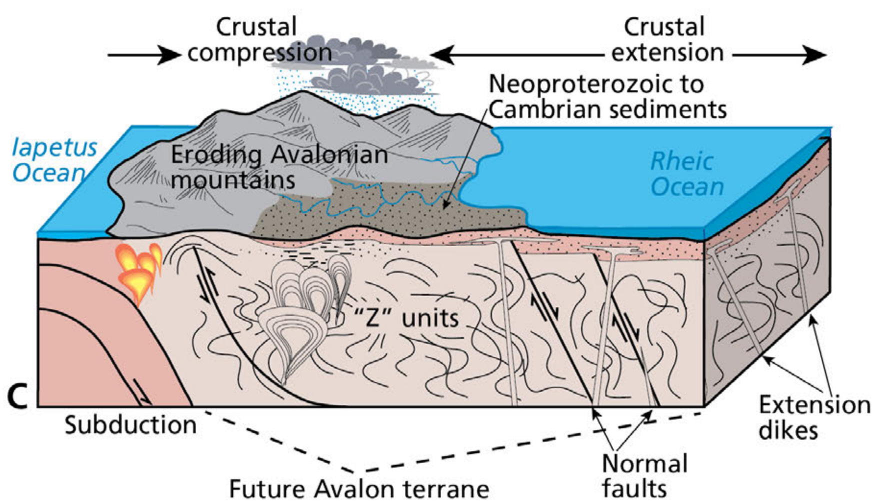
Surficial
Nashoba Terrane
Avalon Terrane
Artificial fill (Qaf)
Floodplain alluvium (Qal)
Swamp deposits (Qsw)
Concord River
Folly Pond
Glacial stratified deposits, fine (Qsdf)
Glacial stratified deposits, coarse (Qsdc)
Thin till (Qt)
Nashoba Formation, undifferentiated (COnu)
Assabet River Fault
Assabet Quartz Diorite (DSaqd)
Marlboro Formation (COm)
Andover Granite (DSag)
Sudbury Granite, Mixed Phase (Sgrm)
Burlington Mylonite Zone-Bloody Bluff Fault
Shear zone (area of pervasive deformation)
Fiske Hill Granite (ZSfhg)
Westboro Formation, mylonite (Zwm)
Road grades, dams, and landfills
Organic muck and peat
Fluvial sand, gravel, silt, and organic material
Sorted sand, silt, and clay
Sorted gravel, cobbles, and sand
Nonsorted sand, silt, clay, gravel, and boulders
Stratified metamorphic rock
Intrusive igneous rock



610 million years ago–the Avalonian Orogeny involved a subduction zone where partial melting of the downgoing plate led to igneous intrusions and volcanism above on the western side of Gondwana, similar to today's Andes Mountains of South America. Extensive deformation and metamorphism occurred. Interlayered sediments and volcanic deposits collected in the basins.



520 million years ago–along a different fragment of Gondwana, the Nashoba terrane formed as a volcanic arc on thinned crust, at least partially marine in origin. COnu and COm formed in the Nashoba terrane.



550 million to 500 million years ago–extension of the crust causes rift basins such as the Boston Basin to open and collect sediments. Avalon terrane rifted away from northwestern Gondwana and the *Rheic Ocean* began to open.

note: colors in cross section represent different periods of geologic time

Figure 4 A–C. Schematic graphics illustrating the evolution of the Minute Man National Historical Park landscape. Graphics are not to scale. See also figures 6 and 7. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University), with information from Skehan (2001); Hepburn et al. (1993); Langford and Hepburn (2007); Coleman (2005); Linneman et al. (2007); Thompson et al. (2007); Kopera (2011); and Chris Hepburn, Boston College, geologist, written communication, 5 August 2016)

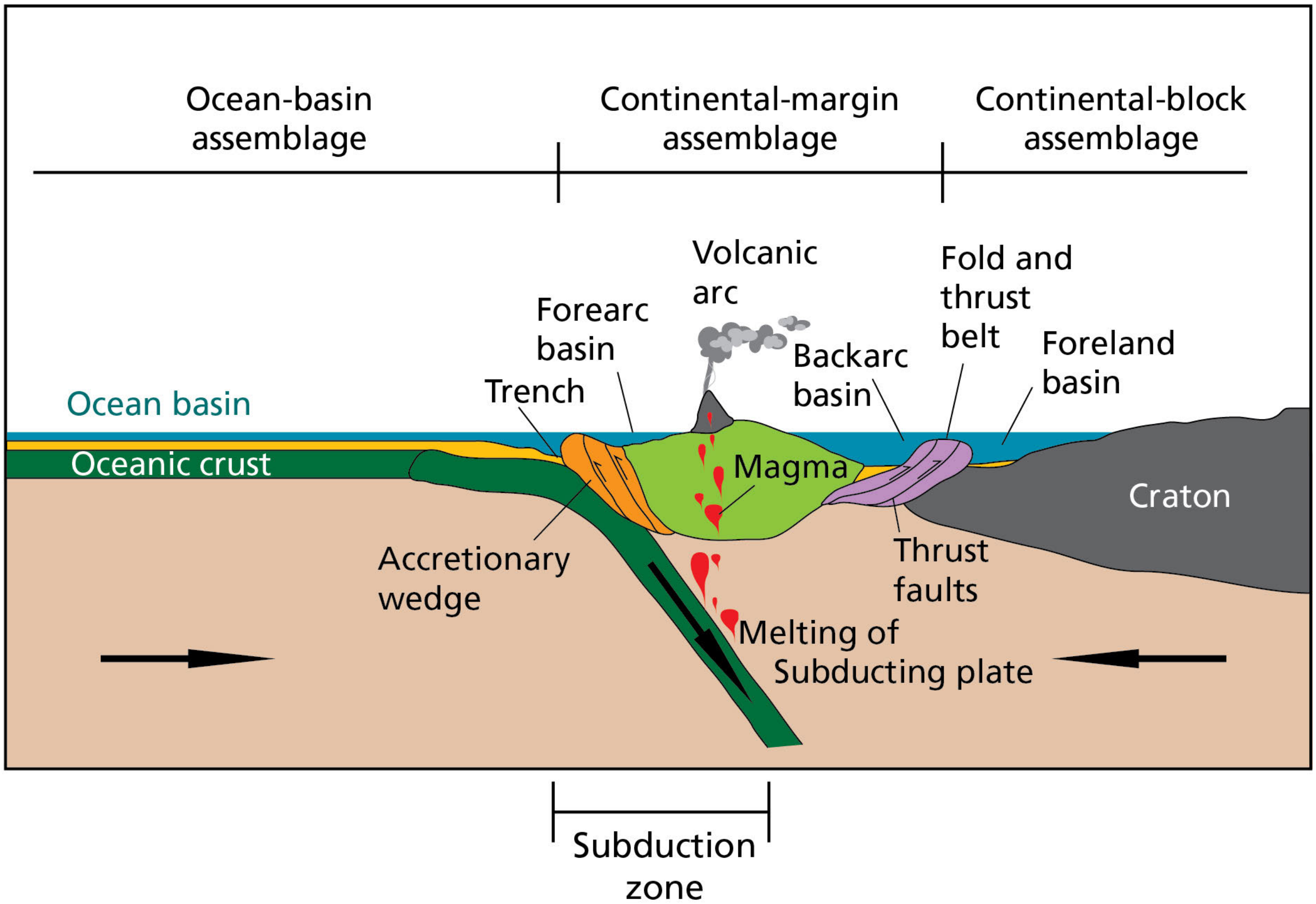
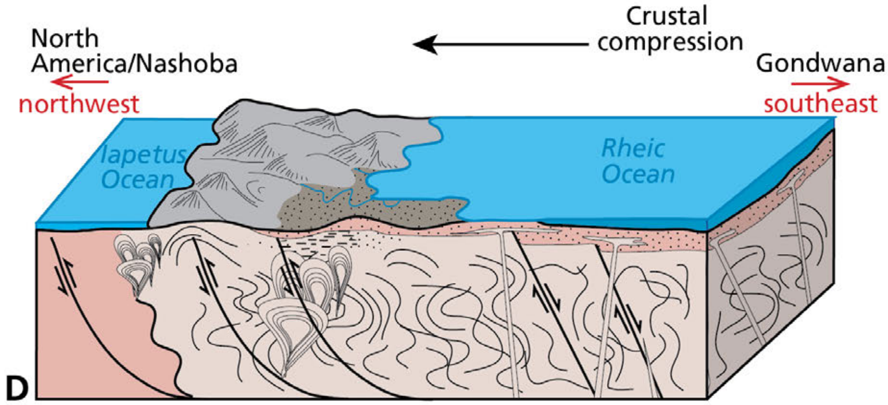


Figure 5. Schematic cross section of a volcanic arc and backarc system. A volcanic arc is a chain of volcanoes (e.g., modern Aleutian Islands) that forms above a subduction zone fueled by melting of the subducting plate. A backarc forms behind the volcanic arc, often as a result of intense deformation associated with the crustal collision. Geologists theorize that the Nashoba terrane and parts of the Avalon terrane formed in similar settings (see fig. 4B). Graphic is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

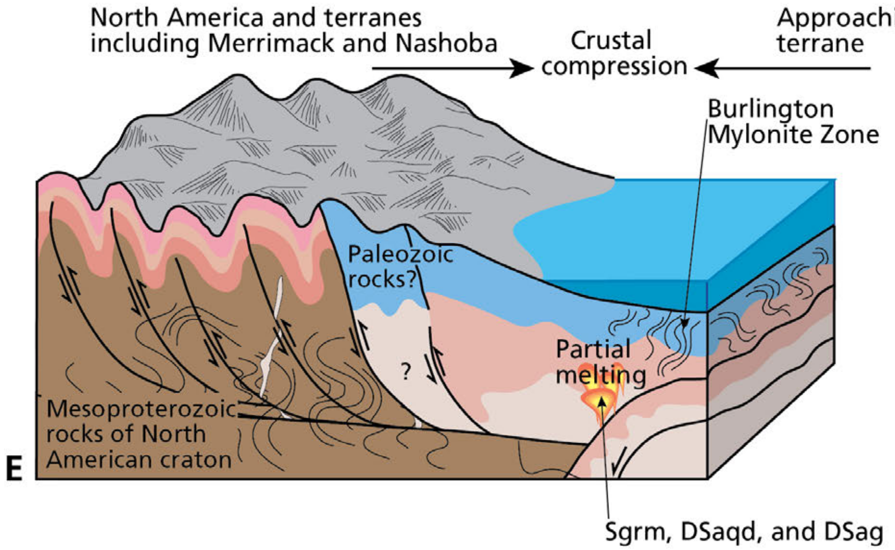
500 million years ago, Gondwana started to break apart. The Nashoba terrane was part of a larger piece that broke off first, called Ganderia or the Ganderian composite terrane. Once apart from Gondwana, it moved northward across the Iapetus Ocean toward Laurentia. Behind the Nashoba terrane an ocean basin, underlain by oceanic crust, formed and widened to about 1000 km (600 mi). This process was similar to the fairly recent (geologically speaking) opening of the Sea of Japan between Japan and mainland Asia. After about 20 million years, a second microcontinent broke off of Gondwana; this was the Avalon terrane (fig. 4C). A marine basin called the Rheic Ocean formed behind the Avalon terrane, between it and the remainder of Gondwana (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). In a setting similar to the still-widening Atlantic Ocean of today, the Rheic Ocean expanded as the Iapetus Ocean shrank by subduction and the Nashoba and Avalon terranes moved northward toward Laurentia (figs. 4C and 6D; Skehan 2001; Coleman 2005; Linnemann et al. 2007; (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016).

Paleozoic Mountain Building and a Supercontinent

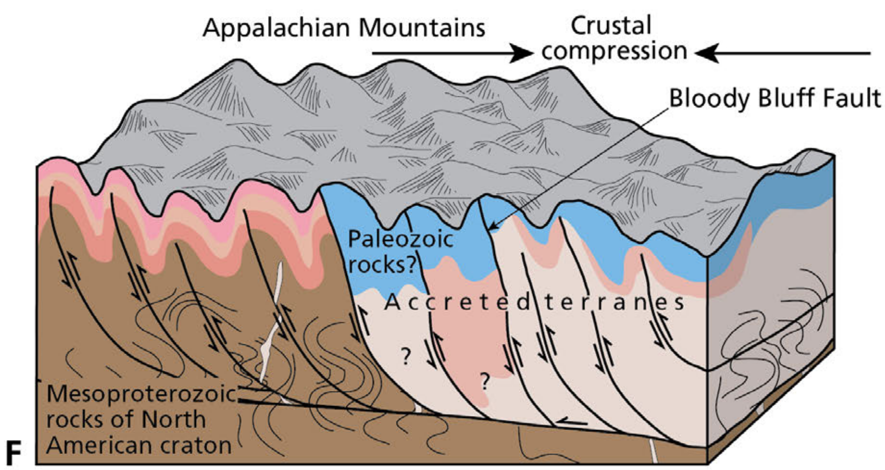
By the Silurian Period (roughly 425 million years ago), Ganderia, with the Nashoba terrane along its trailing edge, had collided with Laurentia and the subduction zone between Ganderia and Laurentia ceased to exist (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). However, because of the expanding Rheic Ocean, a new subduction zone formed along the edge of the Nashoba terrane and subducted the oceanic crust between it and the Avalon terrane with the subducting plate going beneath the Nashoba terrane. As the oceanic plate descended, it



470 million years ago–Avalon, Nashoba, and associated terranes moved between the shrinking *Rheic* and *Iapetus oceans*, traveling northwestward to eventually collide with North America. Internal deformation and crustal melting caused local emplacement of plutons into the Avalon and Nashoba terranes.



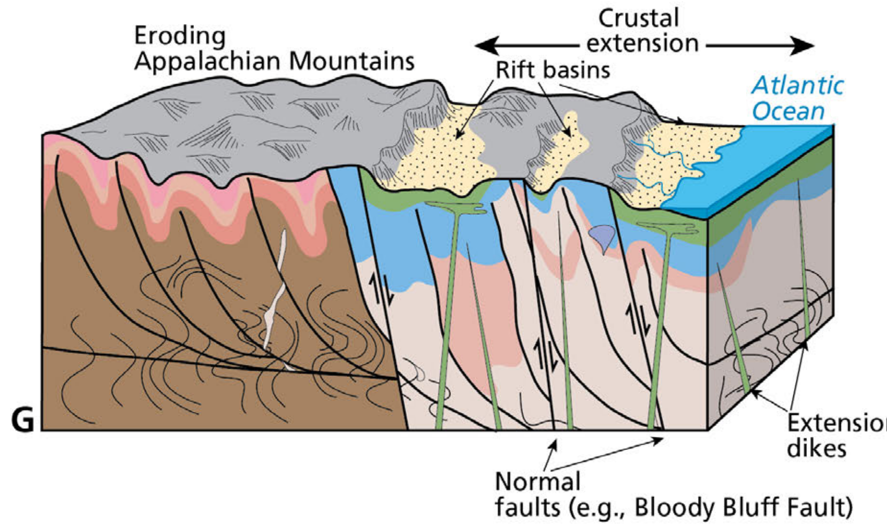
420 million years ago–the Avalon terrane approached the eastern edge of North America and subduction occurred beneath the Nashoba terrane as downgoing slabs of crust partially melted. The Burlington Mylonite Zone formed between the Avalon and Nashoba terranes as the former slid under and along the edge of the latter.



265 million years ago–Terranes were already accreted onto the eastern edge of North America as Gondwana collided during the Alleghany Orogeny. Rocks were moved, deformed, and metamorphosed during the construction of the Appalachian Mountains, the destruction of the *Iapetus* and *Rheic oceans*, and the construction of the supercontinent, Pangaea.

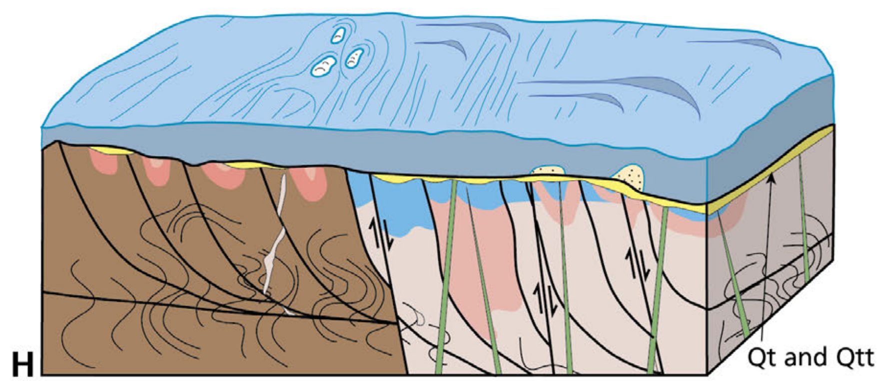
note: sedimentary rock type symbology was omitted for clarity

Figure 6 D–F. Schematic graphics illustrating the evolution of the Minute Man National Historical Park landscape, continued. Graphics are not to scale. See also figures 4 and 7. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University), with information from Skehan (2001); Hepburn et al. (1993); Langford and Hepburn (2007); Coleman (2005); Linneman et al. (2007); Thompson et al. (2007); Kopera (2011); and Chris Hepburn, Boston College, geologist, written communication, 5 August 2016.

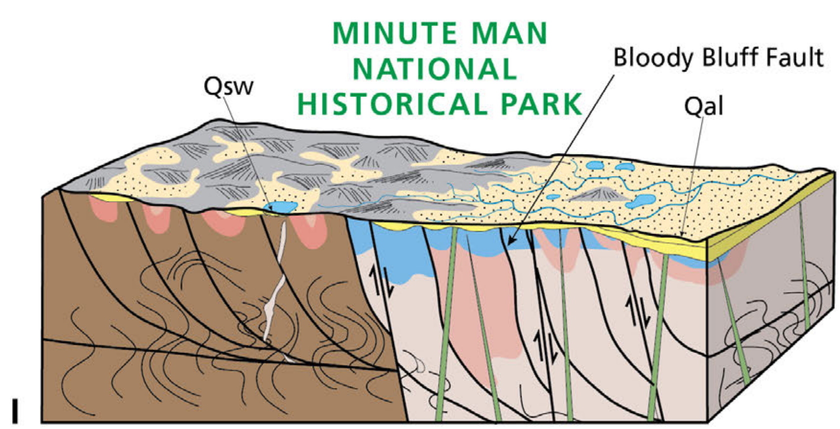


200 million to 145 million years ago–Pangaea began to rift apart. *Atlantic Ocean* began to open. Normal faulting opened basins along the eastern edge of North America and igneous dikes intruded into extension fractures. Sediments accumulated in the basins and onto the Coastal Plain. *Atlantic Ocean* continued to widen as the continental margin became passive.

note: some fault symbology was omitted for clarity



145,000 to 15,000 years ago–Earth surface processes wore away the highlands and removed vast amounts of material from the landscape. Continental ice sheets accelerated the ancient erosion cycle during glacial maxima at 145,000 and 24,000 years ago. The ice deepened and widened valleys, removed all older materials, and built moraines. Upon melting, glacial ice created numerous glacial lakes and streams, which accumulated and reworked vast deposits of till and outwash (Qt, Qsdf and Qsdc).



Past 15,000 years–glaciers retreated, the landsurface rebounded, and Earth surface processes began to form the wetlands and river valleys such as the Concord, Sudbury, and Assabet rivers that now collect alluvium and swamp deposits. Sediments are continually eroded from the highlands and deposited as part of the coastal plain.

Figure 7 G–I. Schematic graphics illustrating the evolution of the Minute Man National Historical Park landscape, continued. Graphics are not to scale. See also figures 4 and 6. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University), with information from Skehan (2001); Hepburn et al. (1993); Stone and Stone (2006); Coleman (2005); Linneman et al. (2007); Thompson et al. (2007); Kopera (2011); and Chris Hepburn, Boston College, geologist, written communication, 5 August 2016.

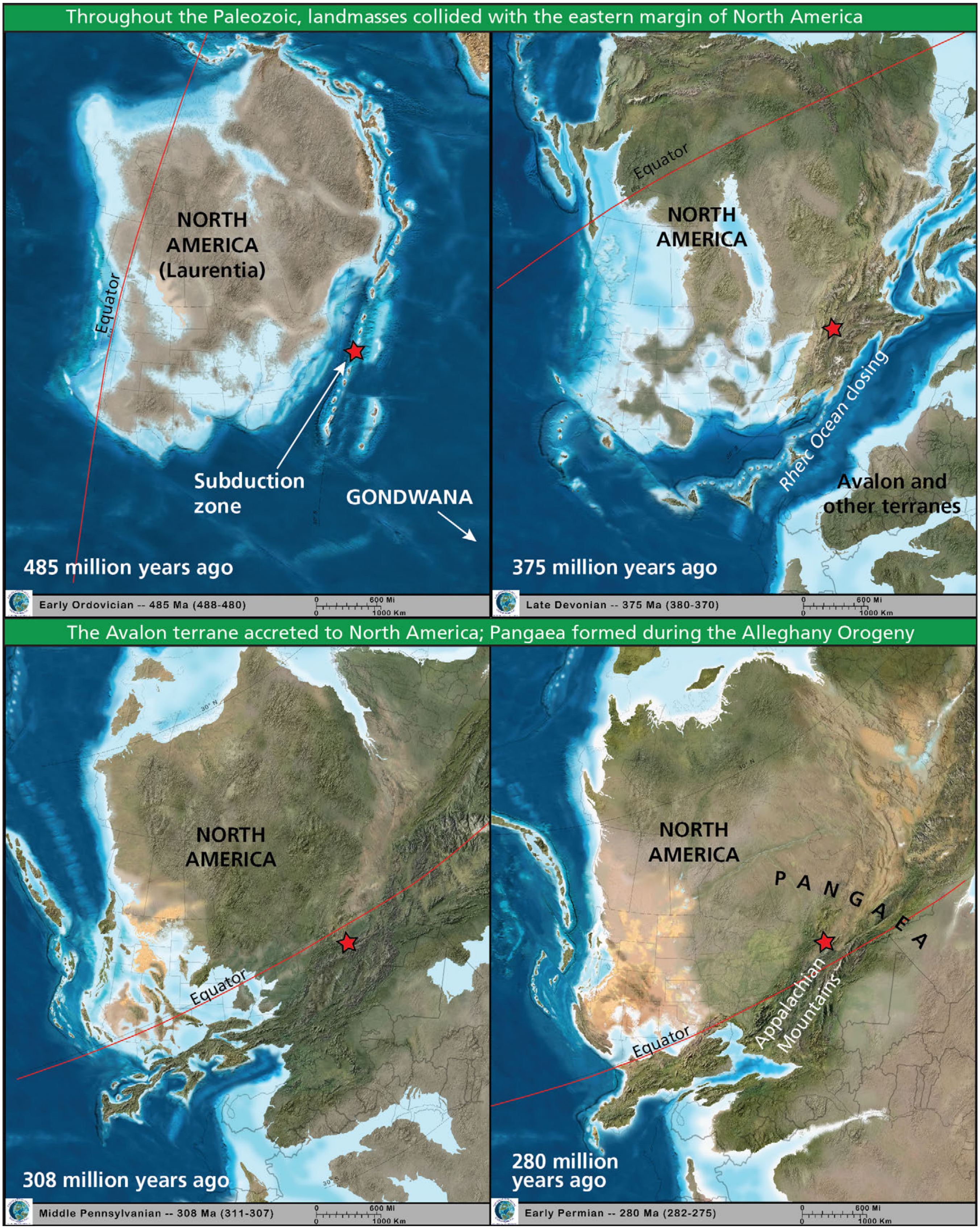
partially melted generating many of the igneous plutons of the Nashoba terrane, including those in the park such as the Assabet Quartz Diorite (**DSaqd**), Sudbury Granite (**Sgrm**), and Andover Granite (**DSag**) (fig. 6E; Langford and Hepburn 2007; Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). Eventually the ocean crust between the Nashoba and Avalon terranes was consumed in the subduction zone and the microcontinent of Avalonia collided into the Nashoba terrane and partially descended into the subduction zone. This collision was likely at a low angle and not a direct perpendicular hit as the Avalon terrane moved northward and under the Nashoba terrane. Research suggests the Burlington Mylonite Zone formed at this time and represents this movement (see fig. 6E; Kohut 1999; Kohut and Hepburn 2004; Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). Because some 15 km (9 mi) of the geologic record have been lost to erosion since this time, what is exposed at the surface today is this shear zone as it was about halfway through Earth's crust. This is analogous to viewing the San Andreas Fault today at a depth of 15 km (9 mi), where the temperature and pressure are much greater. As the Avalon terrane pushed into the Nashoba terrane (and the edge of Laurentia), it gradually crumpled the edge of Laurentia throughout the northeast, forming high mountains across central Massachusetts, similar to modern India moving into Asia and forming the Himalaya Mountains (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016). This was the Acadian Orogeny that took place during the late Silurian and Devonian periods (360 million years ago). The Rheic Ocean between the major continents of Gondwana and Laurentia continued to close and by the Permian Period they came together in the Alleghany Orogeny to form the supercontinent Pangaea (figs. 6F and 8) with continued mountain building.

Throughout millions of years of continental collisions, great deformation, including folding and faulting, occurred in the park rocks (Robinson and Kapo 2003). The individual terranes of eastern Massachusetts were internally deformed and moved along massive faults (see figs. 2 and 6D). The exact timing of accretion is the subject of current study. The Burlington Mylonite Zone-Bloody Bluff Fault, a significant regional geologic structure, transects the park and is named for the Bloody Bluff—an outcrop within Minute Man National Historical Park. The Burlington Mylonite Zone forms the suture along which the Avalon terrane pushed obliquely beneath (subducted under) and next to the Nashoba terrane. The deformation associated with this event took place at great depth, under high temperature and pressure conditions. It may have taken place 420 to 425 million years ago, but the exact date is unknown; the Assabet River Fault may have also been active at this time (Chris Hepburn, Boston College, geologist, professional communication, 30 June 2016). The Bloody Bluff Fault overprinted the mylonites of the Burlington Mylonite Zone, reactivating a pre-existing weakness in the rocks at a later time. The Clinton-Newberry Fault separates the Nashoba and Merrimack terranes (see fig. 2; Hepburn et al. 1987).

The Atlantic Ocean Rifts Open

Once accreted, the Avalon, Nashoba, and other terranes became sutured within the middle of Pangaea. However, Pangaea was not to last, it started to pull apart about 200 million years ago, with rifting between northeastern North America and western Africa during the Late Triassic and Early Jurassic periods opening the Atlantic Ocean basin (figs. 7G and 9; Levin 1999). Crustal stretching may have caused the Bloody Bluff Fault to activate at this time (Chris Hepburn, Boston College, geologist, professional communication, 30 June 2016). Extension is ongoing and the Atlantic Ocean basin continues to widen today. The youngest bedrock in the

Figure 8 (facing page). Paleogeographic maps of North America during the Paleozoic Era. During the Ordovician Period (485 million years ago), the Massachusetts area was dominated by open marine settings as a volcanic arc was approaching the eastern margin of North America. During the Devonian Period (375 million years ago), the Iapetus and Rheic oceans were closing as other landmasses collided with North America during the Acadian Orogeny. The Avalon terrane was one of several terranes accreted to the margin of North America during the Paleozoic orogenies. During the Pennsylvanian Period (308 million years ago), the Alleghany Orogeny formed the Appalachian Mountains. The Appalachian Mountains reached their highest elevation during the Alleghany Orogeny. Red star indicates the location of Minute Man National Historical Park. The approximate location of the Equator is denoted by a red line. Basemaps are from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information. Annotated by Trista L. Thornberry-Ehrlich (Colorado State University).



Throughout the Paleozoic, landmasses collided with the eastern margin of North America
NORTH
AMERICA
(Laurentia)
Equator
Subduction
zone
GONDWANA
485 million years ago
Early Ordovician -- 485 Ma (488-480)
600 Mi
1000 Km
Equator
NORTH
AMERICA
Rheic Ocean closing
Avalon and
other terranes
375 million years ago
Late Devonian -- 375 Ma (380-370)
600 Mi
1000 Km
The Avalon terrane accreted to North America; Pangaea formed during the Alleghany Orogeny
NORTH
AMERICA
Equator
308 million years ago
Middle Pennsylvanian -- 308 Ma (311-307)
600 Mi
1000 Km
NORTH
AMERICA
P A N G A E A
Appalachian
Mountains
Equator
280 million
years ago
Early Permian -- 280 Ma (282-275)
600 Mi
1000 Km

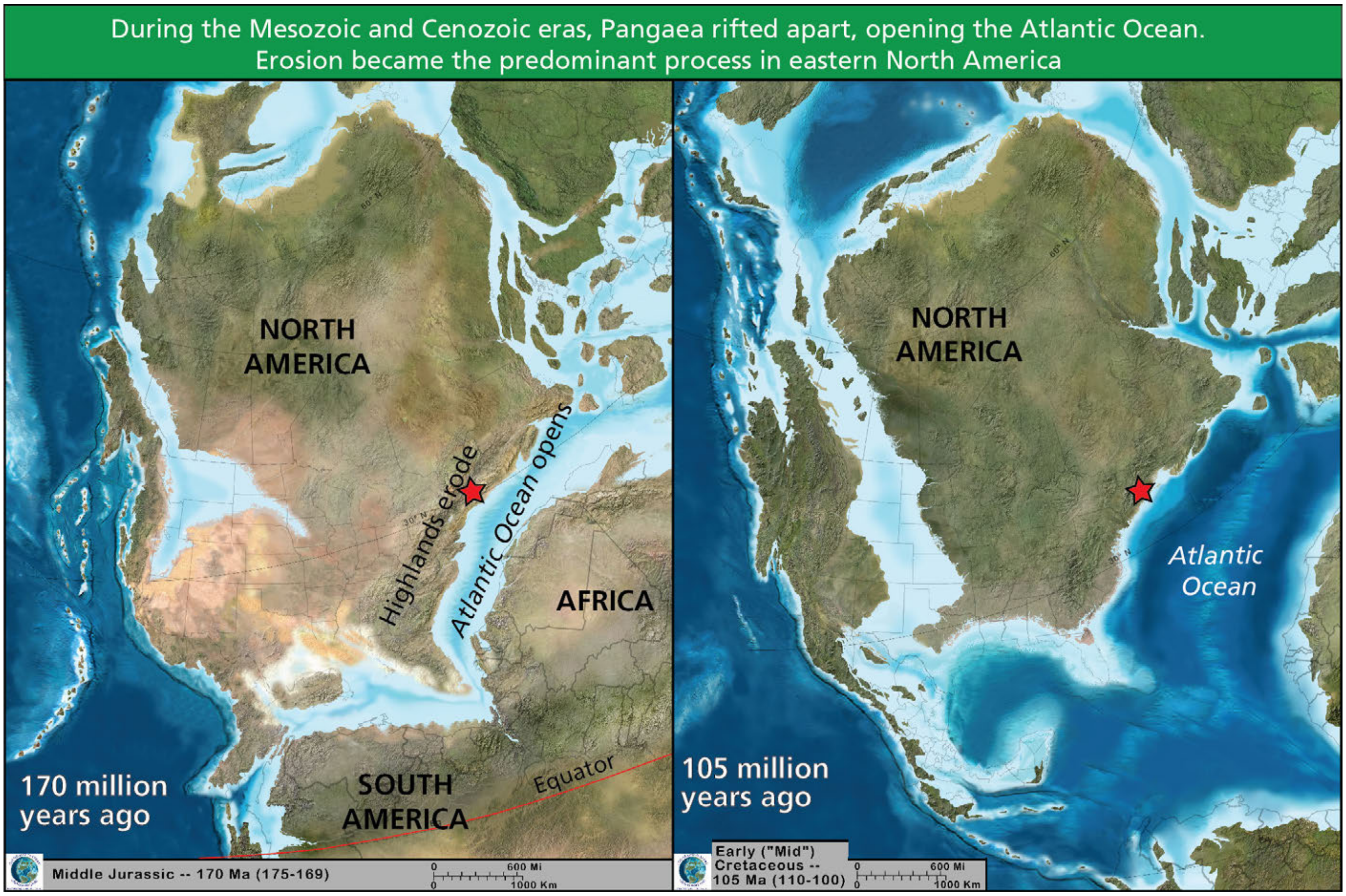


Figure 9. Paleogeographic maps of North America during the Mesozoic and Cenozoic eras. By the Jurassic Period of the Mesozoic Era (170 million years ago), the supercontinent had broken up and roughly the continents that exist today drifted away from North America as the Atlantic Ocean spread. Throughout the rest of the Mesozoic and into the Cenozoic, the Minute Man National Historical Park area was relatively tectonically quiet. Erosion lowered the mountains and built the Coastal Plain toward the widening Atlantic Ocean. Red star indicates the location of the park. The approximate location of the Equator is denoted by a red line. Basemaps are from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information. Annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

park area, diabase (**MZd**), possibly squeezed upwards from deep within the earth along fractures opened during rifting of Pangaea (Langford and Hepburn 2007). The geologic history of eastern Massachusetts has been relatively quiet for nearly the last 180 million years as surface weathering and river erosion whittled away at the massive peaks and ancient valleys across the Nashoba terrane, which contains rocks that once lay some 15 km (9 mi) deep (Chris Hepburn, Boston College, geologist, written communication, 5 August 2016; Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017).

Glaciations and Interglacial Landscape Change

Much later, during the ice ages of the Pleistocene Epoch over the past two million years, huge ice sheets advanced repeatedly from northern Canada over New England, including Minute Man National Historical Park, to ultimately cover more than a third of North America (figs. 7H and 10). Ice sheets significantly altered the pre-glacial landscape by cutting deeply into rocks in the old valley bottoms, eroding hill shapes, and depositing surficial sediments of highly variable composition and thickness across the region. Glacial and post-glacial surficial features of the last two ice sheets dominate the landscape at the park (fig. 11).

About 160,000 to 145,000 years ago, glacial grinding and freezing processes at the base of the older Illinoisan-age ice sheet deepened and widened old valleys, and removed most of the older surficial deposits. The glacial processes produced asymmetric rock-hill

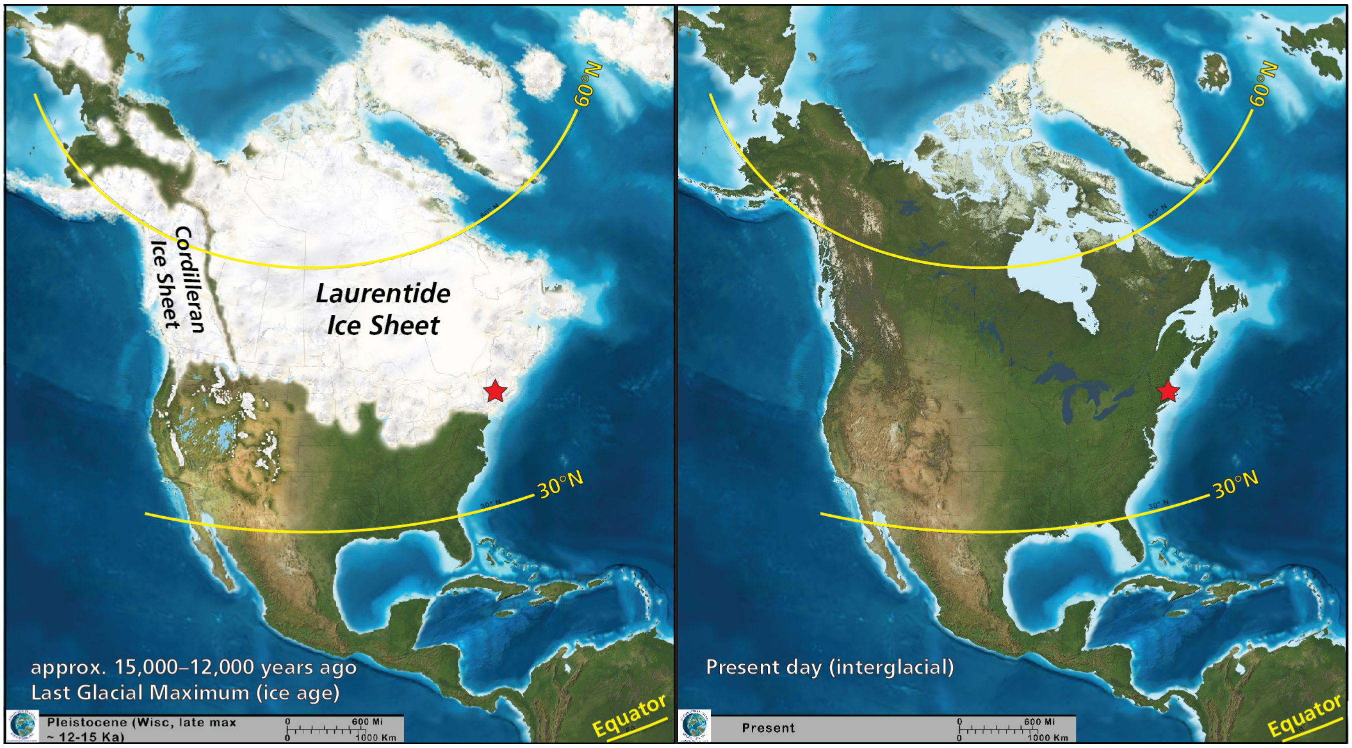


Figure 10. Maps illustrating ice age extent and interglacial conditions. Nearly half of North America was covered by many sheets of ice during the ice age glaciations of the Pleistocene. Relative sea-level drops during glaciations (note the width of Florida). Minute Man National Historical Park is denoted by a red star and was covered by the last ice sheet, which was 1 to 2 km- (0.6 to 1.2 mi-) thick, at least 1 km- (0.5 mi-) thick from about 25,000 to 16,000 years ago. Basemaps are from "North American Key Time Slices" © 2013 Colorado Plateau Geosystems, Inc; used under license. Refer to http://deeptimemaps.com/ for additional information. Annotated by Trista L. Thornberry-Ehrlich (Colorado State University).

shapes—smooth on the north sides while glacially shattered and plucked on south-facing slopes. This typical glacial asymmetry is expressed by Fiske Hill, The Bluff, Smiths Hill at the Concord Turnpike, the hill northwest adjacent to Nashawtuc Hill, and many of the small rock outcrop knobs along the roads of the Park. Thick till deposits (**Qtt**) from this glacier are preserved mostly in drumlins, composed of 15–61 m (50–200 ft) of silt-rich sandy and gravelly, nonsorted, compact till. A weathered olive-brown zone at the top of this till indicates that the Illinoisan drumlins were exposed to surface weathering processes during the subsequent long interglacial time interval. Drumlins are not present within park boundaries, but are located within 2–6 km (1–4 mi) of the borders (Stone and Stone 2006). These include the hill on the west side of Old Bedford Road south of Pine Hill, Hartwell's Hill, Nashawtuc Hill west of Concord village center, Punkatasset Hill northwest of North Bridge. Thick till (**Qtt**) of possible similar origin may underlie the smooth northern slopes of Katahdin Hill and the Hill at Cedar Street east of the headwaters of Kiln Brook (Byron Stone, US Geological Survey, geologist, written communication, 12 February 2017).

About 26,000 years ago, the Wisconsinan ice sheet began to cover the area of Minute Man National Historical Park. The ice thickened here to more than 1.5 km (1 mi) as it flowed, reaching Martha's Vineyard and forming a terminal moraine about 24,000 years ago. Glacial erosion resumed in the lowlands and over rock hills, which produced the large, local- and far-travelled erratic boulders that are so common on today's landscape. The gray till of this glacial event (**Qt**), which lasted to deglaciation about 17,000 years ago, is sandy, gravelly, and bouldery. It forms a thin, discontinuous mantle, generally <1–5 m (1–15 ft) thick over upland rock hills such as Fiske Hill, The Bluff, Pine Hill north of Virginia Road, and the hills east of Lowell Street in the northwestern part of Concord (Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017).

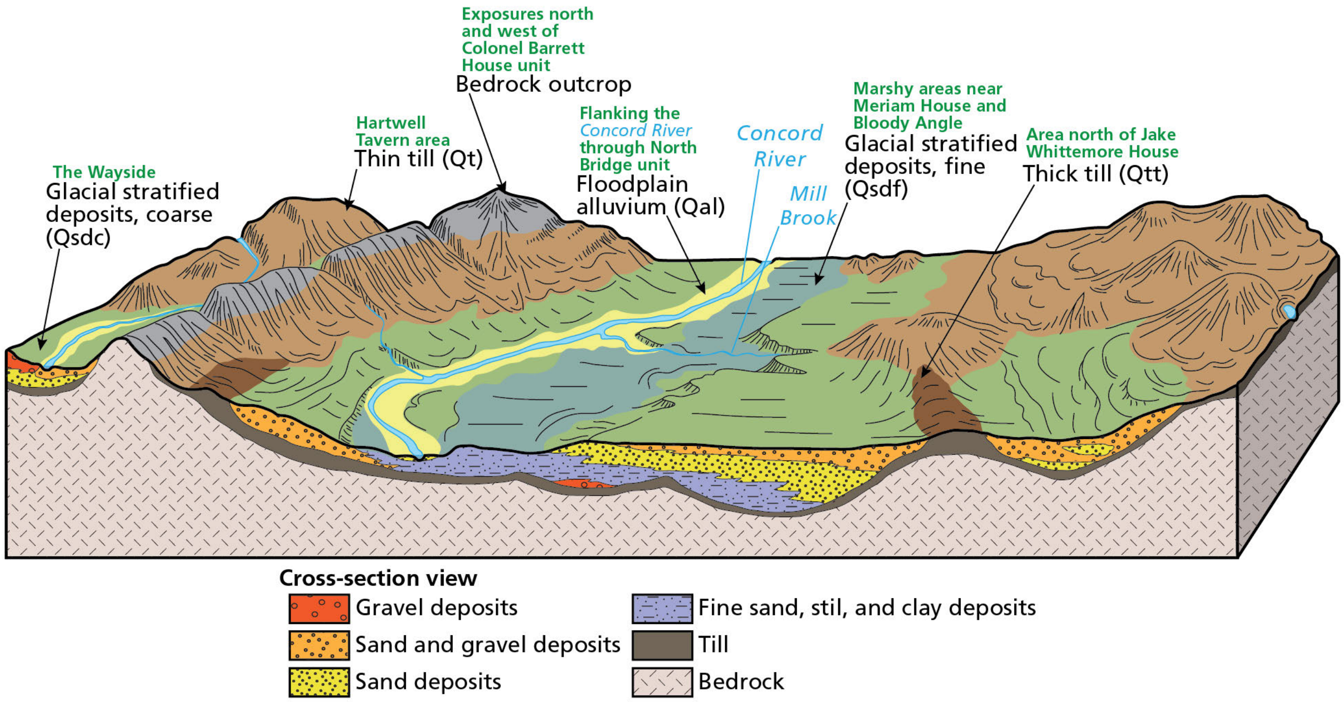


Figure 11. Three-dimensional schematic of surficial deposits. Diagram illustrates the typical areal and vertical distribution of glacial and postglacial deposits overlying uneven bedrock in the park area. Every unit except for Qtt is mapped within the park. Green text refers to local examples, but not with any geographical accuracy on the diagram. Relief and vertical scale are greatly exaggerated to highlight correlations between topography and surficial deposit type. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) after figure 2 in Stone and Stone (2006).

As the ice sheet melted and receded from the terminal moraine, glacial lakes filled basins impounded by rock drainage divides, thick glacial sediments, and the edge of the melting ice. Glacial Lake Sudbury formed between the front of the ice and rock hills to the south where it drained through three spillway channels at 49–47 m (160–155 ft) elevation. To the north, younger Glacial Lake Concord formed at a high, then low level when lake spillways opened at 53 m and 46 m (175 ft and 150 ft) in the Bannon Hill area to the east. Glacial deltas built out into Glacial Lake Sudbury (the Cherry Brook stage) and then into Glacial Lake Concord, and glacial stream deposits accumulated in Hobbs Brook valley as the ice margin melted back across the region. The deltaic and stream deposits accumulated in contact with the stagnant front of the ice sheet, and in part around and over detached ice blocks. Each deposit marks the position of the ice-front and stagnant-ice border during short periods of ice-front stability and concentrated sediment deposition. High, irregular, north dipping ice-contact slopes at the head of each coarse meltwater deposit defines these ice-front positions. Such slopes north of Fiske Hill, north of North Great Road and Nelson Road in the Park, along the northern border of Lake Sudbury deltas south of Cambridge Turnpike and in Revolutionary Ridge are all examples of ice-contact slopes that show the trend of the retreating ice margins. The famous kettle ponds, Folly Pond, Walden Pond, Goose Pond, formed in ice-front deposits after buried ice blocks melted and coarse sandy sediments collapsed into the holes. In Glacial Lake Concord, benches of sand deposits formed along fronts of older high-level deposits, such as along Liberty Street at North Bridge, and north of Buttricks Hill. Lake-bottom sediments filled in depressions on the floors of both lakes. Some lake-bottom deposits contain varved (annual) silt-clay beds, indicative of a few decades of sedimentation (Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017). These units are grouped in the GRI GIS data (**Qsdc** and **Qsdf**), but are delineated in Koteff (1964) into glaciolacustrine and glaciofluvial deposits, including lake-bottom, high stage, and low stage deposits in Minute Man National Historical Park.

When the ice margin retreated north of Billerica, Glacial Lake Concord quickly lowered 14 m (45 ft) and drained into the lake in the Shawsheen valley. This caused a lowering of the water table in the massive deposits of Glacial Lake Sudbury south of the Park such that remaining waters of that lake cut a deep erosional channel as lake waters drained north. This erosion event established an early, periglacial northward drainage of major streams in the area. The integrated Sudbury-Assabet-Concord rivers in Minute Man National Historical Park cut down to bedrock or till outcrops in the Concord-Old North Bridge flood plain, and at other valley narrows along the Concord River to the north. These major rivers developed wide flood plains in river reaches upstream from rocky river-channel knick points or places where the channel slope changes sharply. The Earth's lithosphere tilted when the weight of the ice sheet disappeared from the region. The basins of Glacial Lake Sudbury and Glacial Lake Concord, including their delta and lake-bottom deposits, tilted about 0.9 m/km (4.9 ft/mi) up to the north-northwest. The river channels also tilted, permanently flooding the floodplains upstream of the rock-channel knick points and creating extensive swamps, such as Great Meadows National Wildlife Refuge adjacent to the Park (Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017).

Modern Landscape Development

Following the glacial retreat some 15,000 years ago, and into the beginning of the Holocene, the periglacial climate was still cold and harsh (Thorson and McBride 1988; Ashley and Stone 1995; Ashley et al. 1999; Tweet et al. 2010). Dry conditions continued until approximately 9,500 years ago (Shuman et al. 2001). Streams in the Sudbury, Assabet, and Concord river drainage basins continued to incise deeply into the glacial deposits, reworking them to deposit floodplain alluvium (**Qal**) along their courses and swamp deposits (**Qsw**) in quiet water settings (fig. 7I; Stone and Stone 2006). In recent time, humans have modified landforms in the park area, in some cases on a scale large enough to appear on geologic maps as artificial fill (**Qaf**). These are primarily road and railroad foundations, dams, landfills, filled wetlands, and suburban development areas (Stone and Stone 2006).

Geologic Significance and Connections

As stated in the park's Foundation Document, one of the primary purposes of Minute Man National Historical Park is to preserve the historic landscapes associated with the beginning of the American Revolution, which lie along the route of battle of April 19, 1775 (National Park Service 2015). The historic landscapes—the Battle Road, farmsteads, bridges, stone walls, fields, orchards, and homes—also feature in the park's fundamental resources and significance statements, which express why a park's resources and values are important enough to merit designation as a unit of the National Park System (National Park Service 2015). Each of these landscape features are underpinned by the geologic foundation and evolution of eastern Massachusetts.

Precontact Human Presence

The human history recorded in Massachusetts dates back more than 10,000 years when humans first appeared in the area during the harsher climatic conditions following the ice ages (Ritchie et al. 1990). Outside the park in eastern Massachusetts, shell middens and fossilized food remains attest to early human inhabitants and potential exists for such resources from within Minute Man National Historical Park (Luedtke and Rosen 1993; Tweet et al. 2010). There are at least 35 sites within park boundaries that have not been professionally excavated (Herbster 2005). The Concord area was occupied at least as early as the Middle and Late Archaic periods (8,000 BP to 3,000 BP).

Mylonite (a very fine-grained, deformed rock) from the Burlington Mylonite Zone-Bloody Bluff Fault, Westboro Formation quartzite (**Zwm**), and Marlboro Formation amphibolite (**COm**) were among the local lithic materials used to craft chipped- or ground-stone tools (Herbster 2005). American Indians planted crops, established trail networks, fished and constructed fish weirs in the Musketequid River (Algonquin for "grass-ground river") and today's Concord River and other nearby streams, and used fire to manage the woodlands (Dietrich-Smith 2004; Herbster 2005). American Indian campsites on the hilltop overlooking the Concord River are underlain by glacial deposits (**Qsdc** and **Qt**). A natural sandbar (part of **Qal**) there, formed where Mill Brook enters the Concord River, may have provided a natural crossing place (Dietrich-Smith 2004). The wet meadows bordering the river (**Qal** and **Qsw**) were vital sources of food and weaving materials (Dietrich-Smith 2004). American Indian fields were mostly located just before the confluence of the Assabet and Sudbury rivers (southwest of the North Bridge unit) where floodplain alluvium (**Qal**) provided a rich and fertile substrate (Dietrich-Smith 2004). By the 1630s, diseases introduced by European colonists and displacement by the colonists had decimated the indigenous population (Dietrich-Smith et al. 2008). Herbster (2005) presents a comprehensive overview and assessment of the park's archeological resources.

Early European Colonists and the Lead Up to the American Revolution

Eighty historic sites recorded within the park are testament to its long history and significance as a cultural landscape (Fabos et al. 1993; National Park Service 2015). The recent geologic events of Pleistocene Epoch glaciation and subsequent surficial weathering and reworking of the glaciated landscape by rivers and streams most profoundly influenced the initial settlement patterns of the area. European settlers were attracted to the area because of the relatively flat landscape, fertile soil, wetland meadows, abundance of forests, and fresh water (Dietrich-Smith 2004).

"Concord Plantation" was established by a handful of Puritan families venturing inland in 1635. They dug cellars into the glacial deposits underlying Authors Ridge (behind The Wayside; geologic map unit **Qt**) (Stone and Stone 2006; Dietrich-Smith et al. 2008). Colonists built houses on hills and ridges underlain by **Qt** and overlooking the western side of the Concord River in the North Bridge unit, as well as gentle slopes and terraces underlain by glacial lake deposits **Qsdc** and **Qsdf** (Dietrich-Smith 2004). Authors Ridge and Revolutionary Ridge just to the east are (kame) deltaic deposits left between retreating Pleistocene glacial ice and Glacial Lake Concord (Thornberry-Ehrlich 2008). Homes flanked this ridge for protection from the northern wind and the road ran along its southern flank. The road is on a divide between drainages, flanked by boggy swamplands (Thornberry-Ehrlich 2008). Ridges and areas underlain by the coarser, better-drained glacial deposits (**Qsdc**) were favored for building sites and roads such as the original Battle Road. Grading reduced the steepness of some slopes for roads, for example in the Bloody Angle area (Dietrich-Smith et al. 2012).

The Mill Brook sandbar (**Qal**) provided passage across the Concord River when water levels were low, but a simple wooden bridge was needed the rest of the year. The earliest record of a "North Bridge" was in 1654 (Dietrich-Smith 2004). The bridge was approached by a low and narrow causeway. A new causeway, constructed from local sandy clay (possibly from **Qsdf**) and gravel (possibly from **Qsdc**) and fronted by a stone wall, was in place by 1753 (Dietrich-Smith 2004). A new North Bridge was installed in 1760—a wooden structure covered with loose planks with a railing (Dietrich-Smith 2004).

The glacial till (**Qt** and **Qtt**) underlying much of the upland areas proved a variable substrate with some areas unsuitable for growing traditional barley crops. Instead, colonists cultivated corn on partially cleared land, planted apple orchards, and cleared land for pastures instead of tilled fields (Dietrich-Smith 2004; Thornberry-Ehrlich 2008). The western half of the Battle Road unit, underlain by nutrient-rich Glacial Lake Concord sediments (**Qsdf**) was more fertile than the upland glacial tills that characterize the eastern half (Dietrich-Smith et al. 2012). Some lands underlain by the clay-rich, fine-grained glacial lake deposits (**Qsdf**) were boggy, forming swamps and wetlands (**Qsw**) (Stone and Stone 2006). Some flat wetland areas, such as those bordering Elm Brook, were ditched, drained, and hayed (James-Pirri 2009). Many of these wet meadows were held as "commons" and located throughout the area; their hay provided valuable winter forage for livestock (Dietrich-Smith 2004). Later, as demands for animal feed increased, many wetlands were drained and planted with more nutritious grasses (Dietrich-Smith 2004). Indeed, by 1775, the agrarian society had likely reached its ecological limits and faced diminishing prospects. This may have contributed to a strong sense of the need to defend an endangered way of life from British imperial economic and political rein (Fabos et al. 1993).

Glacial erratics (boulders transported by glaciers and deposited far from their original location) and outwash boulders and cobbles provided abundant stone-wall material, stone road bases (near North Bridge), and are part of local stone building foundations and cellars (Yocum 2003; Dietrich-Smith 2004; Thornberry-Ehrlich 2008). Many of these features would play roles in the battles to come.

Local Landscape and the Start of the American Revolution

By 1775, most of the Lexington and Concord area was colonized and cleared for agriculture. Some families had lived there for generations and felt themselves at odds with British Parliament and King George III and the constrictions imposed by British rule. They had been planning resistance and storing arms in buildings throughout the area. In April, the situation quickly came to a head as 700 British troops marched to Concord (later joined by a relief column of 1,000 regular soldiers) to find and destroy colonial weapons and ammunition (including arms stored at Barrett's Farm unit) to undermine seditious activity. They encountered a force beyond sedition, one that had evolved into open rebellion. The events and history of the battle are well explained in the 1985 historic grounds report "The Scene of the Battle" and in a geologic context in Kaye (1976). The following is a brief summary.

The surficial geology and topography of the area played a pivotal role in the lead up to the battle, the sequence of battle events, and the eventual outcome. The superior knowledge and use of the landscape by the local Minutemen allowed them to keep their casualties low while engaging some of the best trained soldiers (Barosh and Sideris 2006).

The landscape features subtle ridges underlain by glacial deposits (**Qt**, **Qtt**, **Qsdc**) flanked by low-lying areas underlain by glacial and fluvial deposits (**Qal**, **Qsw**, and **Qsdf**; Stone and Stone 2006). Lexington Green and the original Battle Road were constructed, as much as possible, on well-drained, higher ground above marshy meadowlands. In this area, this typically means the substrate is glacial till or coarse glacial stratified deposits laid down by a glacially fed stream (**Qt**, **Qtt**, and **Qsdc**) that form flat-topped plains which fill the old bedrock valleys underneath, and thus were the preferred road way. This is a characteristic of colonial roads (and game trails before) in the glaciated northeastern United States (Kaye 1976; Stone and Stone 2006; Thornberry-Ehrlich 2008; Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017). The first standoff at Lexington Green saw British soldiers shoot and kill eight colonials. The rest of the colonials fled and regrouped later in the day.

Colonial Minutemen and militia gathered on the ridgeline west of the North Bridge underlain by glacial deposits (**Qsdc**). They saw fires in the town of Concord and feared the town was being burned; they needed to cross the bridge being guarded by British troops. North Bridge was the site of the "shot heard 'round the world" that marked the beginning of armed, open rebellion against British soldiers as colonials returned fire, killing one British soldier and mortally wounding two others. Outnumbered and exposed in this narrow neck of land between swampy alluvium, the Concord River, and Poplar Hill, where there was no room for flanking maneuvers, the British could not hold their position and quickly retreated down the road towards the center of Concord. Their dead were buried in glacial deposits (**Qsdf**) bordering the south side of the road crossing the North Bridge; today, the double grave is marked by moss-covered stones (probably glacial erratics) on the north side of the wall that separates the commemorative landscape from the Old Manse field (Dietrich-Smith 2004).

The British retreat to Boston would not be an easy task. The British rear guard and Minutemen exchanged fire at Meriam's Corner and along the eastern flank of Revolutionary Ridge (a glacial feature called a kame delta; see fig. 16), beginning the drawn-out fight known as the "Running Battle" that continued along the Battle Road back to Lexington and beyond on April 19, 1775 (Fabos et al. 1993; Yocum 2004). Lexington (also called "Bay" or "County" road) and Old Bedford (also called "Bellerica" or "Bedfork" road) roads intersected at Meriam's Corner (Yocum 2004). This location took advantage of the higher ground and better drainage of the glacial deposits (**Qt** and **Qsdc**) and avoided as much as possible, the boggy, poorly drained areas underlain by **Qsw** and lake-bottom deposits **Qsdf** (Stone and Stone 2006; **Qlcb** by Koteff 1964). Meriam's Corner forms a point where the kame delta ridge ends, merging with lake-bottom sediments (**Qsdf**) of the flatter surrounding areas. The delta extends from its source esker (subglacial or ice-tunnel stream within a glacier; see fig. 16), composed of sand and gravel originating in an ice-tunnel stream in the ice sheet, to this spot where it passes beneath the land surface and the overlying lake-bottom sediments. This is analogous to a modern stream entering a lake and dumping its sediment load into a stream delta. This esker was short lived as the glacier melted away; it did not exist long enough to spread the kame delta any further east. When meltwater sediment supply was later diverted from the ice channel, the esker and delta deposits were abandoned (Thornberry-Ehrlich 2008; Byron Stone, geologist, US Geological Survey, written communication, 12 February 2017).

Throughout the day, colonists used the local ridges and hills (e.g., Brooks Hill, Bloody Angle, The Bluff, and

Fiske Hill), ditches, bedrock outcrops, stone walls, large glacial erratics, and manmade structures to shield their movements and ambush the British repeatedly as they retreated along Battle Road; families similarly used local hills and other features as places of refuge (Yocum 2004; Zenzen 2010; Thornberry-Ehrlich 2008).

Fighting was most intense along Battle Road between the Meriam's Corner and Bloody Angle (Yocum 2004). Bloody Angle is where the original Battle Road veered sharply from the northeast to the southeast to rise in elevation atop glacial till (**Qt**) and avoid a boggy swampland ahead underlain by **Qsdf** and **Qsw**. Further east, another glacial till hill was the location for "Parker's Revenge" where the Lexington militia leader, Captain Parker, ordered his men to take position and fire a volley against the British. Bloody Bluff (then known as "The Bluff") and Fiske Hill were the locations of the last engagements within what is now the park. The bluff—tracing a significant geologic boundary between terranes—was a steep, thickly wooded hill that the British succeeded in securing; however their advantage was quickly lost when they came within range of the militia at Fiske Hill (Herbster 2005). At this point, the British, outnumbered and surrounded, broke formation and fled towards Lexington. They lost 73 men to the colonists' 49 casualties. The fighting continued along the old Bay Road and proved the rebellion was not to be forgotten, but instead was a serious fight for the right to self-government (Zenzen 2010).

Post Revolution Development and The Wayside

After the American Revolution, the area returned to a rural, agricultural way of life. The landscape was increasingly altered over time. Roads and bridges were improved and in some cases (e.g., North Bridge) moved or replaced (Dietrich-Smith 2004). Forests were cleared to supply timber for growing Boston and more pasture for local livestock (Dietrich-Smith 2004). This clearing removed stabilizing tree roots from the soils and probably led to increased erosion and sediment load in local streams and rivers.

Efforts to commemorate the battle and place memorials began in earnest in the 1820s. The memorials were first placed at the site of the North Bridge. A memorial stone erected at Meriam's corner was likely a glacial erratic. These types of activities attracted thousands of visitors each year, and required new facilities and infrastructure which took a toll on the battleground landscape, altering the historic setting (Dietrich-Smith 2004). In the 1920s, coincident with the sesquicentennial of the battle, commemoration and access needs continued with infrastructure construction including parking lots and new road alignments within and near the North Bridge unit; plants were added to reduce foot-traffic erosion (Dietrich-Smith 2004). The population of Concord and Lexington rapidly increased after World War II and suburbanization quickly obscured the historic setting of Battle Road.

Topography and land use were identified as some of the significant landscape characteristics of The Wayside unit and surrounding areas influencing a local literary legacy with such notable names as Emerson, Thoreau, Alcott, Hawthorne, and Lothrop (Zenzen 2010; Dietrich-Smith et al. 2008). The Alcott literary family purchased The Wayside in 1845, calling it "Hillside" (Dietrich-Smith et al. 2008), no doubt in reference to its location at the base of the Authors Ridge-Revolutionary Ridge kame delta, which forms a sort of amphitheater around the property's lawn. The family terraced the hillside for farming, altered slopes, constructed paths, and installed retaining walls to expand the rear lawn area and hold back the steep slope. At this time, there were nearly no trees with roots to curb erosion on the landscape; it was little more than "sand and gravel." Nathaniel Hawthorne eventually bought the property, renaming it "The Wayside." He planted stabilizing trees on the terraced slopes behind the house. He paced about on a network of paths along the kame-delta ridge for writing inspiration—the most famous of which is the "Hawthorne Path" (Dietrich-Smith et al. 2008). The historic 1938 hurricane during Margaret Lothrop's tenure destroyed most of the stabilizing trees from Hawthorne's time and damaged the Alcotts' stone walls (Dietrich-Smith et al. 2008).

Managing a Cultural Landscape

The park's management strategies seek to preserve the cultural landscape and the effects of humans on the landscape insomuch as they reflect historically significant events (Fabos et al. 1993; Thornberry-Ehrlich 2008). More information about the myriad cultural resources and landscapes at the park are available from Fabos et al. (1993), Yocum (2003), Dietrich-Smith (2004), Earth Tech (2004), Yocum (2004), Herbster (2005), Lee (2007), Rockmore and Carroll (2007), Dietrich-Smith et al. (2008), John Milner

Architects, Inc. (2008), Zenzen (2010), and Dietrich-Smith et al. (2012).

In addition to the historical connections briefly presented here, geologic features and processes are fundamentally connected with soils, water resources, vegetation patterns, and more than 20 animal habitats (Shriver et al. 2004). Additional information is available in the following resources.

- A Soil Resource Inventory including GIS data was completed in 2006 and is available at https://irma.nps.gov/DataStore/Reference/Profile/1048931 (accessed 12 February 2016).
- Information regarding the park's water resources is available from the NPS Water Resources Division at https://www.nps.gov/orgs/1439/index.htm (accessed 25 February 2016); a baseline water quality project is available at https://irma.nps.gov/DataStore/Reference/Profile/2173885; lake, pond, and stream monitoring data are available at https://irma.nps.gov/DataStore/Reference/Profile/2190885.
- The vegetation inventory is still in progress; some data are available at http://www.umesc.usgs.gov/mapping/nps_vip.html (accessed 24 February 2016).
- Land-cover data are available at https://irma.nps.gov/DataStore/Reference/Profile/2167120 (accessed 16 February 2016).
- The Northeast Temperate Network currently monitors natural resources such as water quality, air quality, breeding landbirds, reptiles and amphibians, forests, and invasive species (Shriver et al. 2004; http://science.nature.nps.gov/im/units/NETN/index.cfm, accessed 10 February 2016).
- James-Pirri (2009) provides a current condition of natural resources at Minute Man National Historical Park including land use dynamics, vegetation communities, faunal communities, water resources (including wetlands), and parkwide resources such as soils, air quality, soundscape, and visitor use.
- The Foundation Document (National Park Service 2015) outlines purpose, significance, fundamental resources and values, other important resources and values, and interpretive themes, as well as an assessment of planning and data needs.

Geologic Features, Processes, and Resource Management Issues

These geologic features and processes are significant to the park's landscape and history. Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources.

Minute Man National Historical Park consists of a weathered, glaciated landscape over a major bedrock boundary between two accreted terranes that form part of eastern Massachusetts. The park's history played out on this landscape and its preservation is the most important resource management concern.

During the 2007 scoping meeting (see Thornberry-Ehrlich 2008) and 2016 conference call, participants (see Appendix A) identified the following geologic resource management issues, features, and processes. Each is summarized in a table that provides basic information, park examples, additional resources and potential action items.

- Fluvial Features and Processes (table 2)
- Wetlands (table 3)
- Glacial Features (table 4)
- Eolian Features (table 5)
- Bedrock Exposures (table 6)
- Faults and Shear Zones (table 7)
- Flooding and Wetlands Restoration (table 8)
- Erosion and Slope Movement Hazards, and Risks (table 9)
- Aquifers and groundwater availability (table 10)
- Disturbed Lands and Abandoned Mineral Lands (table 11)
- Seismic Activity Hazards and Risks (table 12)
- Paleontological Resource Inventory, Monitoring, and Protection (table 13)

Geologic Resource Management

The Geologic Resources Division provides technical and policy support for geologic resource management issues surrounding three emphasis areas:

- geologic heritage,
- active processes and hazards, and
- energy and minerals management.

Contact the division (http://go.nps.gov/geology) for assistance with resource inventories, assessments and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs (Geoscientists-in-the-Parks and Mosaics in Science). Park staff can formally request assistance via https://irma.nps.gov/Star/.

The Geoscientists-in-the-Park and Mosaics in Science programs are internship programs which place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. Completed projects are available on the GIP website (http://go.nps.gov/gip). Products created by the program participants may be available on that website or by contacting the Geologic Resources Division. No GIPs have yet completed projects at Minute Man National Historical Park.

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

The park's Foundation Document (National Park Service 2015) and Natural Resource Assessment (James-Pirri 2009) are primary sources of information for resource management within the park. Cultural landscape restoration and management are also addressed in a number of publications, including Fabos et al. (1993), Dietrich-Smith (2004), Herbster (2005); and Dietrich-Smith et al. (2008).

Table 2. Summary of fluvial features and processes.

Geologic Feature and Process	Fluvial Features and Processes
Description	• Fluvial features formed by open-water flow in stream channels. Fluvial processes both construct (deposit alluvium) and erode landforms (fig. 12). Examples of fluvial features include (figs. 13 and 14): □ **Meandering river channels**—as a river flows around curves the flow velocity (and thus erosive energy) is greatest on the outside of the bend. The river erodes into its bank on the outside of a curve and leaves point bar deposits on the inside of the bend. As the process continues, the outside bend retreats farther, while the inside bend migrates laterally, creating migrating meanders (fig. 12). □ **Oxbow lakes**—as meander bends migrate, the "neck" of land between two bends narrows and eventually may be cut through. Then, the meander is abandoned by the stream leaving "oxbow" lakes. □ **Point bars**—point bars are crescent-shaped ridges of sand, silt, and clay deposited on the inside of meander loops where the water's velocity is slowest. □ **Natural levees**—during high flows or floods, a river deposits natural levees of sand and silt along its banks. These deposits represent the relatively coarse-grained component of a river's suspended sediment load and form a high area on an alluvial region's land surface. □ **Backswamps**—backswamps are low-lying areas that retain water during floods or high flow and are commonly separated from the river channel by natural levees.
Related Map Units And Park Examples	• **Qal;** Some examples mapped on figure 14 • The park lies within the Concord, Shawsheen, and Charles rivers' drainage basins, thus straddling several drainage divides. The Assabet and Concord rivers are the primary rivers in the park (see posters, in pocket). • The Assabet and Concord rivers have very low gradients of 1.3 m/km (7ft/mi) for Assabet and 0.03 m/km (1.9 inches/mi) for the Sudbury/Concord river system. The Sudbury/Concord system drops less than 1 m (2 ft) in a distance of 37 km (23 mi) from the small fall line in Saxonville to North Billerica. The very low gradient is characteristic of meandering streams. • The Concord River is a Wild and Scenic River. • Elm Brook drains from marshy areas near Bloody Angle in the Battle Road unit. • Wetlands (including backswamps) flank the Concord and Assabet rivers and streams in the park (see tables 3 and 8). • A sandbar where Mill Brook flowed into the much slower Concord River provided passage over Concord River in colonial times. North Bridge was later constructed at the site (see "Geologic Setting, History, and Significance" section); in some areas, rock outcrops in **Qal** and lake-bottom areas act to limit erosion and preserve the local alluvial and lake sediments from fluvial erosion—a classic geomorphologic relationship in New England (Byron Stone, US Geological Survey, geologist, written communication, 12 February 2017). • 70% of the North Bridge unit lies within the Massachusetts Natural Heritage and Endangered Species Program's core habitat area as a small-river flood plain forest.
Related Resource Management Issues and/or Vital Signs	• Flooding and Wetland Restoration (table 8) • Hydrology, stream geomorphology vital sign (Shriver et al. 2004
Potential Action Items	• If the park desires quantitative information regarding rates of change and channel morphology, repeat photography could be performed at designated photo points to monitor changes. Refer to http://go.nps.gov/grd_photogrammetry for information about using photogrammetry for resource management.
Primary References or Resources	• GRI GIS surficial geologic map data source: Stone and Stone (2006) • Archeological assessment: Herbster (2005) • Northeast Temperate Network Vital Signs: Shriver et al. (2004) and Mitchell et al. (2006) • Natural Resource Assessment: James-Pirri (2009)

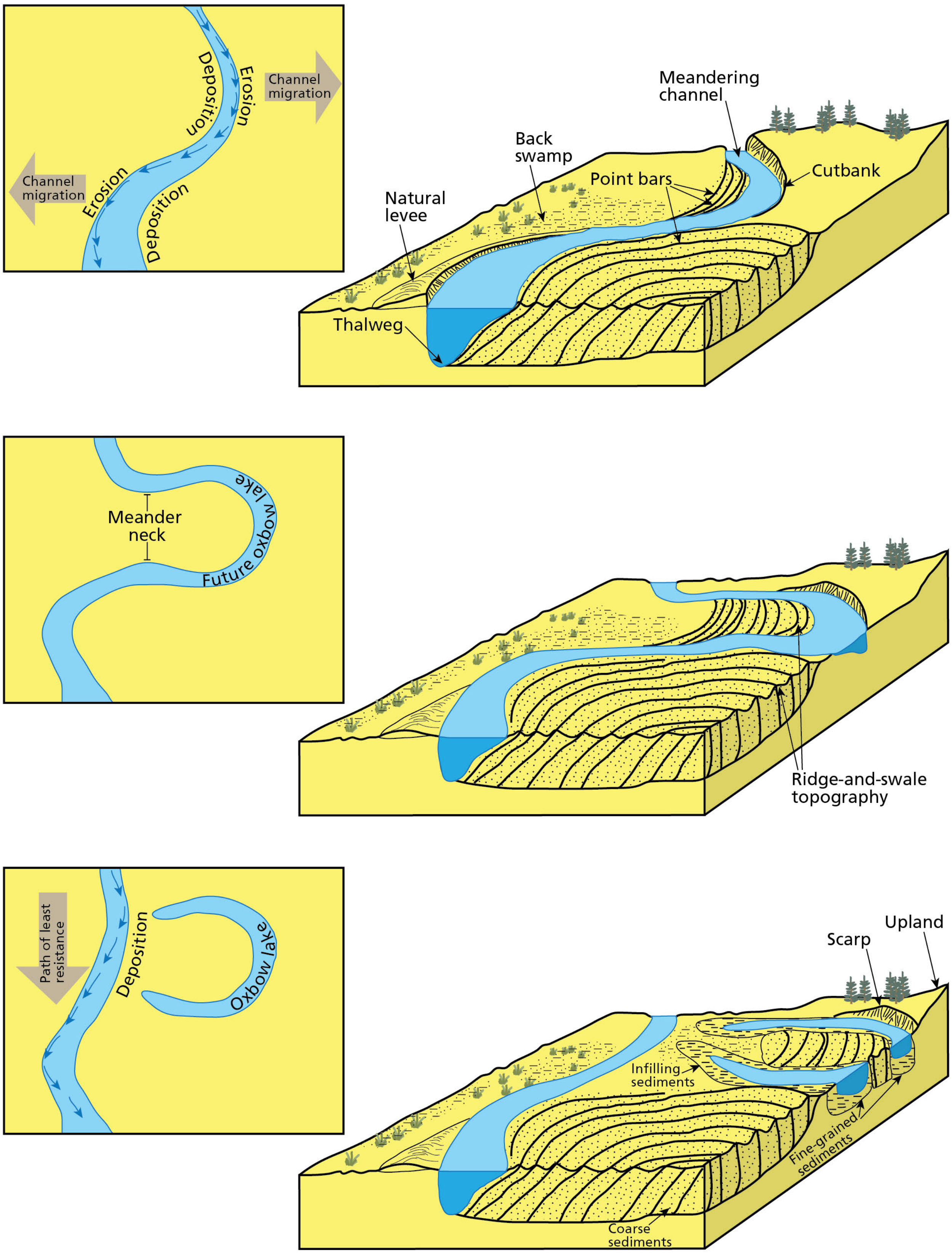


Figure 12. Schematic illustrations of stream meandering. The Assabet and Concord rivers meander across their floodplains creating characteristic patterns of abandoned meanders and oxbow lakes. See figures 13 and 14 for more detail. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

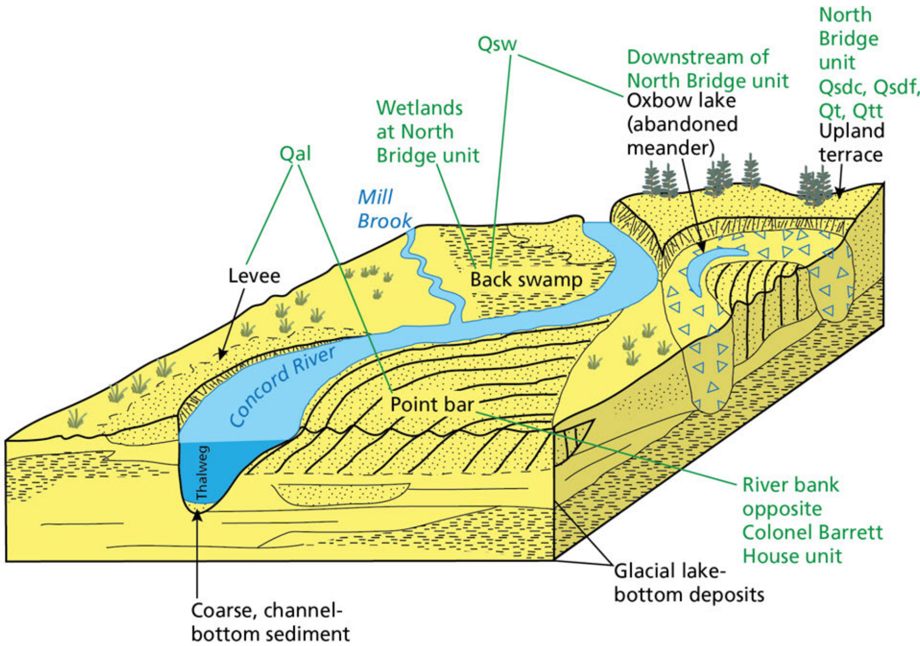


Figure 13. Schematic illustration of alluvial deposits and depositional settings. The Concord River is flanked by swamps and wetlands in the park area. At the North Bridge unit, the river passes an upland area that was high ground during the April, 1775 battle. Green text refers to local examples and relevant geologic map units present at Minute Man National Historical Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

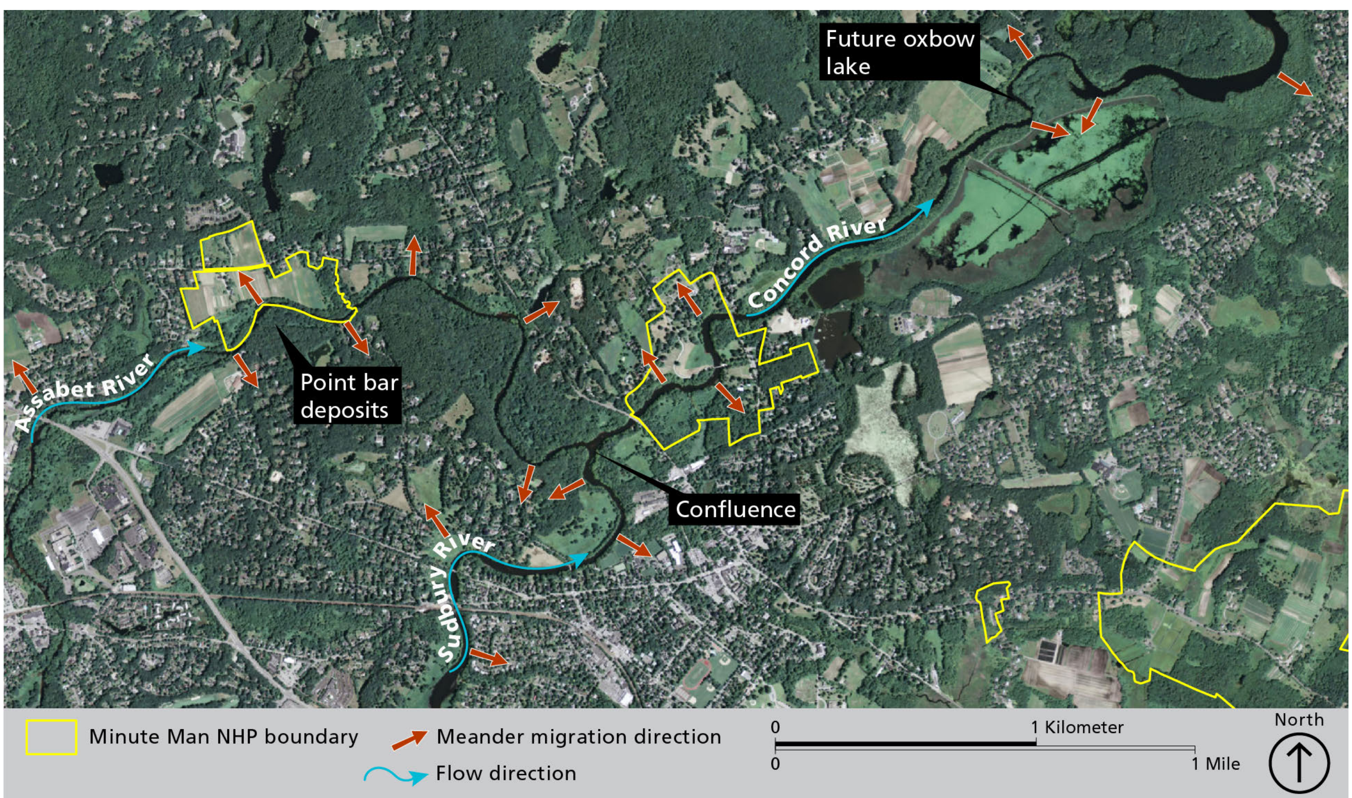


Figure 14. Aerial image of fluvial features. Minute Man National Historical Park (yellow boundary) has characteristic fluvial features created by the Assabet, Sudbury, and Concord rivers as well as numerous small streams and brooks. Red arrows indicate directions in which the rivers' meanders are migrating. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) and using ESRI World Imagery basemap (accessed 16 June 2016).

Table 3. Summary of wetland features and processes.

Geologic Feature and Process	Wetlands
Description	• Transitional areas between land and water bodies, where water periodically floods the land or saturates the soil and includes marshes, swamps, seeps, pools, and bogs. • May be covered in shallow water most of the year, or be wet only seasonally. • Wetlands provide several significant functions, including (1) provision of bird and other wildlife habitat, (2) surface water detention, (3) nutrient transformation, and (4) retention of sediments. • Some wetlands developed over glacial features such as kettle ponds (see table 4 Glacial Features).
Related Map Units And Park Examples	• **Qsw** • Wetlands restoration is a major resource management effort in the park (see table 8). • One-third of the park is wetlands, which flank most local streams and rivers (fig. 15). These palustrine (marsh) wetlands are inland freshwater, non-tidal wetlands characterized by trees shrubs, and emergent vegetation. Park wetland types: forested wetlands, shrub swamps, and emergent wetlands. • Folly Pond and other small ponds. • Kettlehole (glacial feature) wet meadows (considered a "vulnerable" community by the Massachusetts Natural Heritage and Endangered Species Program: http://www.mass.gov/eea/agencies/dfg/dfw/natural-heritage/). • A red maple-black gum swamp (considered an "imperiled" community by the Massachusetts Natural Heritage and Endangered Species Program: http://www.mass.gov/eea/agencies/dfg/dfw/natural-heritage/). • Elm Brook wetland. • Vernal pools. • Wetland landcover acreage within the park increased 45% between 1974 and 2000 largely due to beaver activity and restoration efforts. • Boggy wetland areas forced the original Battle Road to curve sharply at Bloody Angle. • The "Great Meadows" just outside the North Bridge unit. • The North Bridge unit is within the Massachusetts Natural Heritage and Endangered Species Program's rare wetlands area.
Related Resource Management Issues and/or Vital Signs	• Flooding and Wetland Restoration (table 8) • Disturbed Lands and AML (table 11) • Hydrology vital sign (Shriver et al. 2004)
Potential Action Items	• Inventory and monitor the condition of park wetlands, particularly with regards to invasive plants, impacts from roads (habitat dissection and runoff), and impaired water quality. • Inventory vernal pools. • Follow wetland assessment guidance outlined in James-Pirri (2009).
Primary References or Resources	• NPS Water Resources Division (https://www.nps.gov/orgs/1439/index.htm) • Foundation document: National Park Service (2015) • Forest monitoring: e.g., Miller et al. (2010; 2013) http://science.nature.nps.gov/im/units/netn/index.cfm • Landcover change: Wang and Nugranad-Marzilli (2009) • Natural Resource Assessment: James-Pirri (2009) • The Wetlands Protection Act: http://www.mass.gov/eea/agencies/massdep/water/regulations/310-cmr-10-00-wetlands-protection-act-regulations.html • Northeast Temperate Network Vital Signs Monitoring: Shriver et al. (2004) • Northeast Temperate Network vital signs monitoring plan: Mitchell et al. (2006)

Figure 15. Photograph of palustrine wetlands flanking the Concord River at North Bridge. At Minute Man National Historical Park, many low-lying areas are wetlands. These natural features affected the movement of both British troops and colonial militiamen in April 1775. Wetlands have yet to be comprehensively inventoried at the park. NPS photograph, taken in spring 2014 when adjacent wetlands flooded.

Table 4. Summary of glacial features and processes. Table continues on next page.

Geologic Feature and Process	Glacial Features
Description	● Glaciers, particularly the continental ice sheets during the ice ages, profoundly shaped landscapes and created a variety of distinctive features (figs. 16 and 17). ● Glacial features abound in and near the park including (figs. 16 and 17): □ **Kettle ponds**—kettle ponds formed where glaciers left huge detached blocks of remnant ice that were surrounded and buried by sediments, then later melted forming a water-filled depression (see fig. 17). □ **Kame deltas**—glacial lake deltas (also referred to locally as kame deltas) formed where sediment-bearing meltwater streams emerged from the front of the ice sheet or at the mouth of a river and deposited sandy beds in the lake and gravelly fluvial beds in the delta plain that extended out on top of the sand (Byron Stone, US Geological Survey, geologist, written communication, 12 February 2017). □ **Outwash plains**—sand and gravel outwash plains emanated from the melting glacier as meltwater fluvial channels transported water and sediments down valley. □ **Glacial till**—till was deposited by plastering-on of particles (lodgement) one grain at a time during glacial cover (Byron Stone, US Geological Survey, geologist, written communication, 12 February 2017). When glacial ice melted quickly, a nonsorted and nonlayered mixture of sediments was dumped in place. □ **Eskers**—eskers are long, narrow, sinuous ridges of stratified sand and gravel deposited by a subglacial or ice-tunnel stream within a glacier. □ **Erratics**—glacial erratics are large rocks that accumulated on the glacier, were transported some distance, and then were dumped on the landscape as the glacier retreated. Glacial boulders are of similar size, but have travelled less distance and are located within their source rock (Byron Stone, US Geological Survey, geologist, written communication, 12 February 2017). □ **Glacial lake deposits**—glacial lake sediments were deposited in glacial lakes Sudbury and Concord (see fig. 16). Glacial Lake Concord covered the park area. Glacial Lake Concord formed between the massive deposits of Lake Sudbury to the south and the northward retreating ice margin. The older, high level of Lake Concord graded to a lake spillway channel at 53 m (175 ft) elevation near Bannon Hill to the east. Spillways controlled the younger, low level of Lake Concord at about 44 m (145 ft) elevation in the Bannon Hill area. Glacial Lake Concord was at least 30 m (100 ft) deep and 16 km (10 miles) wide (fig. 18); Glacial Lake Concord high stage was about 18 m (60 ft) deep over the lake bottom plain in the park. □ **Striated and/or grooved bedrock**—"scratched" exposures record the south-southeast direction of glacial movement. They formed when rocks and grit entrained in the glacial ice cut striations or larger grooves into the underlying bedrock as the glacier flowed.
Related Map Units And Park Examples (continues on next page)	● **Qsdc**, **Qsdf**, are units that combine (lump) all meltwater deposits into coarse and fine units. Stratigraphic units related to the glacial lakes and streams are detailed in Koteff (1964). **Qt** is also mapped within the park. ● Glaciers repeatedly advanced over and retreated from the park landscape (and all of New England) during Pleistocene ice ages; sediments from four or five ice sheets are present across the region. ● Glacial features are prominent on the park's landscape, but have not yet been mapped at a large scale (e.g., greater than 1:24,000) for features within the park. Surficial units in the GRI GIS data were mapped (Koteff 1964) at 1:24,000 and compiled at 1:50,000 scale (see Stone and Stone 2006). ● Glacial features were strategic landforms during the American Revolution battles (see "Geologic Setting, History, and Significance" section). ● Kettle ponds include Folly Pond, Goose Pond, and the famous Walden Pond. ● A single glacial ice-contact, esker-fed delta at the high stage of Lake Concord includes Revolutionary Ridge, Authors Ridge, The Wayside, and Meriam's Corner (fig. 17). The large pit excavation at the east end exposed delta topset fluvial beds overlying delta dipping foreset beds at altitude 56 m (185 ft), the approximate level of the lake surface (Koteff 1964). ● Kame deltas form ridges the colonials used to shield their movements near Meriam's Corner and along Battle Road.

Table 4, continued. Summary of glacial features and processes.

Geologic Feature and Process	Glacial Features
Related Map Units And Park Examples (continued)	• High ground at the North Bridge unit is underlain by **Qsdc** and **Qt** (Poplar Hill), which may overlie preexisting bedrock knobs of DSaqd. • **Qt** till forms a smooth mantling deposit on bedrock on the lower north-facing slopes of Brooks Hill and Fiske Hill. These hills feature steep, glacially plucked rock slopes on the southerly sides • Drumlins exist near the park area as part of the large drumlin field of southern New England that extends as far away as Boston Harbor (refer to Boston Harbor Islands NRA GRI report by Thornberry-Ehrlich 2017). • Younger till is **Qt** and commonly overlies an older, thicker till (**Qtt**; not exposed in park boundaries); both tills mantle almost all local bedrock. • Glacial boulders and erratics (fig. 19) include Minute Man Boulder (ca. 1885), commemorative stone at Meriam's Corner, stone walls, historic building foundations, grave markers, and cellars. • **Qsdf** was deposited in glacial Lake Concord and contains varves, alternating beds of fine- and coarse-grained material reflecting seasonal deposition in lakes. • The high level of glacial Lake Concord, impounded by stranded deltaic deposits of Lake Sudbury, covered the park up to altitudes of about 185 ft. The lower stage of Lake Concord reached levels of about 160 ft, leaving the older deltas, many till hills, and stranded blocks of ice surrounded by lake water. • Local ridges formed between the retreating glacial ice and stages of Glacial Lake Concord. • A set of low terraces ranging from about 37 to 49 m (120 to 160 ft) in elevation contain sand, gravel, silt, and clay associated with the low stage of Glacial Lake Concord in the North Bridge unit. • Bedrock exposures ("outcrops") in the park contain glacial striations and grooves.
Related Resource Management Issues and/or Vital Signs	• Slope Movement Hazards, and Risks (table 9) • Geomorphology vital sign (Shriver et al. 2004) • Northeast Temperate Network vital signs monitoring: http://science.nature.nps.gov/im/units/netn/monitor/monitoringprotocols_vital.cfm
Potential Action Items	• Consider more detailed park-specific glacial feature mapping (larger than 24,000 scale). This is a potential GIP project: https://go.nps.gov/gip. • LiDAR data may reveal subtle glacial topographic features.
Primary References or Resources	• GRI GIS surficial geologic map data source: Stone and Stone (2006) based on work by Koteff (1964; see copy of Koteff map in pocket) • Local glacial features websites: http://surroundingtownsgeologytour.weebly.com/authors-ridge.html and http://middlesexgeology.weebly.com/index.html • Administrative history: Zenzen (2010) • Northeast Temperate Network Vital Signs Monitoring: Shriver et al. (2004) • Cultural Landscape Inventory for Meriam's Corner: Hammond (2015b) • GRI scoping meeting summary: Thornberry-Ehrlich (2008) • Boston Harbor drumlins: Newman and Mickelson (1994) • Boston area geology and history: Kaye (1976); GRI report for Boston Harbor Islands NRA by Thornberry-Ehrlich (2017). • Glacial lakes: Koteff (1963) • Northeast Temperate Network vital signs monitoring plan: Mitchell et al. (2006)

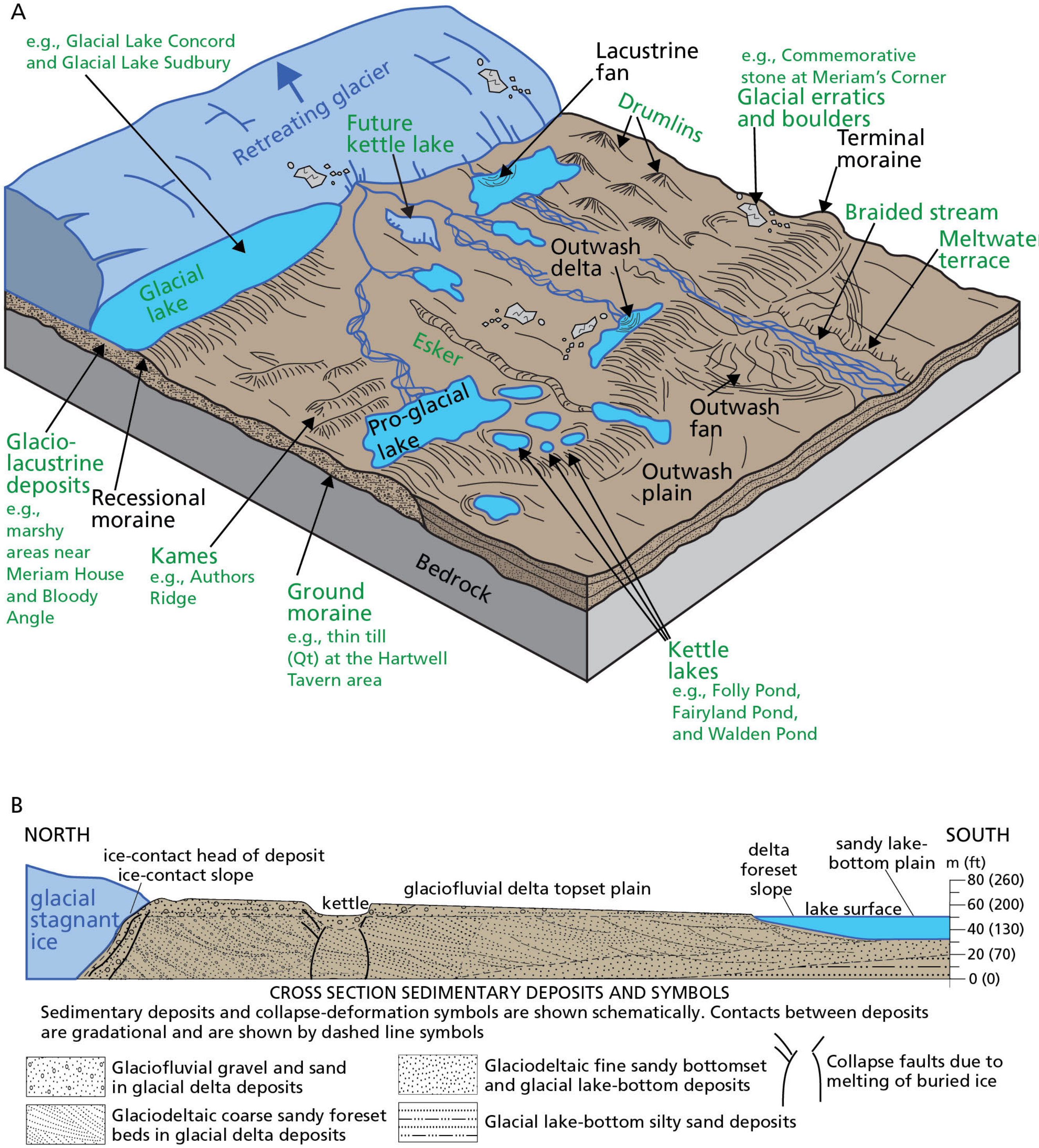
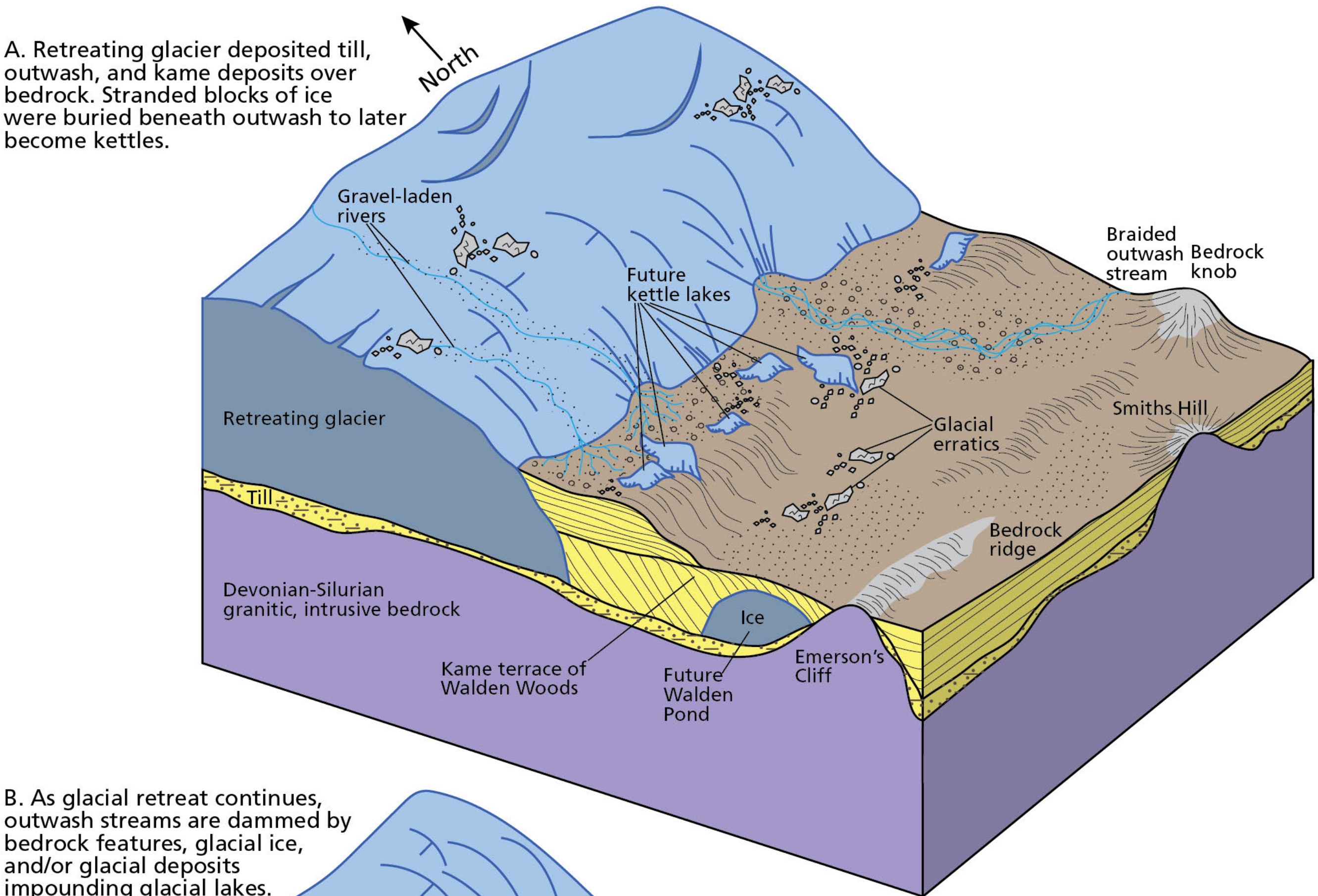


Figure 16. Schematic illustration of glacial features and deposits. (A) Glacial features that occur within Minute Man National Historical Park are labeled in green with local examples indicated. Local kame deltas (e.g., Authors Ridge) are now being referred to by surficial geologists as glacial, ice-contact or ice-marginal deltas to emphasize sedimentologic features and stratigraphy of lake basins (Glacial Lake Concord). (B) Deposits modified from the sedimentary facies of B. Stone et al. (2004), J.R. Stone et al. (2005); faults modified from McDonald and Shilts (1975). Not all facies (deposits) in the original diagrams are shown here, for simplicity. Graphics by Trista L. Thornberry-Ehrlich (Colorado State University) and Byron Stone (US Geological Survey).


A. Retreating glacier deposited till, outwash, and kame deposits over bedrock. Stranded blocks of ice were buried beneath outwash to later become kettles.
North
Gravel-laden rivers
Future kettle lakes
Braided outwash stream
Bedrock knob
Retreating glacier
Smiths Hill
Glacial erratics
Till
Bedrock ridge
Devonian-Silurian granitic, intrusive bedrock
Ice
Kame terrace of Walden Woods
Future Walden Pond
Emerson's Cliff

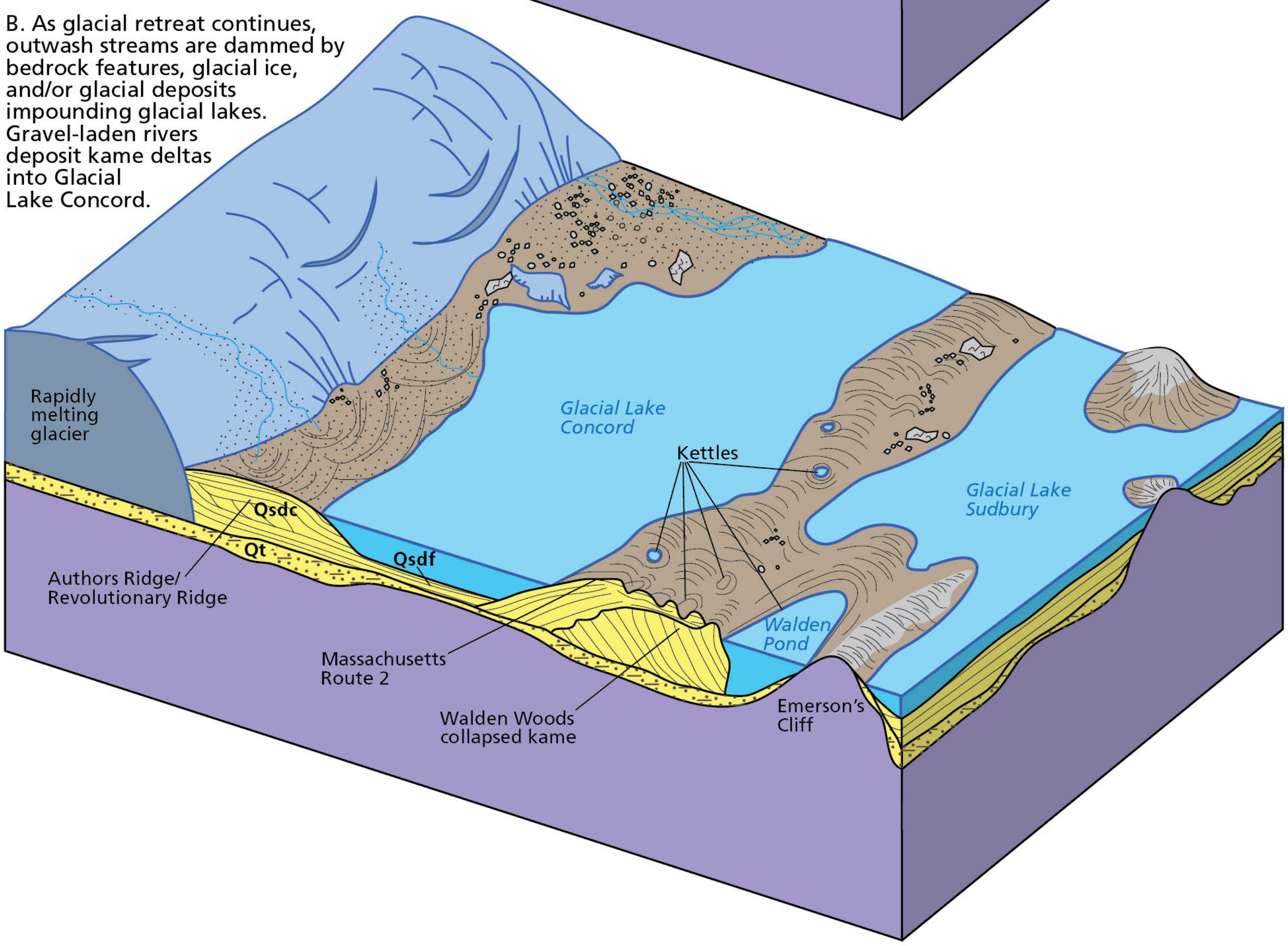

B. As glacial retreat continues, outwash streams are dammed by bedrock features, glacial ice, and/or glacial deposits impounding glacial lakes. Gravel-laden rivers deposit kame deltas into Glacial Lake Concord.
Rapidly melting glacier
Glacial Lake Concord
Kettles
Glacial Lake Sudbury
Qsdc
Qt
Qsdf
Authors Ridge/ Revolutionary Ridge
Walden Pond
Massachusetts Route 2
Walden Woods collapsed kame
Emerson's Cliff

Figure 17 (facing page). Schematic illustrations of the formation of modern landscapes via glacial processes. Glacial features and surficial geologic map units that occur within Minute Man National Historical Park and the surrounding region formed in large part as glaciers flowed over the landscape and deposited vast amounts of sediment upon their retreat into outwash areas and glacial lakes. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Skehan (2001) and http://middlesexgeology.weebly.com/index.html (accessed 10 February 2016).

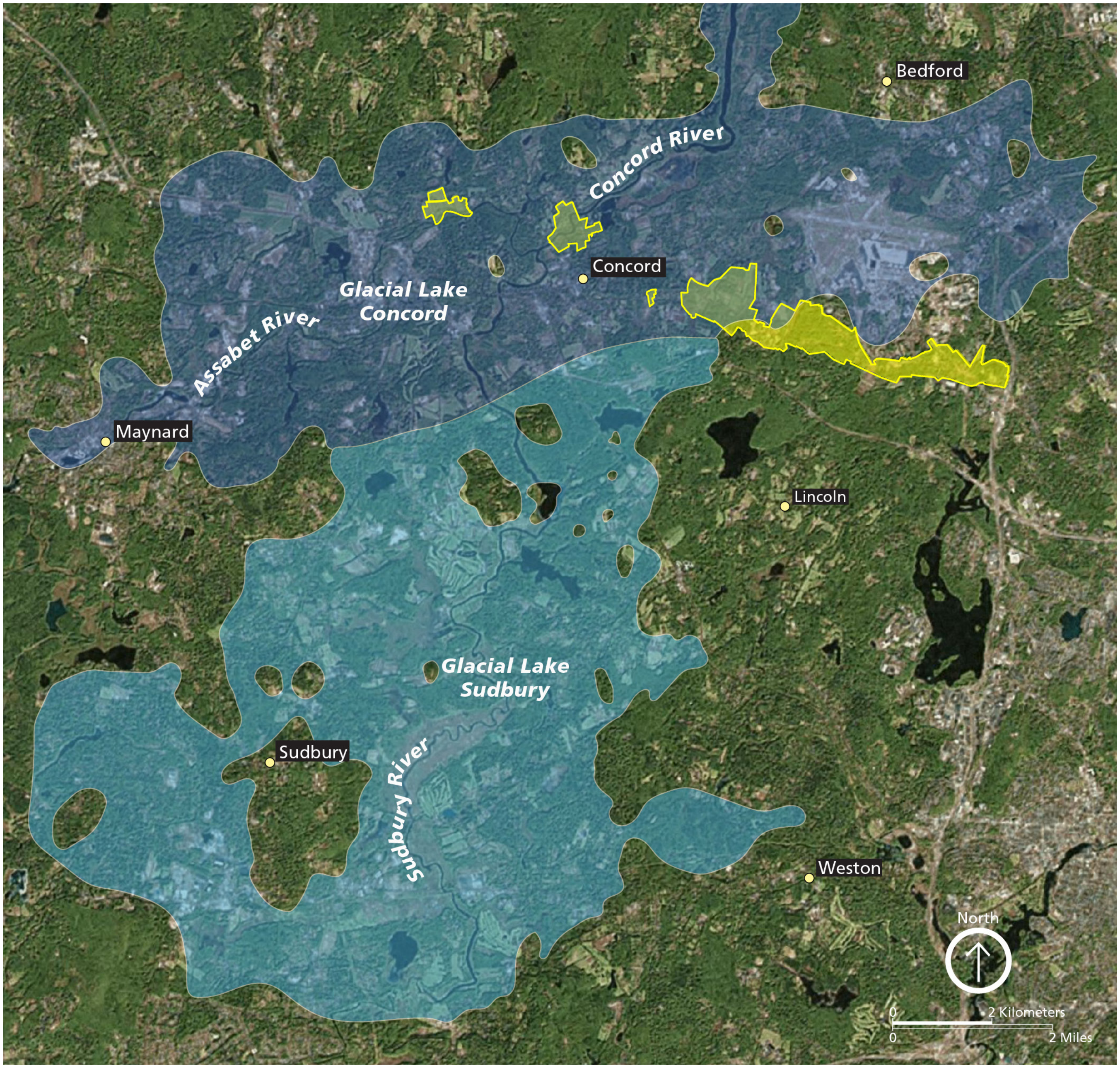


Figure 18 (above). Map of the extent of Glacial Lake Sudbury and Glacial Lake Concord. Glacial Lake Concord covered portions of Minute Man National Historical Park (yellow area). Glacial Lake Sudbury formed first as the glacier retreated northward. A bedrock ridge and deltaic deposits dammed the southern outlet of the next basin northward, impounding Glacial Lake Concord. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with information from Koteff (1963) using ESRI World Imagery basemap (accessed 12 September 2016).

Figure 19. Photographs of glacial erratics. At Minute Man National Historical Park, glacial erratics served many purposes from building foundations, stone walls, and grave markers. Originally a thorn in the side of early settlers hoping to clear vast tracts of land for plowing, abundant glacial erratics and other deposits provided valuable building material for building houses, cellars, property boundaries, and stone fence enclosures. In the battle, they provided strategic cover for combatants. Clockwise from top left, glacial erratics in a stone wall at Hartwell Tavern (NPS photograph by Deidra Goodwin). During a reenactment, Colonial militia pursue British soldiers and take cover behind a stone wall (NPS photograph). Large erratic near the park's visitor center parking lot (NPS photograph by Deidra Goodwin) and a glacial erratic grave marker in front of a stone wall (photograph by Victor Grigas, available at https://en.wikipedia.org/wiki/User:Victorgrigas#Concord.2C_Massachusetts, under Creative Commons Attribution-Share Alike 3.0 Unported (CC BY-SA 3.0) license.

Table 5. Summary of eolian features and processes.

Geologic Feature and Process	Eolian Features and Processes
Description	• Eolian processes refer to wind-blown erosion, transportation, and deposition of sediments. These processes create large scale features such as dunes, loess (wind-blown silt), sand sheets, desert pavement, yardangs, and alcoves. Small scale "sandblasting" features, called "ventifacts", may be present on individual rocks or outcrops. • Large eolian features are not currently present or forming in Minute Man National Historical Park, however, following retreat of ice age glaciers, winds scoured the barren landscape forming dunes and mantles of loess, and sandblasting rocks (ventifacts).
Related Map Units And Park Examples	• Qsdf was likely source material for windblown features. • Ancient dunes may exist on the park landscape. • Surficial mapping revealed ventifacts in the park—stones or pebbles shaped, worn, faceted, cut, or polished by "sandblasting."
Related Resource Management Issues and/or Vital Signs	• Slope Movement Hazards, and Risks (table 9) • Geomorphology vital sign (Shriver et al. 2004) • Northeast Temperate Network vital signs monitoring: http://science.nature.nps.gov/im/units/netn/monitor/monitoringprotocols_vital.cfm
Potential Action Items	• Eolian features could be included in detailed glacial features mapping project. This may identify the presence of ancient dune features. See table 4 (Glacial Features and Processes).
Primary References or Resources	• GRI GIS surficial geologic map data source: Stone and Stone (2006). • Eolian features and processes monitoring: Lancaster (2009; http://go.nps.gov/monitor_aeolian). • Northeast Temperate Network Vital Signs Monitoring: Shriver et al. (2004).

Table 6. Summary of bedrock exposures.

Geologic Feature and Process	Bedrock Exposures
Description	• "Bedrock" is the solid, very old rock that underlies the younger unconsolidated surficial and glacial deposits of the park. • Bedrock can be sedimentary, igneous, or metamorphic. Sedimentary rocks form from fragments of other rocks or chemical precipitation. Igneous rocks form by the cooling of molten material. Metamorphic rocks are those that have been altered by high temperature, high pressure, and/or fluids. • Geologic formations are named for geographic features that are near its type locality, which is a place with exposures extensive enough to show all the mappable features of the formation. • Major geologic structures, such as faults, in bedrock are also commonly named for local geographic features (see table 7). • The "Geologic Attitude Observation Localities" layer in GRI GIS data include the orientation of bedrock features such as foliation (preferred orientation of minerals), joints (fractures in rock), and minor folds.
Related Map Units And Park Examples	• The bedrock exposed in the park is composed of igneous and metamorphic rocks that range in age from about 600 million years old (e.g., **Zwm**) to about 420 million years old (e.g., **DSag**). See table 1 for geologic time scale. • Refer to "Shallow Bedrock Areas" and "Outcrops" layers in GRI GIS data for locations of bedrock exposures, also called "outcrops." • Outcrops of **DSaqd** occur in the North Bridge unit (fig. 20). One has an inclined foliation measurement point. • Outcrops of **DSag** and **ZSfhg** (fig. 20) occur in the Battle Road unit. Inclined foliation measurements of bedrock also occur in this unit. • The contact between **DSag** and **Sgrm** is visible at The Bluff. • Bedrock exposures are most common in the Fiske Hill area; Fiske Hill is the type locality for the Fiske Hill Granite (fig. 20). Shallow bedrock areas are mapped in the Battle Road unit. • The Hubbard Hill Gabbro (**UNKhhg**) was named for Hubbard Hill near Concord; The White Pond Gabbro (**DSwd**) was named for White Pond in Concord; The Nashoba Formation, Balls Hill Gneiss (**COnbh**) was named for Balls Hill in Concord; The Marlboro Formation, Jupiter Ridge Schist Member (**COmjs**) was named for Jupiter Ridge in Lincoln, Massachusetts; The **Bloody Bluff Fault** was named for the American Revolution skirmish fought nearby.
Related Resource Management Issues and/or Vital Signs	• Slope Movement Hazards, and Risks (table 9) • Geomorphology vital sign (Shriver et al. 2004) • Northeast Temperate Network vital signs monitoring: http://science.nature.nps.gov/im/units/netn/monitor/monitoringprotocols_vital.cfm
Potential Action Items	• Interpret the historic and geologic significance of the bedrock exposed in context of the Burlington Mylonite Zone-Bloody Bluff Fault area. The significance includes the formation of the Appalachian Mountains, Pangaea, and the landscape of New England, as well as the influence on the earliest battles of the American Revolution (see "Geologic Setting, History, and Significance" section).
Primary References or Resources	• GRI GIS bedrock geologic map data source: Langford and Hepburn (2007) • Contact Office of the Massachusetts State Geologist (as of 2017, Joe Kopera) • Contact Boston College (as of 2017, Chris Hepburn) • Cultural Landscape Inventory for Fiske Hill: Hammond (2015a) • Regional lithology: Robinson and Kapo (2003) • US Geological Survey's online database of geologic names: http://ngmdb.usgs.gov/Geolex • Northeast Temperate Network Vital Signs Monitoring: Shriver et al. (2004) • Ages of metasedimentary rocks: Wintsch et al. (2007)

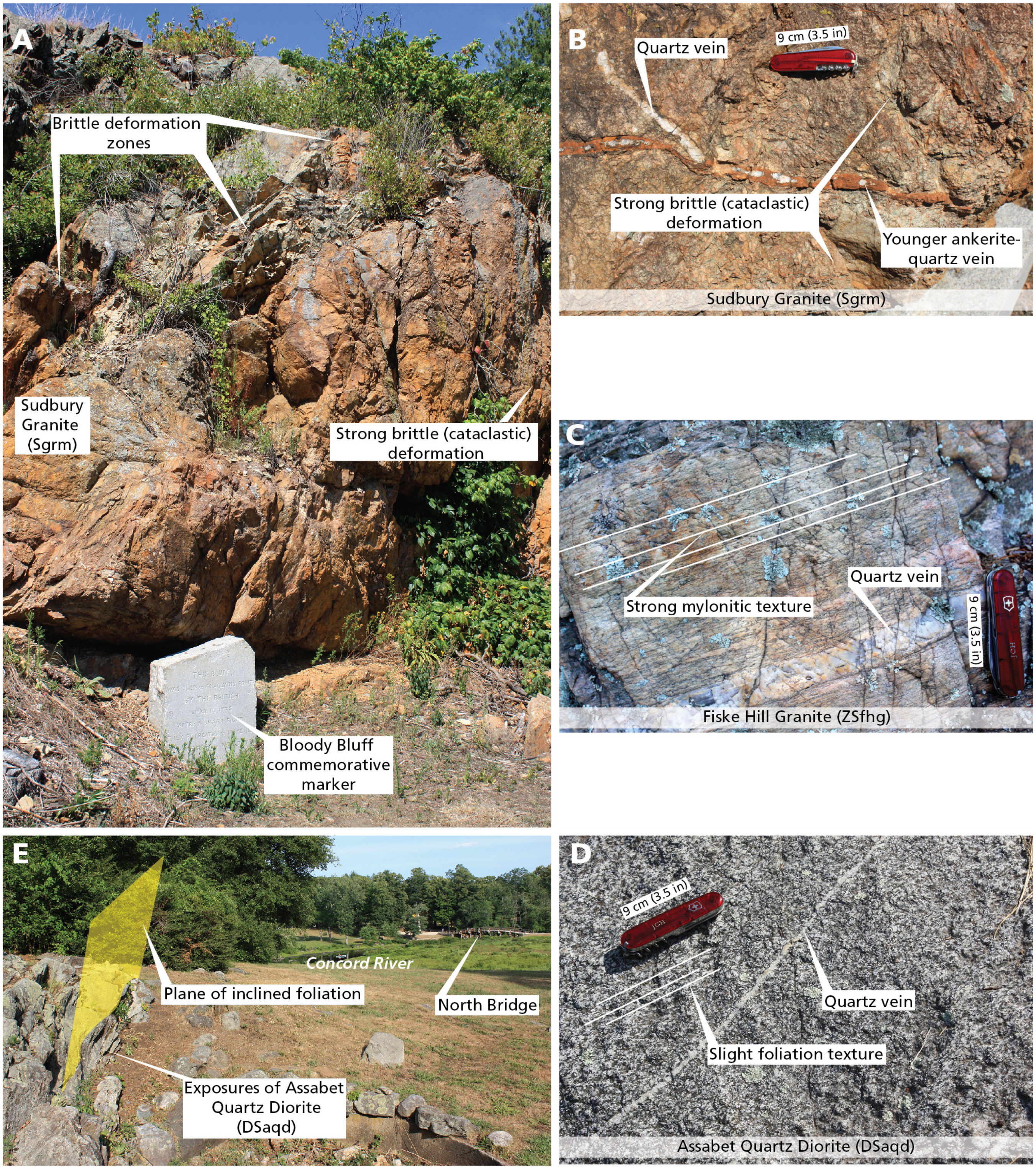


Figure 20. Photographs of bedrock exposures and features. (A) The Bluff is the type location for the Bloody Bluff Fault—a brittle structure that reactivated a preexisting zone of weakness within the rock (i.e., the Burlington Mylonite Zone). (B) Brittle deformation cracks and zones of crushed rocks (cataclasites) cut across the rock exposures at the bluff. (C) Under higher temperature and pressure conditions, deformation is ductile, “smearing” the rocks as visible along Massachusetts Avenue. (D-E) In the North Bridge Visitor Center garden, outcrops of Assabet Quartz Diorite show slight foliation and inclined foliation textures. Photographs by Chris Hepburn (Boston College) taken in summer 2016. Annotation by Trista L. Thornberry-Ehrlich (Colorado State University).

Table 7. Summary of faults and shear zones.

Geologic Feature and Process	Faults and Shear Zones
Description	● A fault is a fracture in rock along which rocks have moved. Faults are defined by the direction of movement along the fracture as normal faults, reverse faults, and strike-slip faults (fig. 21) ● Shear zones are areas where rock has been fractured, crushed, and deformed ("sheared"). They often occur near major faults and are indicative of tremendous stress and tectonic forces. ● A mylonite is a type of metamorphic rock formed when other rocks are ground, crushed, squeezed, and/or stretched under high pressure and temperature (ductile conditions) at a depth of approximately 10 to 15 km (6 to 9 mi) in Earth's crust
Related Map Units And Park Examples	● **COnu, DSaqd, Zgrt, Sgrm, Zwm, and ZSfhg** ● See "Faults" and "Deformation Areas" layers in GRI GIS data and poster (in pocket). ● All three types of faults are mapped in the GRI GIS data (although they are labeled as unknown offset/displacement; fig. 21). Most faults follow a regional northeast-southwest trend. ● Northeast-southwest trends of local drainages conforms to the trends of regional bedrock structures, including faults. ● The major fault in the park (and regionally) is the Burlington Mylonite Zone-Bloody Bluff Fault which separates the Nashoba Terrane (west) from the Avalon Terrane (east). ● The Bloody Bluff Fault formed along a preexisting zone of deformation from an earlier orogeny—the Burlington Mylonite Zone, which continues north of the park. Timing of fault movements is not well constrained or known. ● The Burlington Mylonite Zone-Bloody Bluff Fault crosses the eastern end of Battle Road unit and forms "The Bluff" (see fig. 20). This is also a powerline corridor which is kept free of concealing vegetation. ● Assabet River Fault transects the North Bridge unit. Timing of movement along this fault may be concurrent with that of the Burlington Mylonite Zone deformation. Dating of these structures (using minerals such as monazite) is currently underway. Results may be available in 2017 (contact: Chris Hepburn, Boston College). ● The Sedge Meadows Fault runs between The Wayside and North Bridge units ● Deformation areas (shear zones; fig. 20) are mapped at the eastern end of the Battle Road unit within **ZSfhg** and **Zwm** bedrock and follow the Burlington Mylonite Zone-Bloody Bluff Fault. ● A sheared zone in **COm** is mapped immediately south of the park near Folly Pond.
Related Resource Management Issues	● Seismic Activity Hazards and Risks (note: mapped faults are ancient structures and no longer considered active)
Potential Action Items	● Interpret the historic and geologic significance of the bedrock exposed in context of Bloody Bluff Fault-Burlington Mylonite Zone area. The significance includes the formation of the Appalachian Mountains, Pangaea, and the landscape of New England, as well as the influence on earliest battles of the American Revolution (see "Geologic Setting, History, and Significance" section). ● Detailed surficial mapping may yield evidence of offset beds or other features that indicate more recent seismicity or local, smaller scale faults. ● Collaborate with landscape architecture planning studio students to determine how visitors could better understand the geology of the park from what they see at the surface with landscape design.
Primary References or Resources	● GRI GIS bedrock geologic map data source: Langford and Hepburn (2007) ● Contact Office of the Massachusetts State Geologist (as of 2017, Joe Kopera) ● Contact Boston College (as of 2017, Chris Hepburn) ● Geology and history of eastern Massachusetts: Goldsmith (1991a, 1991b)

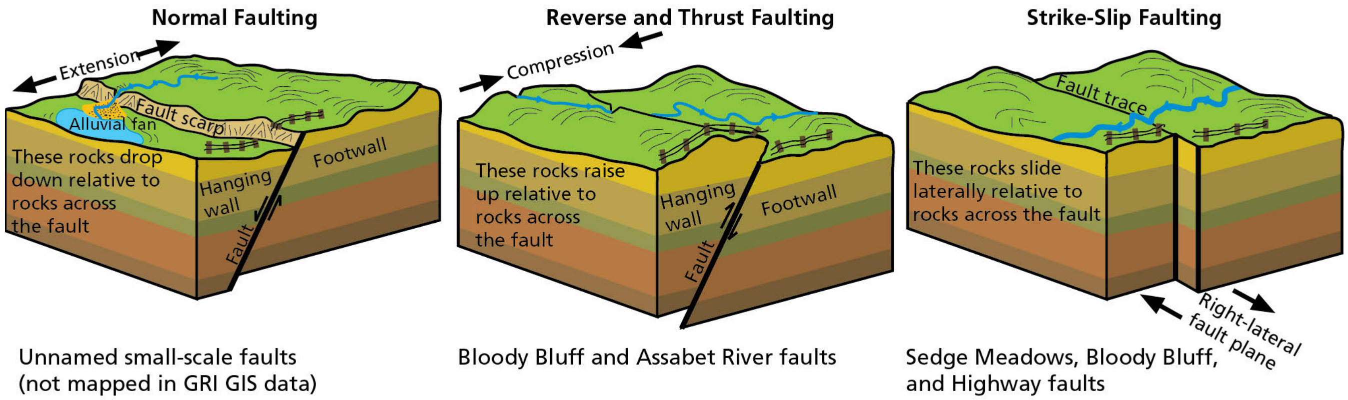


Figure 21. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Table 8. Summary of flooding and wetlands restoration resource management issues. Table continues on next page.

Resource Management Issue	Flooding and Wetlands Restoration
Description	• Flooding occurs along the Concord and Assabet rivers (fig. 22) and would impact only low-lying areas within the rivers' floodplain in the North Bridge and Barrett's Farm units. • Flooding could undermine streambank stability and in turn impact cultural and archeological resources, as well as wetlands, along river banks or on floodplain. • Beaver activity, clogged culverts, and failing water diversion structures contribute to local flooding. • Urban landcover acreage in park and 5-km (3-mi) buffer increased nearly 281% between 1974 and 2000 (James-Pirri 2009), increasing runoff from impervious surfaces that also contribute to higher stream flow. • Restoring the disturbed landscape commonly includes removing water control infrastructure and restoring topography. • Wetlands are significant natural resources (see table 3) that have been impacted by draining, filling, and/or channelization. Restoring wetlands often provides regulatory protection to control local development. Flooding frequency and severity could increase as climate continues to change. For example, between 1958 and 2010, the northeast experienced more than a 70% increase in the amount of precipitation falling in heavy storms (Melillo et al. 2014).
Related Fundamental Resources	• Battle Road and cultural landscape • Battle Road, North Bridge, The Wayside, Barrett's Farm units • Natural resources

Table 8, continued. Summary of flooding and wetlands restoration resource management issues.

Resource Management Issue	Flooding and Wetlands Restoration
Related map units and park examples	• **Qaf, Qal, and Qsw** • Alterations have modified and rechanneled Mill Brook's flow near Meriam's Corner and The Wayside from its battle-era course. • Sunnyside Brook flows diverted into an underground flow system of pipes and culverts. The park is restoring the original brook trace as of 2016. • A wetlands and riparian area restoration project is underway in the park, including in the Battle Road unit along Elm Creek and near Bloody Angle. • Pipes, leachfields, excavated ponds, and filled-in areas are among the water-relevant features at the park potentially in need of restoration. • Deforestation and land clearing contributed to severe periodic flooding that damaged local wetlands. • Percentage of urbanized land cover was assessed in James-Pirri (2009) with a condition considered "caution" and a declining trend. • Wetland condition was assessed in James-Pirri (2009). Kettlehole wet meadows are considered in "good" condition but other wetlands and vernal pools were rated as "caution." Wetlands have a declining condition trend.
Potential Action Items	• Assess condition and function of stormwater engineering structures. • Continue restoration work along park streams (Mill Brook, Sunnyside Brook) and riparian buffers. • Examine impacts of beaver activity on park streams. • For climate change study past dynamics and investigate how future conditions may shift beyond the historical variability range; employ strategies described in Melnick et al. (2015). • Consult NPS planning documents including Director's Orders 77-1 (Wetland Protection) and 77-2 (Floodplain Management), as well as the other laws, regulations, and policies listed in Appendix B and available at https://www.nps.gov/applications/npspolicy/index.cfm.
References and Additional Resources	• Technical assistance: NPS Water Resources Division https://www.nps.gov/orgs/1439/index.htm • Natural Resource Assessment: James-Pirri (2009) • Landcover change: Wang and Nugranad-Marzilli (2009) • FEMA flood hazard mapping: http://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping • Northeast Temperate Network Vital Signs Monitoring: Shriver et al. (2004); http://science.nature.nps.gov/im/units/netn/parkPages/MIMA.cfm • GRI scoping meeting summary: Thornberry-Ehrlich (2008) • Battle Road Wetlands Restoration Project Proposal (Karish 2003) • Monitoring Fluvial Geomorphology: Lord et al. (2009) • Climate change projections, impacts, and NPS policy considerations: Davey et al. (2006), Melillo et al. (2014), Fisichelli (2014), Kunkel et al. (2013), Melnick et al. (2015), Rockman et al. (2016), see Appendix B.

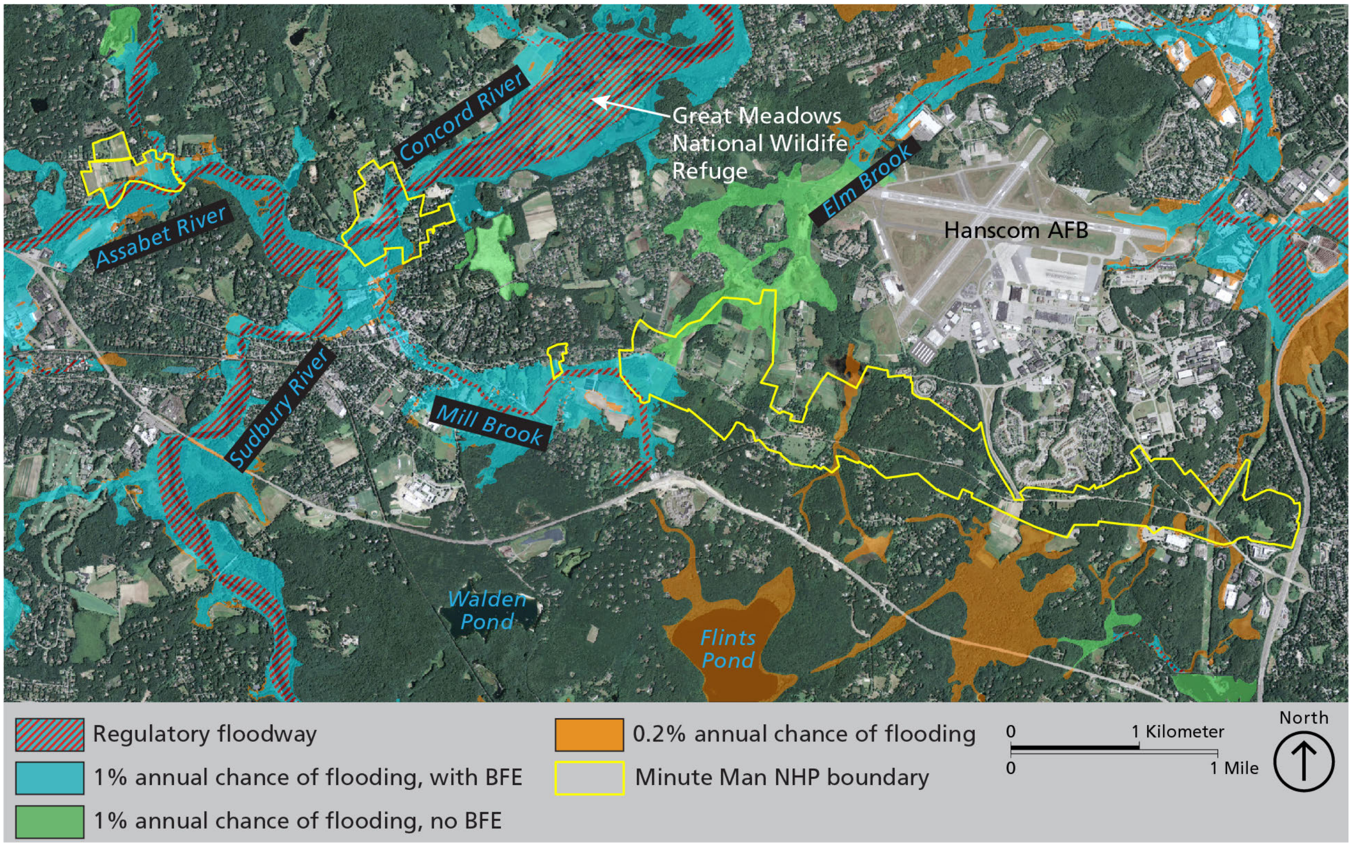


Figure 22. Map of flood-prone areas. Minute Man National Historical Park (yellow boundary) has vast areas at risk of flooding (red cross-hatched, blue, green, and orange areas). BFE refers to the base flood elevation. A base flood is a national standard for a flood having a one percent chance of being equaled or exceeded in any given year (often referred to as a "100-year flood"). Base flood elevation is a computed elevation to which floodwater is anticipated to rise during the base flood. BFE is a regulatory requirement for the elevation or flood proofing of structures to be including in flood in insurance determinations. A regulatory floodway refers to the channel of a river or stream and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the floodwater surface elevation more than a designated height. Any development in these areas must be regulated by the community to ensure there are no increases in upstream flood elevations. Note also the proximity of the park's northern boundary with Hanscom Air Force Base. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University) with data from FEMA (https://hazards.fema.gov/femaportal/wps/portal/NFHLWMS, accessed 21 January 2015) and using ESRI World Imagery basemap (accessed 21 January 2015.

Table 9. Summary of erosion and slope movement resource management issues.

Resource Management Issue	Erosion and Slope Movement Hazards and Risks
Description	• Slope movements are the downslope transfer of material (e.g., soil, regolith, and/or rock) (fig. 23). Slope movements can occur very rapidly (e.g., rockfall) or over long periods of time (e.g., slope creep). • Frost weathering, plant-root wedging, streambank erosion, and differential erosion cause slope instability. • Areas with denuded or disturbed vegetation are susceptible to increased erosion which can reduce slope stability.
Related Fundamental Resources	• North Bridge, The Wayside, Barrett's Farm units • Natural resources
Related map units and park examples	• Erosion occurs along walking trails at North Bridge and Battle Road units (fig. 24). • North Bridge is a heavily used area with erosion issues particularly along trails and other infrastructure. The park is pursuing a new road material that will be stronger with an impermeable surface, but will not accelerate runoff. Contracting on this project was underway as of 2016. • The condition of terrace steps (stone) and historic terraces at The Wayside are rated as fair to poor, respectively (Dietrich-Smith et al. 2008). The steps are located on **Qt**. • Blowdowns, or tree felling by wind, associated with a hurricane in 1938 exacerbated erosion on park slopes, particularly above The Wayside. • Eastern slope of Buttrick Hill and the base of the eastern slope of Poplar Hill (both in the North Bridge unit) are among the park's steepest slopes at 18% grade. • Sandy substrates throughout the park are easily eroded, causing slope stability issues.
Potential Action Items	• Slope movements in the park are of a relatively small scale and are unlikely to impact visitor safety. They could impact cultural resources. • If the park desires quantitative information regarding rates of change and channel morphology, repeat photography could be performed at designated photo points to monitor changes. Refer to http://go.nps.gov/grd_photogrammetry for information about using photogrammetry for resource management. • Consult NPS planning documents including Director's Orders 77-1 (Wetland Protection) and 77-2 (Floodplain Management), as well as the other laws, regulations, and policies listed in Appendix B and available at https://www.nps.gov/applications/npspolicy/index.cfm.
References and Additional Resources	• Monitoring slope movements: Wieczorek and Snyder (2009; https://go.nps.gov/geomonitoring) • Slope Stability Map of Massachusetts: https://mgs.geo.umass.edu/biblio/slope-stability-map-massachusetts • US Geological Survey landslides guide: Highland and Bobrowsky (2008) • US Geological Survey landslides website: http://landslides.usgs.gov/

Figure 23 (facing page). Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Grayed areas depict conditions unlikely to exist at Minute Man National Historical Park. The abundant vegetation in the park stabilizes most slopes, but potential exists and slope issues could be exacerbated by natural or anthropogenic removal of vegetation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) redrafted after a graphic and information in Varnes (1978) and Cruden and Varnes (1996).

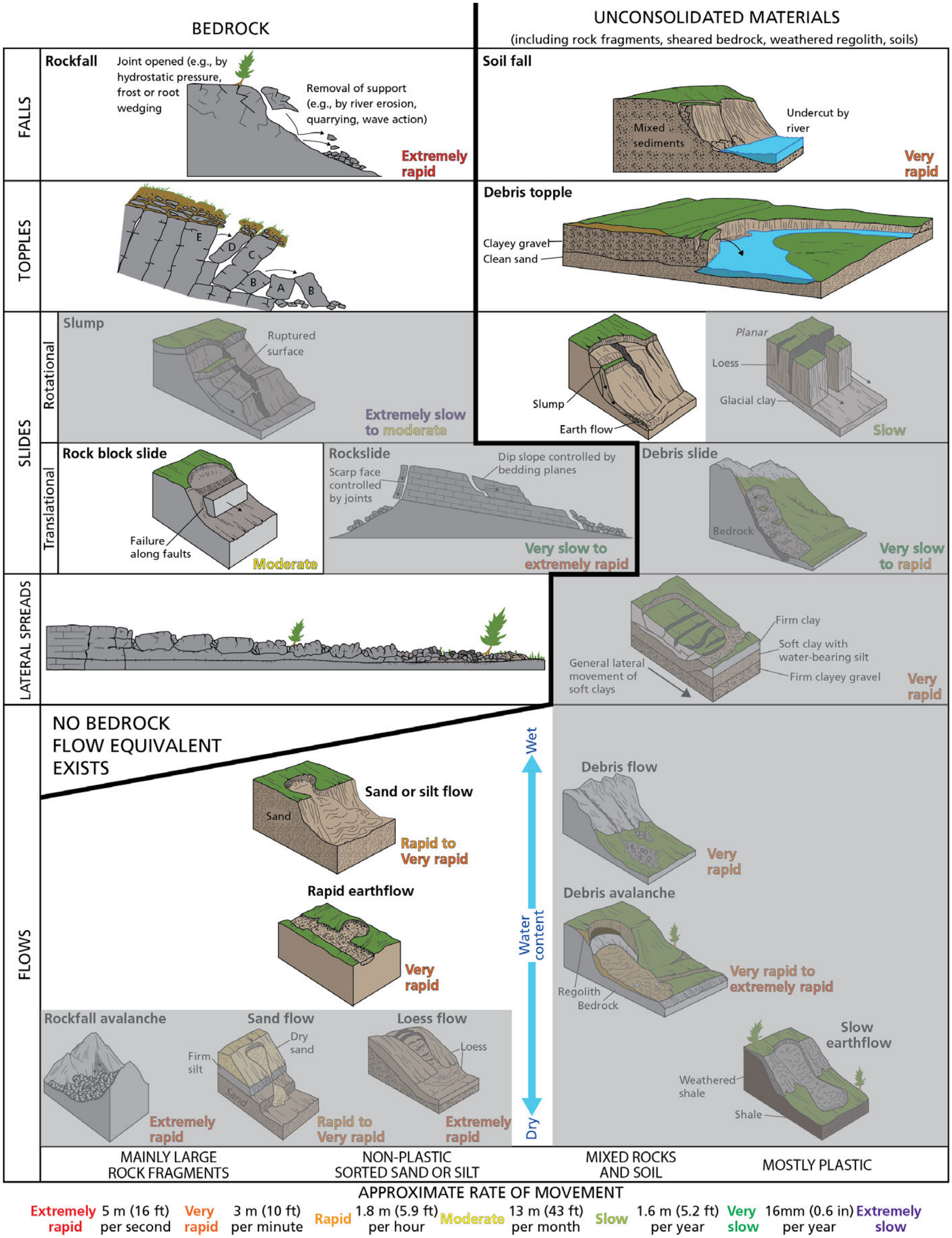

BEDROCK
UNCONSOLIDATED MATERIALS
(including rock fragments, sheared bedrock, weathered regolith, soils)
FALLS
Rockfall
Joint opened (e.g., by hydrostatic pressure, frost or root wedging
Removal of support (e.g., by river erosion, quarrying, wave action)
Extremely rapid
Soil fall
Mixed sediments
Undercut by river
Very rapid
TOPPLES
E
D
C
B
A
B
Debris topple
Clayey gravel
Clean sand
SLIDES
Rotational
Slump
Ruptured surface
Extremely slow to moderate
Slump
Earth flow
Planar
Loess
Glacial clay
Slow
Translational
Rock block slide
Failure along faults
Moderate
Rockslide
Scarp face controlled by joints
Dip slope controlled by bedding planes
Very slow to extremely rapid
Debris slide
Bedrock
Very slow to rapid
LATERAL SPREADS
General lateral movement of soft clays
Firm clay
Soft clay with water-bearing silt
Firm clayey gravel
Very rapid
FLOWS
NO BEDROCK FLOW EQUIVALENT EXISTS
Sand or silt flow
Sand
Rapid to Very rapid
Rapid earthflow
Very rapid
Wet
Water content
Dry
Debris flow
Very rapid
Debris avalanche
Regolith
Bedrock
Very rapid to extremely rapid
Rockfall avalanche
Extremely rapid
Sand flow
Firm silt
Dry sand
Sand
Rapid to Very rapid
Loess flow
Loess
Extremely rapid
Slow earthflow
Weathered shale
Shale
MAINLY LARGE ROCK FRAGMENTS
NON-PLASTIC SORTED SAND OR SILT
MIXED ROCKS AND SOIL
MOSTLY PLASTIC
APPROXIMATE RATE OF MOVEMENT
Extremely rapid
5 m (16 ft) per second
Very rapid
3 m (10 ft) per minute
Rapid
1.8 m (5.9 ft) per hour
Moderate
13 m (43 ft) per month
Slow
1.6 m (5.2 ft) per year
Very slow
16mm (0.6 in) per year
Extremely slow

Figure 24. Photograph of sparse vegetation along the approach road to the North Bridge. Heavy foot traffic at the bridge degrades stabilizing vegetation along park slopes and contributes to localized erosion. Minute Man statue is in the background. National Park Service photograph by Deidra Goodwin (Minute Man National Historical Park).

Table 10. Summary of aquifers and groundwater availability resource management issues.

Resource Management Issue	Aquifers and Groundwater Availability
Description	• As part of the effort to restore battle-era agricultural conditions, some farming occurs within the park. • The region is experiencing persistent drought conditions, park staff are considering the need for additional water sources. • Further study is needed to determine whether groundwater pumping would adversely affect surficial wetlands and fluvial systems as well as the overall groundwater supply. • There is an overall need to understand the local hydrogeologic system.
Related Fundamental Resources	• Battle Road and cultural landscape • Battle Road, North Bridge, The Wayside, Barrett's Farm units • Natural resources
Related map units and park examples	• Fractured bedrock aquifers in **COnu, DSaqd, Zgrt, Sgrm, Zwm, and ZSfhg** • Shallow surficial aquifers in thicker glacial deposits **Qsdc, Qsdf, Qt, Qtt**
Potential Action Items	• Consider more detailed park-specific hydrogeologic surveying or aquifer delineation. This is a potential GIP project: https://go.nps.gov/gip • Contact the NPS Water Resources Division and US Geological Survey office in Marlborough for hydrology-related questions.
References and Additional Resources	• Technical assistance: NPS Water Resources Division https://www.nps.gov/orgs/1439/index.htm • Massachusetts Geological Survey (as of 2017, Steve Mabee is hydrogeology contact) https://mgs.geo.umass.edu/ • Water Resources of Massachusetts: http://ma.water.usgs.gov/ and http://pubs.usgs.gov/wri/wri904144/ • Searchwell database for water-well boring records: https://mgs.geo.umass.edu/news/searchwell-massdeps-new-database-search-water-well-boring-records • Massachusetts Hydrogeologic Information Matrix: http://www.mass.gov/eea/docs/dep/water/compliance/hydromat.pdf

Table 11. Summary of disturbed lands and abandoned mineral lands resource management issues.

Resource Management Issue	Disturbed Lands and Abandoned Mineral Lands (AML)
Description	• Disturbed lands are where natural conditions and processes have been directly impacted by development, including facilities, roads, dams, and abandoned campgrounds; agricultural activities such as farming, grazing, timber harvest, and abandoned irrigation ditches; overuse; or inappropriate use • Prior to establishment of the park, most of the battle-era landscape was subdivided into smaller lots for suburban homes and farms with roadside stands. Much of the area reverted to woods, while Hanscom Airfield and Air Force Base expanded to the north • Abandoned Mineral Lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the NPS takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources. • Small sand and gravel quarries into glacial deposits are common throughout the area.
Related Fundamental Resources	• Battle Road and cultural landscape • Battle Road, North Bridge, The Wayside, Barrett's Farm units • Natural resources
Related map units and park examples	• **Qsw, Qt** • Although there are no AML features from Minute Man National Historical Park documented in the NPS AML database as of December 2013 (Burghardt et al. 2014); small quarries are present inside the park. They are largely overgrown with vegetation; some are now considered wetlands. • Since the 1960s, more than 200 structures have been removed from the park (fig. 25). • Urban lands make up 17% of the park. • Urban expansion (land use) immediately around the park increased since the late 1970s by as much as 27% (see table 8). • Some park ponds are impounded by human-made dams; most agricultural and mill dams are part of the cultural landscape.
Potential Action Items	• Continue cultural landscape restoration. • The National Park Service considers abandoned quarries or borrow pits to be AML features. Although no resource impacts or hazards are currently documented at the borrow pits within the park, park staff should consider documenting the features in the NPS AML database. Refer to Burghardt et al. (2014) and https://www.nps.gov/subjects/abandonedminerallands/inventory.htm for information about AML in the National Park System, as well as a comprehensive inventory of sites, features, and mediation needs. • Prepare a cultural landscape report and treatment plan for Barrett's Farm unit. • Inventory and produce condition assessments for all park ponds.
References and Additional Resources	• GRD Abandoned Mineral Lands website https://go.nps.gov/aml • Abandoned mineral lands inventory: Burghardt et al. (2014) • Natural Resource Assessment: James-Pirri (2009)

Figure 25. Historical and recent photographs of landscape restoration areas in Minute Man National Historical Park. Restoring disturbed lands to their battle-era appearance has involved removing buildings, planting fields, clearing stone walls, removing asphalt, and restoring water courses. NPS photographs.

Table 12. Summary of seismic activity resource management issues.

Resource Management Issue	Seismic Activity Hazards and Risks
Description	• The park is not located near an active seismic zone; however, earthquakes with magnitudes between 2 and 3 are not uncommon. There is a 4% to 6% probability of a magnitude-5.0 or greater earthquake within 100 years (fig. 26). The 2011 Virginia earthquake caused major damage in an area that was likewise considered to be relatively inactive. • Historically, there have been several large earthquakes, including one in 1727 and a 1755 earthquake near Cape Anne. Although there is a low probability of occurrence, earthquakes could directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. • A 2011 earthquake in upstate New York was felt at the park.
Related Fundamental Resources	• Battle Road and cultural landscape • Battle Road, North Bridge, The Wayside, Barrett's Farm units • Minute Man National Historical Park archeological resources • Natural resources
Related map units and park examples	• Bedrock faults mapped in the GRI GIS data (see table 7 and "Faults" layer) are hundreds of millions of years old. There are no quaternary faults mapped in the area and most movement is intraplate.
Potential Action Items	• If the park is concerned about potential earthquake hazards and risk, resource managers could identify areas and features at risk of damage during a moderate earthquake
References and Additional Resources	• New England Seismic Network (Boston College): http://aki.bc.edu • Weston Observatory (Boston College): http://www.bc.edu/research/westonobservatory/ • US Geological Survey Earthquakes Hazards website: http://earthquake.usgs.gov/ • Seismic hazard maps: Petersen et al. (2008) • Monitoring seismicity: Braile (2009; https://go.nps.gov/geomonitoring) • Liquefaction susceptibility: Brankman and Baise (2008) • Boston area geology and history: Kaye (1976) and GRI report for Boston Harbor Islands NRA by Thornberry-Ehrlich (2017).

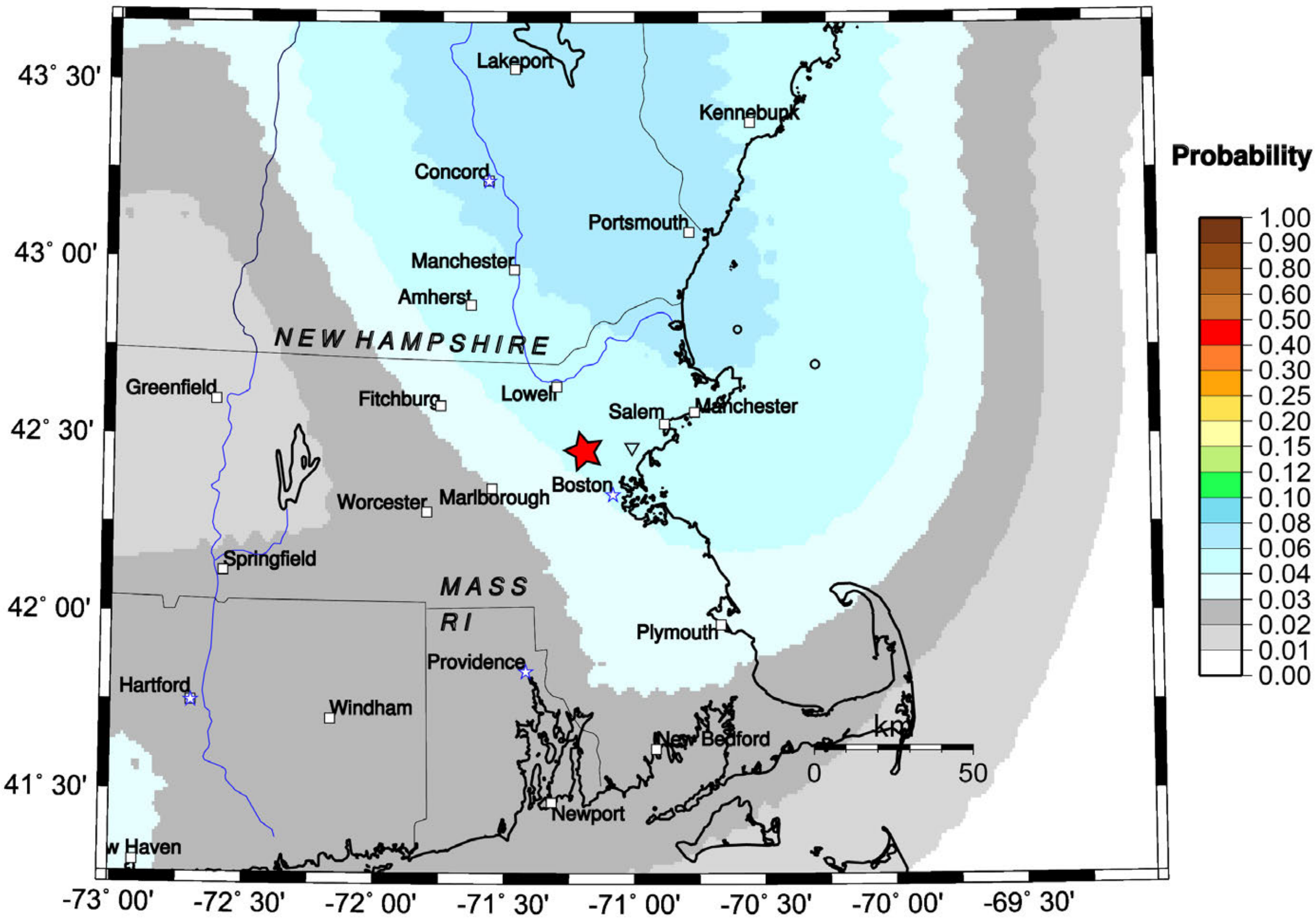


Figure 26. Map of probability of earthquakes with magnitude greater than 5.0 (moderate earthquake). This probability assumes a 100-year timespan and a 50-km (30-mi) radius around Concord, Massachusetts (red star). Graphic was generated by the US Geological Survey earthquake probability mapping program (https://geohazards.usgs.gov/eqprob/2009/index.php, accessed 22 April 2015).

Table 13. Paleontological resource inventory, monitoring, and protection management issues.

Resource Management Issue	Paleontological Resource Inventory, Monitoring, and Protection
Description	• Fossils have not yet been documented within the park. However potential exists for fossil resources in the park's glacial and postglacial deposits. The igneous and metamorphic bedrock of the park do not preserve fossils. • All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act.
Related Fundamental Resources	• Battle Road, North Bridge, The Wayside, Barrett's Farm units • Natural resources
Related map units and park examples	• **Qal**, **Qsw**, **Qsdc**, **Qsdf**, and **Qt** could potentially preserve fossils; plant or pollen fossils from **Qsw** are the most likely. • North American fossils (*Paradoxides*) occur on the western side of the Bloody Bluff Fault and fossils similar to those found in parts of Africa are on the eastern side—these fossil occurrences were used to help unravel the geologic history of the eastern US.
Potential Action Items	• A field-based survey of fossil resources would provide more detailed, site-specific information. This is a potential GIP project.
References and Additional Resources	• Northeast Temperate Network paleontology summary: Tweet et al. (2010) • Monitoring in situ paleontological resources: Santucci et al. (2009; https://go.nps.gov/geomonitoring) • NPS Fossils and Paleontology website: http://go.nps.gov/paleo. • Fossils have been found in the bedrock or surficial deposits, museum collections, and/or cultural contexts of 267 NPS areas.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the park follows the source maps and includes components listed here. Posters (in pocket) display the data over shaded relief of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by relative age, sediment type, and inferred geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, https://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses. US Geological Survey National Geologic Map Database (NGMDB): https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html provides cartographic standards for features on geologic maps, and more than 80,000 downloadable maps and map images.

Source Maps

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

- Preliminary bedrock geologic map of the Concord Quadrangle, Massachusetts (scale 1:24,000) by Langford and Hepburn (2007).
- Surficial geologic map of the Clinton-Concord-Grafton-Medfield 12 Quadrangle area in east central Massachusetts (scale 1:50,000) by Stone and Stone (2006)
- Geology and mineral resources of the Hudson and Maynard quadrangles, Massachusetts (scale 1:24,000) by Hansen (1956).

The Stone and Stone (2006) map relied heavily on earlier mapping by Koteff (1964). The GRI GIS data present combined (lumped) units of all glacial meltwater deposits (units **Qsdc** and **Qsdf**) but does not show the well-established glacial stratigraphic history in the park. The US Geological Survey mapping project (contact, as of 2017: Byron Stone) is presently compiling the stratigraphy of the northeastern map sheet of Massachusetts as part of the State map, but the units in the Concord quadrangle are not yet complete. The glacial history is discussed by Koteff (1963) and displayed in map form in Koteff (1964), available at https://pubs.er.usgs.gov/publication/gq331. Including the detailed glacial units in GIS form remains a data need for Minute Man National Historical Park. Such a project may be considered as part of "inventories 2.0"; contact the NPS Inventory and Monitoring Division for more information.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for the park using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home. Enter "GRI" as the search text and select a park from the unit list. The following components are part of the data set:

- A GIS readme file (mima_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (tables 14 and 15);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (mima_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- ESRI map documents that displays the surficial (mmsr_geology.mxd) and bedrock (mima_geology.mxd) GRI GIS data; and
- A KML/KMZ version of the data viewable in Google Earth (tables 14 and 15).

GRI Map Posters

Posters of the bedrock and surficial GRI GIS data draped over shaded relief images of the historic site and surrounding area are included with this report. Not all GIS feature classes are included on the posters (tables 14 and 15). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact GRI for assistance locating these data..

Use Constraints

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

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on the source map scales (1:24,000 and 1:50,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are expected to be horizontally within 12 m (40 ft) and 25 m (83 ft), respectively, of their true locations.

Table 14. Data layers in the bedrock GIS data.

Data Layer	On Poster?	Google Earth Layer?
Geologic Attitude and Observation Points	No	No
Bedrock Geologic Contacts	No	Yes
Bedrock Geologic Units	Yes	Yes
Point Geologic Units	No	No
Faults	Yes	Yes
Deformation Area Boundaries	Yes	Yes
Deformation Areas	Yes	Yes
Shallow Bedrock Areas and Outcrops	Yes	Yes
Shallow Bedrock Area and Outcrop Boundaries	No	Yes

Table 15. Data layers in the surficial GIS data.

Data Layer	On Poster?	Google Earth Layer?
Glacial Till Deposits	Yes	Yes
Glacial Till Deposit Contacts	No	Yes
Glacial Stratified Deposits	Yes	Yes
Glacial Stratified Deposit Contacts	No	Yes
Postglacial Deposits	Yes	Yes
Postglacial Deposit Contacts	No	Yes
Artificial Fill	Yes	Yes
Artificial Fill Contacts	No	Yes

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of February 2017. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

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

NPS Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Geologic monitoring manual: http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm http://etic.nps.gov/

Climate Change Resources

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

Geological Surveys and Societies

- Massachusetts Geological Survey: http://www.geo.umass.edu/stategeologist/
- US Geological Survey: http://www.usgs.gov/
- USGS Publications: http://pubs.er.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- Geologic glossary (simplified definitions): http://geomaps.wr.usgs.gov/parks/misc/glossarya.html
- Geologic names lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Minute Man National Historical Park, held on 11 July 2007, or the follow-up report writing conference call, held on 30 June 2016. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Marc Albert	NPS Saugus Iron Works NHS and Boston Harbor Islands NRA	Natural Resource Specialist
Tim Connors	NPS Geologic Resources Division	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Chris Hepburn	Boston College	Geologist
Joe Kopera	University of Massachusetts, Amherst	Geologist
Steve Mabee	University of Massachusetts, Amherst	State Geologist
Brian Mitchell	NPS Northeast Temperate Network	Network Coordinator
Lou Sideris	NPS Minute Man NHP	Planning Chief
Meg Thompson	Wellesley College	Geologist
Trista Thornberry-Ehrlich	Colorado State University	Geologist-Report Writer
Suzanne Wall	Andover Geologic Consulting	Geologist
Don Wise	University of Massachusetts, Amherst	Geologist

2016 Conference Call Participants

Name	Affiliation	Position
Margie Coffin Brown	NPS Minute Man National Historical Park	Resource manager
Chris Hepburn	Boston College	Geologist emeritus
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Thornberry-Ehrlich, Trista	Colorado State University	Geologist, Writer, Graphic designer

Appendix B: Geologic Resource Laws, Regulations, and Policies

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. DOI regulations in association with 2009 PRPA are being finalized (July 2017).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

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

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

NPS 406/140236, September 2017

National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov

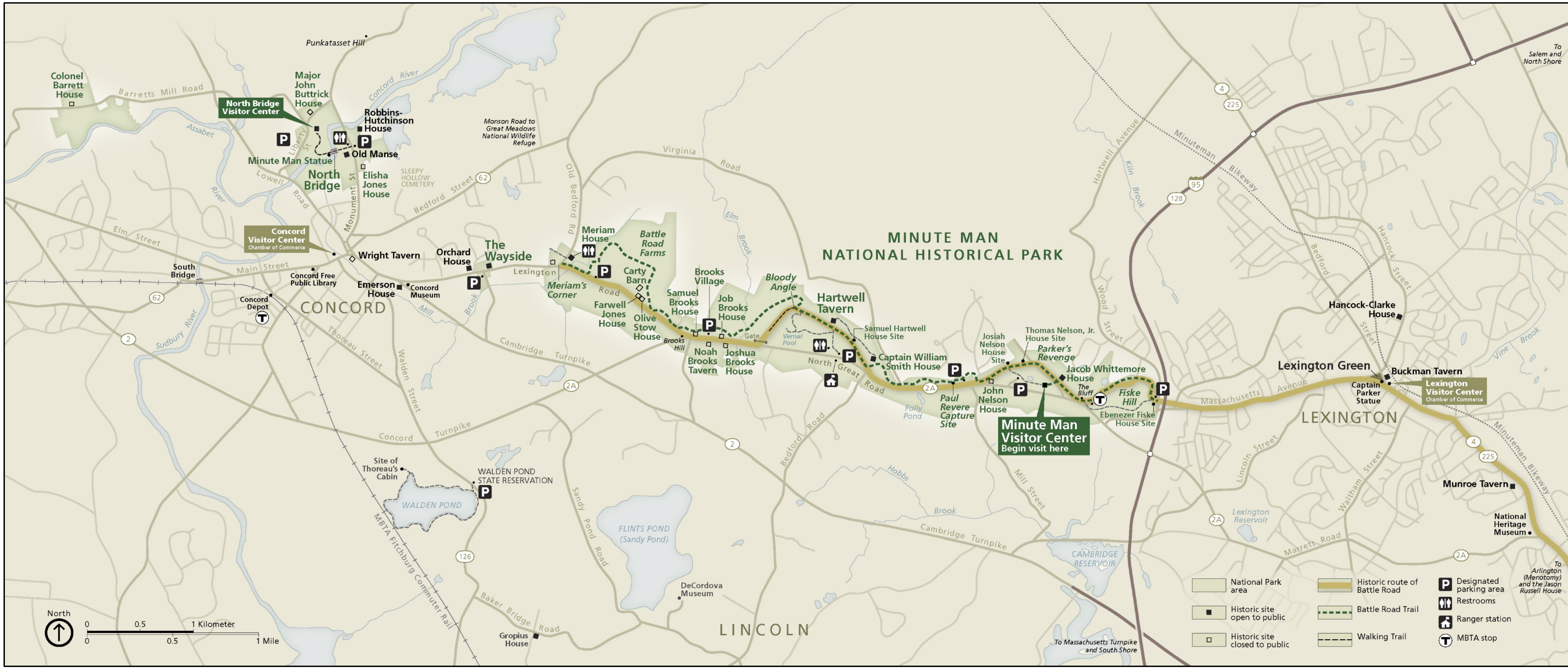
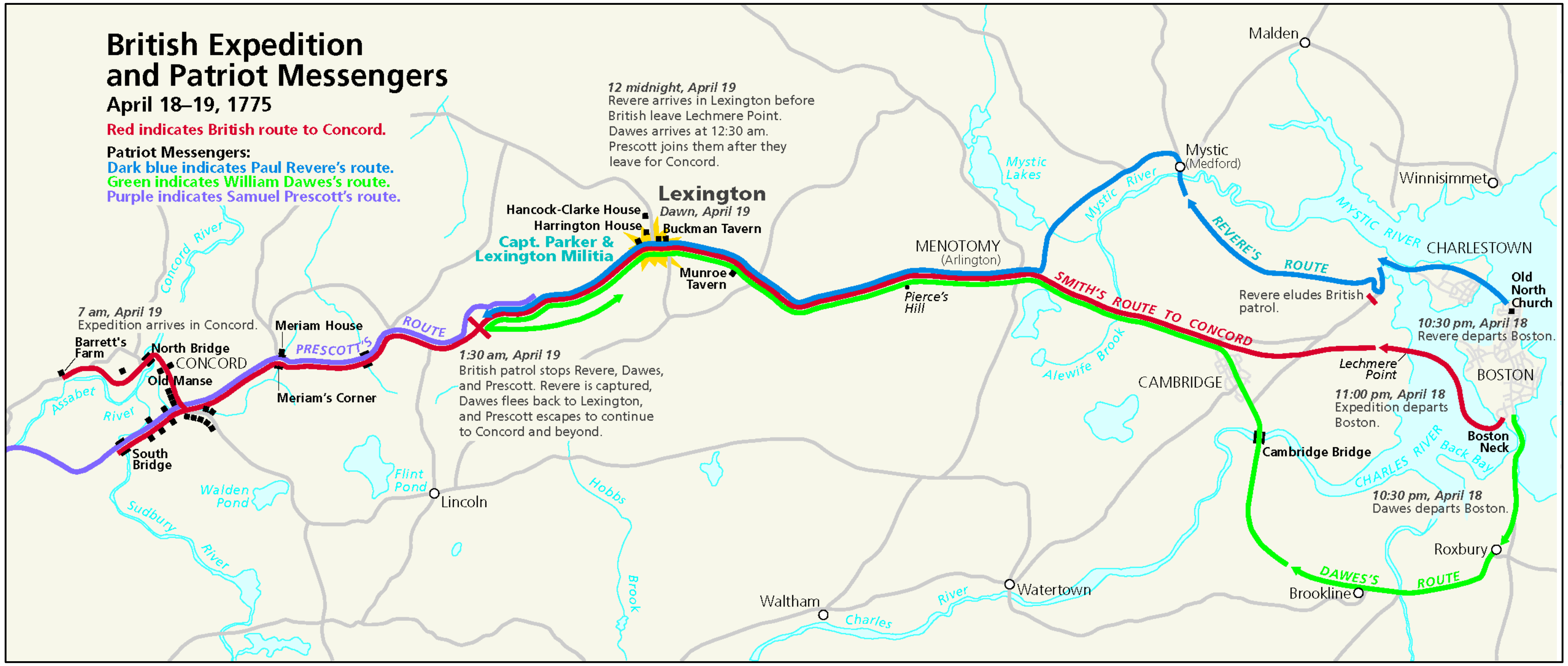


Plate 1. Maps of Minute Man National Historical Park. The map on this side shows the location of park sites and surrounding areas. The maps on the reverse side show the routes of the British Expedition and Patriot Messengers (April 18–19, 1775) and the British return from Concord (April 19, 1775). National Park Service maps, available at https://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=MIMA.



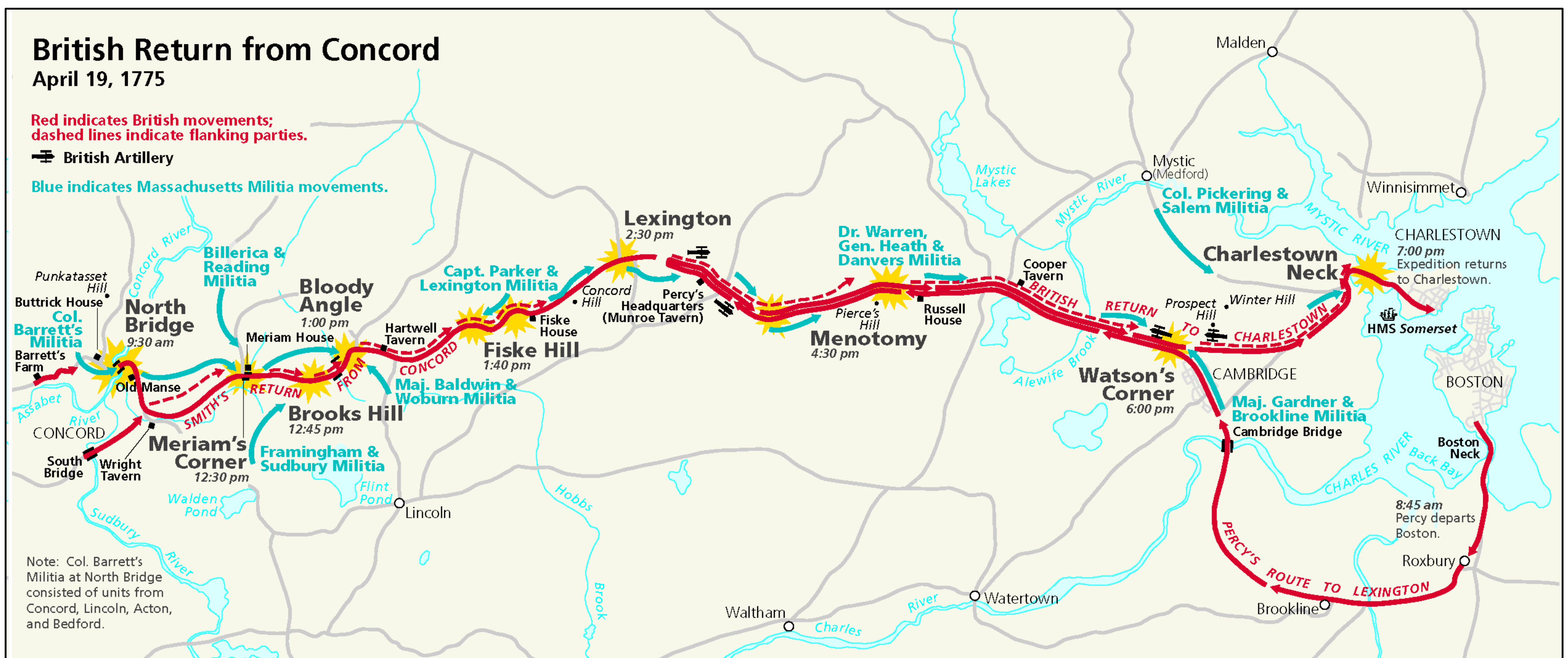


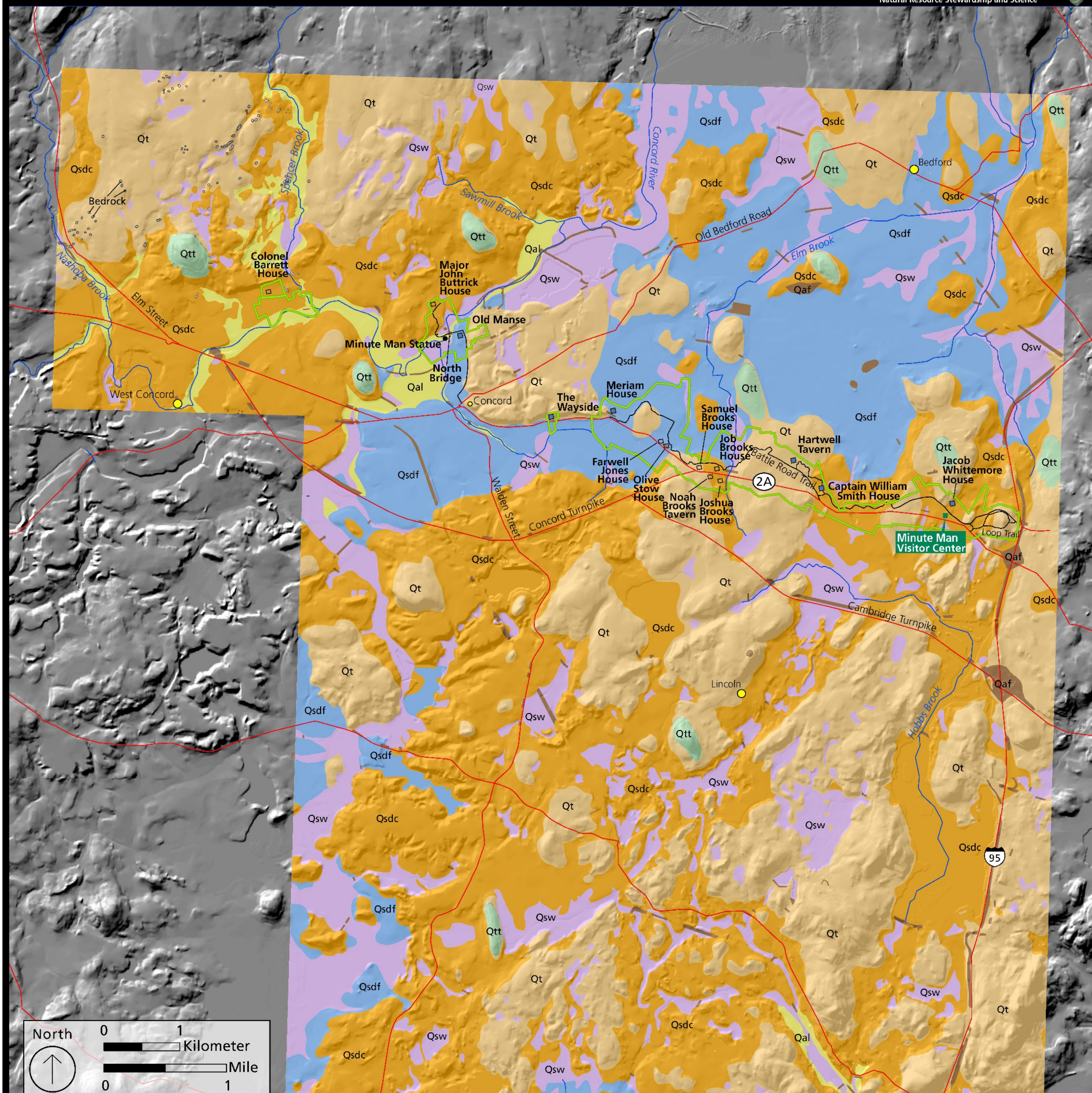
Plate 1. Maps of Minute Man National Historical Park. The maps on this side show the routes of the British Expedition and Patriot Messengers (April 18–19, 1775) and the British return from Concord (April 19, 1775). The map on the reverse side shows the location of park sites and surrounding areas. National Park Service maps, available at https://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=MIMA.

Surficial Geologic Map of Minute Man National Historical Park

Massachusetts

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



This map was produced by Karl Lanphier and Georgia Hybels (Colorado State University) in August 2017. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

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

Stone, J.R. and B.D. Stone. 2006. Surficial geologic map of the Clinton-Concord-Grafton-Medfield 12 quadrangle area in east central Massachusetts (scale 1:50,000). Open File Report 2006-1260A. US Geological Survey, Reston, Virginia.

As per source map scale and US National Map Accuracy Standards, geologic features represented here are within 25 m (83 ft) of their true location.

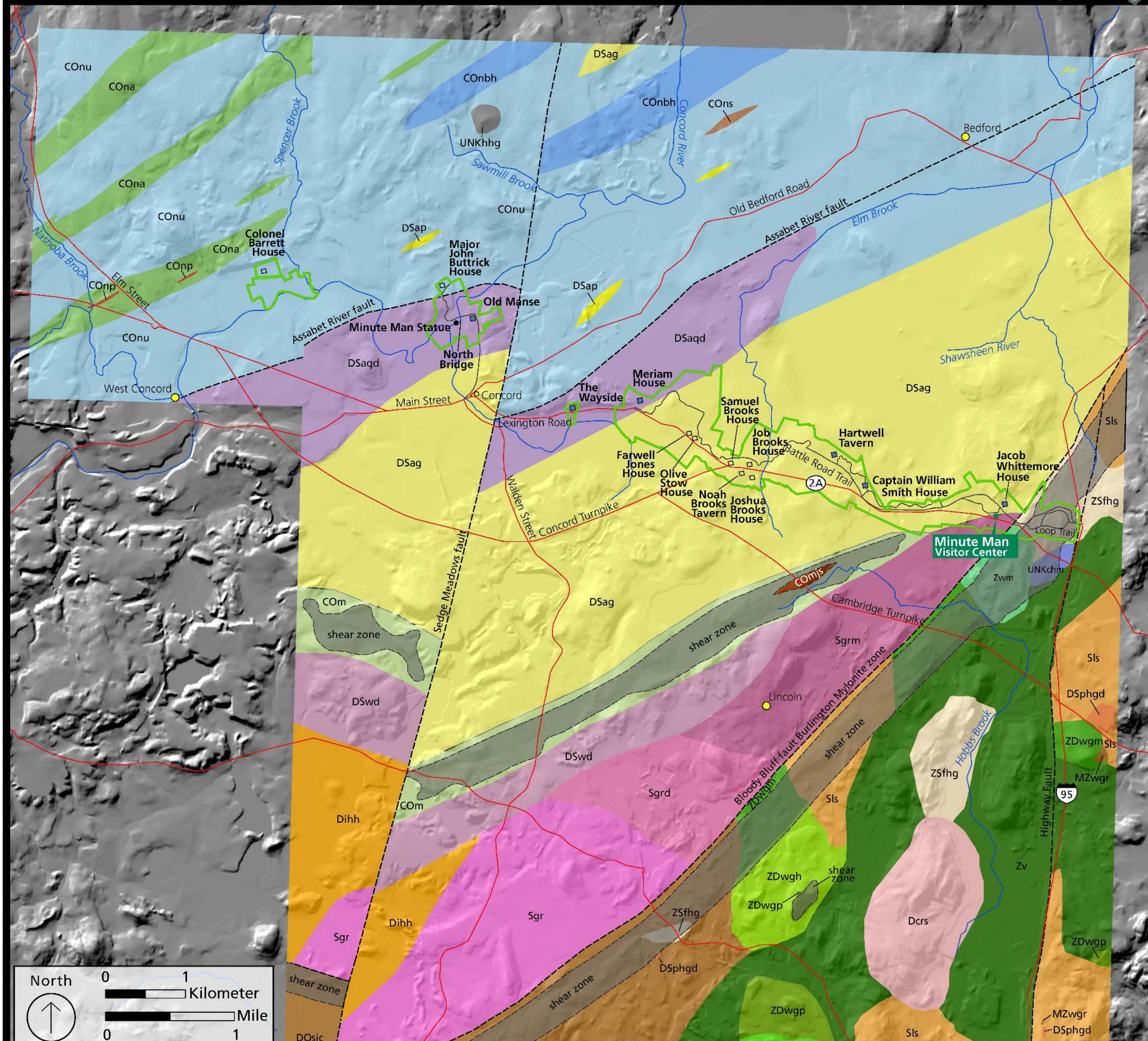
All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.

Bedrock Geologic Map of Minute Man National Historical Park

Massachusetts

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



NPS Boundary

Water Bodies
- Rivers

Infrastructure
- City
- Historic building, open to public
- Historic building, closed to public
- Trails
- Roads

Faults
- Unknown offset/displacement, approximate
- Unknown offset/displacement, inferred and queried

Deformation Areas
- Shear zone

Geologic Units

Nashoba Terrane

Intrusive Igneous Rocks

Dihh	Indian Head Hill Igneous Complex (Mississippian and Devonian)
UNKhhg	Hubbard Hill Gabbro (unknown age)
DSwd	White Pond Gabbro (Devonian? to Silurian?)
Dsag	Andover Granite (Devonian? to Silurian?)
DSap	Pegmatite (Devonian? to Silurian?)
DSaqd	Assabet Quartz Diorite (Devonian? to Silurian?)
Sgr	Sudbury Granite (Silurian?)
Sgrd	Sudbury Granite, dark phase (Silurian?)
Sgrm	Sudbury Granite, mixed phase (Silurian?)

Stratified Rocks

COnu	Nashoba Formation, undifferentiated (Cambrian to Ordovician)
COnbh	Nashoba Formation, Balls Hill Gneiss (Cambrian to Ordovician)
COna	Nashoba Formation, amphibolite (Cambrian to Ordovician)
COns	Nashoba Formation, schist (Cambrian to Ordovician)

Stratified Rocks continued

COnp	Nashoba Formation, pegmatite (Cambrian to Ordovician)
COm	Marlboro Formation (Cambrian to Ordovician or Older?)
COmjs	Marlboro Formation, Jupiter Ridge Schist Member (Cambrian to Ordovician or Older?)

Avalon Terrane

Intrusive Igneous Rocks

MZd	Diabase (Mesozoic)
Dcrs	Cambridge Reservoir Suite (Devonian)
DSphgd	Prospect Hill Gabbro-Diorite (Devonian to Silurian?)
MZwgr	Waltham Granite (Mid-Paleozoic)
Sls	Lexington Suite (Silurian)
ZSfhg	Fiske Hill Granite (Neo-Proterozoic to Silurian)
DOsic	Sudbury Valley Igneous Complex (Devonian to Ordovician?)
Odgd	Draper Gabbro-Diorite (Ordovician?)

Stratified Rocks

Zwm	Westboro Formation, mylonite (Age older than ~600 Ma to as old as ~1,000 Ma)

Tectonized-Mylonitized Rocks of the Avalon Terrance

UNKkgu	Kendall Green Ultramylonite (unknown age)
UNKchm	Cranberry Hill Mylonite (unknown age)
Zhm	Haywood Brook Mylonite (Neo-Proterozoic?)
ZDwgh	Weston Group, Hornblende Member (Neo-Proterozoic to Devonian)
ZDwghb	Weston Group, Hornblende-Biotite Member (Neo-Proterozoic to Devonian)
ZDwgp	Weston Group, Plagioclase-Hornblende-Biotite Member (Neo-Proterozoic to Devonian)
ZDwgm	Weston Group, Mylonitized Member (Neo-Proterozoic to Devonian)
Zv	Mafic to Felsic Tectonite (Neo-Proterozoic)

Location Map

This map was produced by Kari Lanphier and Georgia Hybels (Colorado State University) in August 2017. It is an overview of compiled geologic data prepared as part of the NPS Geologic Resources Inventory. This map is not a substitute for site-specific investigations.

The source maps used in creation of the digital geologic data were:

Hansen, W.R. 1956. Geology and mineral resources of the Hudson and Maynard quadrangles, Massachusetts (scale 1:24,000). Bulletin 1038, 3 plates. US Geological Survey, Reston, Virginia.

Langford, C.D. and C.J. Hepburn. 2007. Preliminary bedrock geologic map of the Concord quadrangle, Massachusetts (scale 1:24,000). Master's thesis. Boston College, Newton, Massachusetts.

As per source map scale and US National Map Accuracy Standards, geologic features represented here are within 12 m (40 ft) of their true location.

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs.