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The Geology and Landscapes of Wawayanda State Park and Surrounding Areas in Sussex and Passaic Counties, New Jersey and Orange County, New York

by Richard A. Volkert and Scott D. Stanford

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Cover photo: Wawayanda Lake viewed from Double Pond Trail. Photo by R. Volkert.

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INTRODUCTION

Wawayanda State Park, managed by the Department of Environmental Protection, Division of Parks and Forestry, State Park Service, was officially opened to the public in 1963. From an initial acquisition in 1962 of Wawayanda Lake and 3,400 surrounding acres, the Park currently encompasses about 35,161 acres. The Park is located in a sparsely developed area of northern New Jersey in eastern Sussex County and northern Passaic County, and lies entirely within the New Jersey Highlands Physiographic Province (fig. 1).

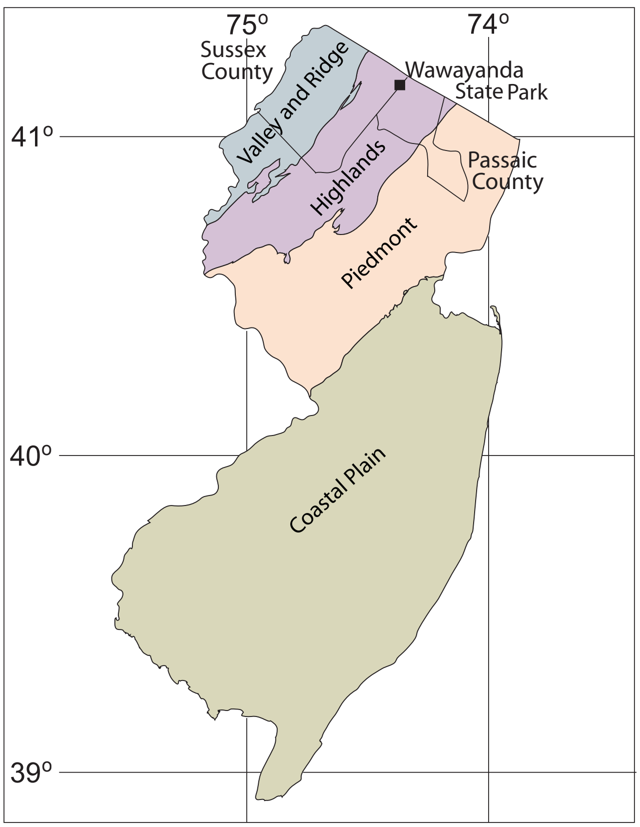


Figure 1. Physiographic provinces of New Jersey.

The area surrounding Wawayanda State Park is scenic and rugged. It is characterized by the mountainous uplands of Wawayanda and Bearfort Mountains, as well as extensive natural woodland and wetland areas, and an abundance of streams, ponds and lakes. Because the rocks forming Wawayanda and Bearfort Mountains are fairly resistant to erosion, ridgetop elevations are as much as 1,480 ft. above sea level, distinguishing them as the highest in the Highlands region. Most of the ridges forming the crest of Wawayanda Mountain are wide, with broad, flat tops, and ridge flanks that are commonly steep and locally form cliffs. By contrast, ridge crests on Bearfort Mountain are narrow, sharp, and straight, but the ridge flanks are generally steep and locally form cliffs similar to those on Wawayanda Mountain.

Wawayanda and Bearfort Mountains extend in a generally northeast direction, as do most of the major stream valleys in the region. This pattern of landforms has been naturally shaped by geologic processes that have operated during the past 1,300 million years. These processes, and their point in geologic time, are discussed in more detail in the following sections.

GEOLOGIC HISTORY OF NORTHERN NEW JERSEY

The northern part of New Jersey has undergone a long and complex geologic evolution, resulting in the formation of a variety of rock types and geologic features of varied age. A geologic time scale is provided to aid in visualizing this history (fig. 2).

Mesoproterozoic Era

The most ancient part of New Jersey, the New Jersey Highlands Province, formed about 1,300 and 980 million years ago, during the Mesoproterozoic Era (fig. 2). Rocks of the Highlands consist mainly of granite, gneiss (pronounced "nice"), quartzite, and marble. The gneisses were formed from the metamorphism (metamorphism means to change form) of volcanic rocks, or from sedimentary rocks that were formerly sandstone and shale. Quartzite was formed from the metamorphism of quartz-rich sandstone, and marble formed from limestone. Some of the gneisses, quartzite and marble were deposited in an ocean basin located off the ancestral eastern North American continent 1,300 to 1,250 million years ago. A chain of volcanic islands underlain mainly by various igneous rocks similar to those of the present-day Aleutian Islands in Alaska was situated farther off shore.

About 1,185 to 980 million years ago, the gneisses, quartzite and marble were intruded by several types of granite that had formed from molten magma pooled in large magma chambers within the Earth's crust. The most abundant of the granites are the Byram and Lake Hopatcong, named for Byram Township and Lake Hopatcong, respectively, where they are well exposed. These granitic rocks underlie about 50 percent of the Highlands. Together, the Byram and Lake Hopatcong granites make up the Vernon Supersuite, named for

Hamburg Mountain in Vernon Township where both granites are co-mingled.

About 1,050 million years ago, nearly all of the rocks of the Highlands were metamorphosed under conditions of high temperature at about 770°C (1,300 °F) and pressure of 5,500 atmospheres (approximately 80,000 pounds/square inch) during their burial to a depth of about 13 miles in the Earth's crust. This metamorphism aligned the minerals in the rocks, giving them a banded appearance. Deep burial of the rocks and their metamorphism is a result of the collision of the ancestral eastern North American and South American continents. This collision was the earliest event in the formation of the Appalachian Mountains, which were uplifted in the Highlands to heights possibly rivaling those of the present-day Rocky Mountains. Rocks of the Highlands are exposed today because of the uplift and erosion of younger rocks that formerly covered them.

Geologic Time Scale

Years Ago[1]	Eon	Era	Period	Epoch	Geology, Life, and Environment	
0 to 10,000	PHANEROZOIC	CENOZOIC	QUATERNARY	Holocene	Climate change from boreal (cold) to temperate (mild).	Modern humans evolve.
10,000 to 2.5 million				Pleistocene	Northern New Jersey glaciated at least 3 times.	
2.5 to 66 million			TERTIARY	Pliocene Miocene Oligocene Eocene Paleocene	First large mammals appear. Abundant mammals; first hominids. Grasses and modern birds appear.	414.2 million-year gap estimated in geologic record at High Point State Park
66 to 146 million		MESOZOIC	CRETACEOUS	Late Early	Heyday of dinosaurs, pterosaurs and marine reptiles until their extinction at end of period. First flowering plants.	
146 to 200 million			JURASSIC	Late Middle Early	Earliest birds appear. Giant dinosaurs (sauropods) flourish. Plants: ferns, cycads and ginkos.	
200 to 251 million			TRIASSIC	Late Middle Early	Age of dinosaurs begins. First mammals. Mollusks are dominant invertebrate.	
251 to 299 million		PALEOZOIC	PERMIAN	Late Early	Age of Amphibians. Pangea forms. Greatest mass extinction ever. Trilobites go extinct.	
299 to 359 million			PENNSYLVANIAN[2]	Late Middle Early	Widespread coal swamps. First winged insects and reptiles.	
			MISSISSIPPIAN[2]	Late Early	Many ferns and amphibians.	
359 to 416 million			DEVONIAN	Late Middle Early	Age of Fishes. First shark. Many diverse land plants. Earliest amphibians, ferns and mosses.	
416 to 444 million			SILURIAN	Late Middle Early	Bloomsburg Red Beds Shawangunk Formation	First insects, jawed fish, vascular land plants.
444 to 488 million			ORDOVICIAN	Late Middle Early	Martinsburg Formation • High Point Member • Ramseyburg Member • Bushkill Member	First corals, moss. Primative fish, fungi and seaweed.
488 to 542 million			CAMBRIAN	Late Middle Early	Age of Trilobites. Cambrian explosion of life occurs. First vertebrates. Earliest fish. First shells appear.	Rocks of these ages are not found at (or near) the surface at High Point State Park. They may be at depth.
542 to 2500 million	PROTEROZOIC[3]		Neoproterozoic	Lower limit of Eoarchean is not currently defined. Estimated to be 4600 million years.	Cold climate with three episodes of glaciation in late Proterozoic.	
			Mesoproterozoic		First soft-bodied invertebrates and colonial algae. Oxygen build-up in atmosphere during Mesoproterozoic.	
			Paleoproterozoic			
2500 to 4600 million	ARCHEAN[3]		Neoarchean		Life appears. First bacteria and blue-green algae begin freeing oxygen to Earth's atmosphere.	
			Mesoarchean			
			Paleoarchean		Earth molten.	
			Eoarchean		Sun and planets form.	

[1] Gradstein, F.M. and others, 2004, A Geologic Time Scale: Cambridge University Press, 589 p.
[2] Pennsylvanian and Mississippian comprise the Carboniferous System.
[3] Also called Precambian, a non-specific time term.

Figure 2. Major divisions of geologic time. Number indicates million years ago.

About 1,020 million years ago, after continental collision and regional metamorphism, the ancestral Highlands were intruded by more granite that formed from melting of small amounts of the Earth's crust. These include the Mount Eve Granite, which crops out mainly in and around Mount Eve in Orange County, New York and less abundantly in Sussex County, New Jersey. Small bodies of coarse-grained granite known as pegmatite were intruded throughout the Highlands at about 990 million years ago. Following their intrusion, the Highlands underwent slow uplift and cooling as the overlying rocks were eroded.

Rocks of Mesoproterozoic age underlie most of the area of Wawayanda State Park. These include a variety of gneisses, granites and granite pegmatite. Marble is absent in the park but is abundantly exposed to the west in Vernon Valley.

Neoproterozoic Era

During the Neoproterozoic Era (fig. 2), from 950 until about 542 million years ago, the Highlands were uplifted and subsequently slowly cooled following their deep burial; they then underwent erosion upon reaching the Earth's surface. Sometime around 700 million years ago the ancestral North American and South American continents began to split and drift apart, creating deep fractures in eastern North America. About 600 million years ago magma from the mantle rose and filled the fractures that had formed in the Highlands. Upon cooling, the magma produced diabase dikes that are common throughout the region. As upland areas of the Highlands continued to erode, some of the eroded sediment was deposited in small basins that formed on land and the rest was transported to the ocean.

Rocks of Neoproterozoic age do not crop out in the park. However, diabase dikes of this age are common in surrounding areas and sedimentary rocks are preserved locally along the edge of Vernon Valley south of the park.

Paleozoic Era

Rocks of Paleozoic age belong to the Cambrian and Devonian Periods (fig. 2) and they range in age from 542 million to about 359 million years. At the start of the Paleozoic, most of the mountainous area of the Highlands had been eroded to a nearly flat surface that was slowly covered by a shallow sea. The North American continent that contained ancestral New Jersey had begun to drift apart from ancestral South America, creating an ocean basin. As the continents once again changed from drifting apart to colliding, part of this ocean basin was destroyed during a collision about 450 million years ago, and the remainder was destroyed about 290 million years ago during the collision of Africa and Europe with the North American continent.

In the area of present-day New Jersey, these collisions renewed uplifting and mountain building in the Highlands and also to the west in the Valley and Ridge Province (fig. 1).

The Paleozoic rocks in the area of Wawayanda State Park are sedimentary. They include conglomerate, quartzite, sandstone, siltstone and shale, formed from gravelly, sandy, silty and clayey sediments, respectively, as well as dolomite (magnesium-bearing limestone) and limestone formed by the accumulation of calcareous material from marine organisms. Most of the conglomerate, quartzite and sandstone in the Bearfort Mountain area was deposited on land directly on the Mesoproterozoic rocks and contains sedimentary deposits eroded from them. Some of the sandstones that are currently exposed north and west of the park were deposited in a shallow marine environment. They are overlain by limestone and dolomite, both overlain by shale, which formed from sediments deposited as the ocean basin became deeper. During the Paleozoic, especially during the Devonian Period (fig. 2), the ocean covering ancestral New Jersey was teeming with marine life. Some of the sandstone and limestone exposed in Vernon Valley, a few miles west of Wawayanda State Park, and in Orange County, New York, to the north, contains fossils of marine life such as trilobites, algae, and enigmatic fossils known as conodonts.

Mesozoic Era

The Mesozoic Era, from about 251 million to 66 million years ago, began a new cycle of erosion from renewed uplift of the Highlands following continental collision. During the Triassic and Jurassic Periods (fig. 2), the continents again began to split and drift apart, creating deep fractures in eastern North America and forming the modern Atlantic Ocean. In the Highlands, the Ramapo fault east of Wawayanda State Park is one of these fractures. As the Earth's crust slowly dropped down along the Ramapo fault, a deep basin was created on land east of the Highlands into which large amounts of sediment were deposited from the eroding Highlands. In addition, magma from the mantle intruded these sediments, forming diabase bodies such as the Palisades, and lava poured out onto the surface as three separate basalt flows, creating the Watchung Mountains. Fish swam in the lakes, dinosaurs roamed the lowland floodplains, and plants flourished. During this time the Piedmont Province (fig. 1) was formed in New Jersey. Sedimentary and igneous rocks of Mesozoic age do not crop out in the area of Wawayanda State Park, but some of the faults in the region may have been activated, or at least reactivated, then.

During the Cretaceous Period (fig. 2) about 146 to 66 million years ago, an ocean once again covered the continental margin of southern and central New Jersey, depositing a thick accumulation of unconsolidated sediment that today forms the Coastal Plain Province in New Jersey (fig. 1). The Highlands and most of the Piedmont remained above sea level during this time.

Cenozoic Era

Throughout the Cenozoic Era (Tertiary and Quaternary Periods) (fig. 2), continental collisions and mountain building processes ended and the Highlands remained relatively stable and quiescent. The predominant process in the region was erosion. As a result, most of the Highlands was reduced to a nearly flat surface. Starting at about 10 million years ago, streams began to incise and deepen their valleys. They cut more deeply into the softer rocks such as limestone, dolomite, marble, and shale, and left the resistant gneiss, granite and quartzite towering above them as ridges.

About 2.5 million years to 21,000 years ago, during the Pleistocene Epoch (fig. 2), the climate in New Jersey became much colder and the northern part of the state was covered by glacial ice sheets. The climate alternated between cold and warm periods. In New Jersey, ice sheets advanced at least three times during the colder glacial stages, which were frigid enough to permanently freeze the ground and create a tundra-type environment in the state resembling that in northern Canada. The ice sheets melted and receded during the warmer interglacial stages.

The landscape of New Jersey continues to undergo gradual change even today as sediment is eroded from rocks of the Highlands and is carried away by local tributaries of the Wallkill and Passaic Rivers. These tributaries, Pochuck Creek and the Wanaque and Pequannock Rivers and their watersheds, comprise the predominant drainage basins in the area encompassing Wawayanda State Park. Most of the main park area falls within the Pochuck Creek drainage basin, but the southern part of the park is in the Pequannock River drainage basin. Bearfort Mountain, and Abram S. Hewitt State Forest, located to the east-southeast of the park, are in the Wanaque River drainage basin.

GEOLOGY OF WAWAYANDA STATE PARK AND SURROUNDING AREAS

Bedrock Geology

The oldest rocks in the area of Wawayanda State Park are Mesoproterozoic in age and were formed more than 1 billion years ago. They underlie all of Wawayanda Mountain and most of the park, as shown in a simplified geologic map of the area (fig. 3). To the west of the park, Mesoproterozoic rocks

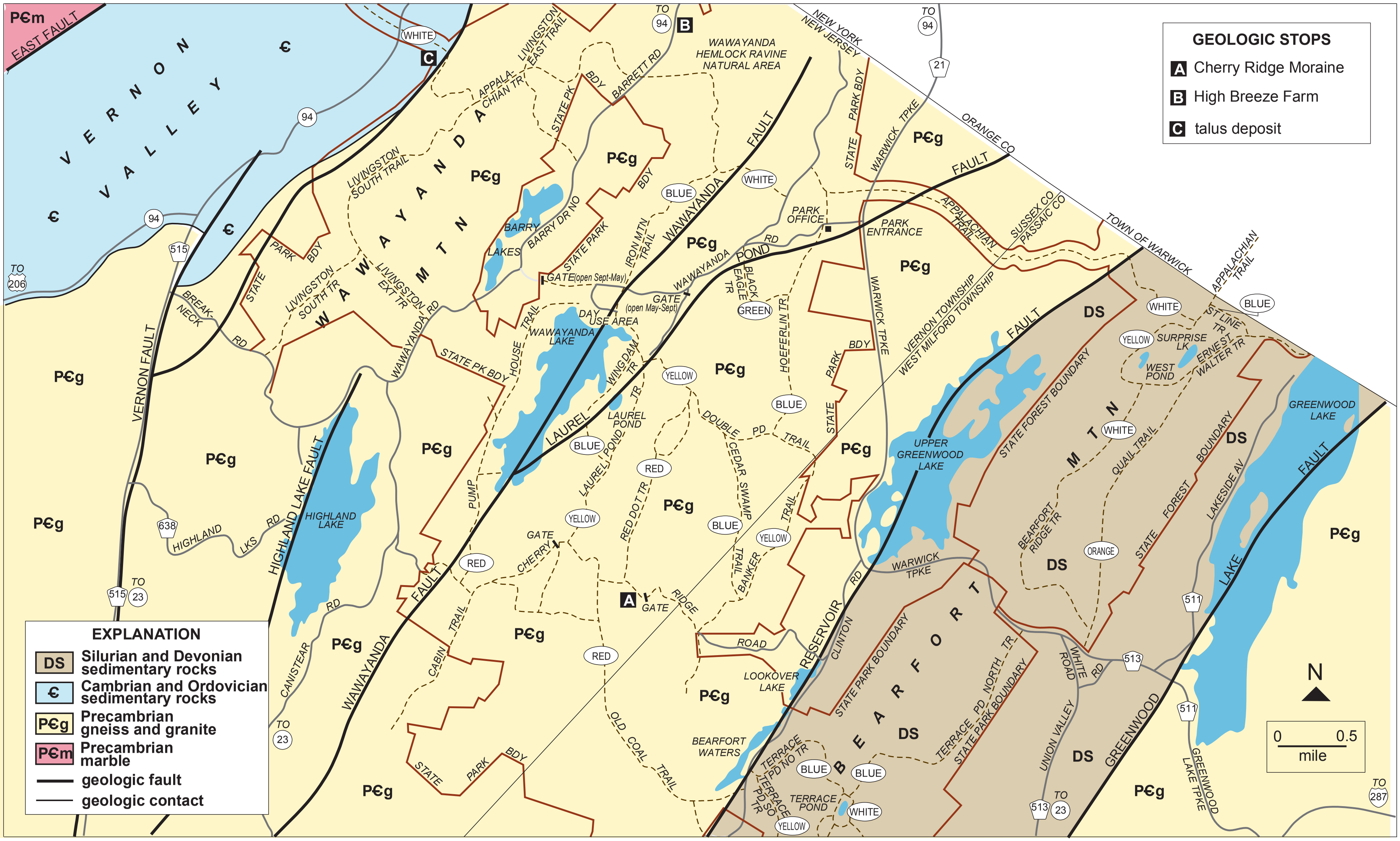


Figure 3. Bedrock geologic map of Wawayanda State Park and surrounding area, New Jersey, generalized from Drake and Others (1996).

underlie the Vernon Valley, but are partially covered by Paleozoic sandstone and dolomite. The same is true north of Wawayanda Mountain, in Orange County, New York. East of Wawayanda Mountain, some of the Mesoproterozoic rocks were forced downward along the Reservoir fault and now occur at considerable depth beneath Bearfort Mountain, where they are covered by Paleozoic conglomerate, quartzite, sandstone, and shale.

Mesoproterozoic rocks on Wawayanda Mountain consist mainly of several different types of gneiss and granite. Granite underlies much of the western edge of the mountain. Because it is more resistant to erosion than most of the gneiss, it forms the steep, prominent cliffs east of Route 94 that extend northward from Vernon to the New York State border. Less resistant gneiss underlies the northern part of Wawayanda Mountain, so steep cliffs are absent and the mountain slopes more gently toward the valley north of Route 94. Marble does not occur on the mountain, but is exposed along the western side of Vernon Valley at the base of Pochuck Mountain (fig. 3).

All of the faults on Wawayanda Mountain formed in response to ruptures in the Earth's crust throughout geologic time during eastern North America's intermittent collisions with other continents. The Wawayanda fault and the Laurel Pond fault (fig. 3) cut through Wawayanda State Park. The Wawayanda fault extends along the eastern side of Canistear Reservoir and Cherry Ridge Brook, passes through Wawayanda Lake and ends near the New York State border. A small fault segment branches off of the Wawayanda fault and continues northward along the eastern side of Highland Lake (fig. 3). The Laurel Pond fault also extends northeastward from the southern end of Wawayanda Lake, and continues east across Warwick Turnpike and beyond. There is little evidence to suggest that any of the faults in the area of the park have been active seismically in modern times.

Paleozoic rocks crop out directly west of Wawayanda Mountain in Vernon Valley in a belt that extends west to Pochuck Mountain and north of Route 94 into New York (Є in fig. 3). Paleozoic rocks also crop out east of Clinton Road on Bearfort Mountain (DS in fig. 3). The oldest Paleozoic rock is the Hardyston Quartzite of Cambrian age (fig. 4). This formation, a mixture of sandstone and quartzite, is a light-gray rock composed primarily of silica-cemented quartz grains. The Hardyston was deposited directly on older Mesoproterozoic rocks, initially in a terrestrial environment, and later in a marine environment, as sea levels rose and eventually covered this part of the state.

The contact between the top of the underlying Mesoproterozoic rocks and the base of the Hardyston Quartzite is known as an unconformity, which is a substantial gap in the geologic record. This break in geologic time represented a 430-million-year period of erosion prior to deposition of Hardyston Quartzite.

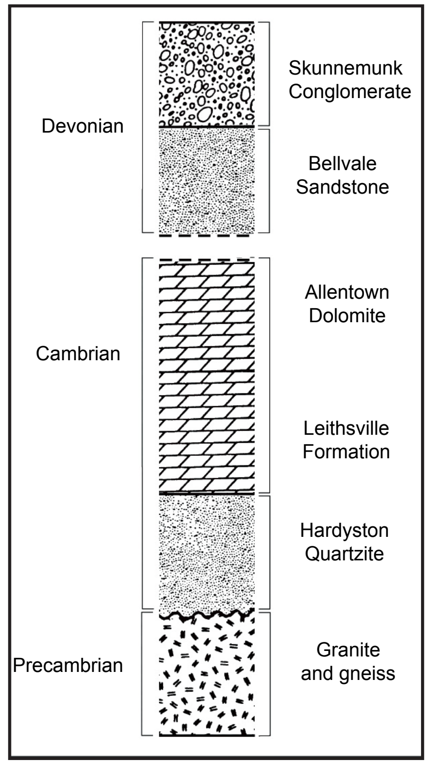


Figure 4. Stratigraphic column of bedrock formations in Wawayanda State Park.

The Hardyston Quartzite grades upward into dolomite of the Leithsville Formation of Cambrian age, which is overlain by the Allentown Dolomite also of Cambrian age (fig. 4). The dolomite grains of both formations are characteristically light gray to dark gray in color, prompting early geologists to refer to them as 'blue limestone.' The Leithsville and Allentown were deposited in a marine environment similar to that of the present-day continental shelf in the Caribbean Sea. Sedimentary layers in these Paleozoic rocks initially were deposited horizontally, but have been tilted throughout geologic time during mountain-building processes.

In Wawayanda State Park, Paleozoic rocks crop out in the Wawayanda Hemlock Ravine Natural Area (fig. 3). Here, the Hardyston Quartzite crops out along the stream east of Barrett Road. Paleozoic conglomerate and sandstone also underlie Bearfort Mountain and extend north into the Abram S. Hewitt State Forest. These rocks are about 380 million years old, making them younger than the Hardyston Quartzite and dolomite formations. The Skunnemunk Conglomerate (fig. 4) of Devonian age underlies most of Bearfort Mountain. It consists mainly of reddish-purple conglomerate, quartzite, and minor shale, all composed of silica-cemented quartz grains and rock fragments. The Bellvale Sandstone, also of

Devonian age, underlies the Skunnemunk. It is mainly dark gray sandstone composed of silica-cemented quartz grains and rock fragments and gray shale. The Skunnemunk and Bellvale originated from sediments deposited by streams in a terrestrial environment during mountain building and uplift of the region during the Devonian Period (fig. 2).

Sedimentary beds in the Bearfort Mountain area are buckled into a down-arched fold known as a syncline. All of the beds trend northeast, but those on the east side of the mountain dip to the west, whereas those on the west side of the mountain dip east. The sedimentary layers initially were deposited horizontally, but have been tilted steeply and folded throughout geologic time in response to mountain-building processes.

Whereas Paleozoic sandstone and dolomite west and north of Wawayanda Mountain rest directly on, or overlie, Mesoproterozoic rocks on which they were deposited, Paleozoic rocks of Bearfort Mountain are separated from the Mesoproterozoic rocks of Wawayanda Mountain by the Reservoir fault (fig. 3). This fault extends for miles in a northeast direction and dips nearly vertically. Movement along the Reservoir fault several hundred million years ago resulted in the dropping downward of Paleozoic rocks on Bearfort Mountain relative to the Mesoproterozoic rocks on Wawayanda Mountain, which were pushed upward. Largely due to this fault motion, the Paleozoic rocks are preserved today whereas ordinarily they would have been removed through erosion.

Glacial Geology

Northern New Jersey was covered by glacial ice at least three times in the past 2.5 million years. The glacial features in Wawayanda State Park are almost entirely the product of the most recent glaciation, which reached its maximum extent in what is now New Jersey about 21,000 years ago and had retreated from the state by about 18,000 years ago. Although the major valleys and mountains in the area had been shaped primarily by river erosion during the several million years before the arrival of glaciers, nearly all of the landform details of the park are the result of glacial action. The rocky ridges and knobs formed when soil and sediment that formerly mantled the land surface were frozen onto the bottom of the glacier and then stripped away as the ice moved, exposing the underlying bedrock. Between the ridges, basins were scoured out by the glacier in bedrock softened or easily broken by preglacial weathering. Some of these basins formed when sediment deposited by the retreating glacier formed dams across valleys. The many swamps, marshes, and natural ponds in the park now fill these basins.

The shape and form of the rock outcrops and ridges reflect the direction of movement of the glacial ice. Slopes that faced north, into the advancing ice, were abraded and scoured to form broad sloping ledges (see Stop 3 of the geologic tour). Rock on south and southeast-facing slopes was quarried to form cliffs (Stop 4). This quarrying process provided the many boulders scattered throughout the park, most of which consist of gneiss and quartzite from local rock outcrops. Some boulders consist of dolomite plucked from rock outcrops in the Wallkill Valley north of the park. Rock fragments embedded in the base of the glacier carved grooves known as striations in bedrock as the ice dragged them across the rock surface. Most striations have been weathered away since retreat of the glacier, but on especially hard, or freshly exposed rock, they are still visible. In Wawayanda State Park, striations are abundant on Bearfort Mountain and may also be seen on some freshly exposed gneiss surfaces along the park trails. They indicate that ice moved to the south, or slightly west of south, as it advanced over this region.

As the glacier moved, it eroded soil and rock in places while depositing it in others. This ice-laid material is a mixture of boulders, gravel, sand, silt, and clay and is known as till. Till can form several types of landforms, all of which are represented in, or near, the park. Drumlins are streamlined, ice-molded hills composed mostly of till. They are elongated in the direction of glacier flow. There is a small drumlin near Cherry Ridge (fig. 5) and several drumlins just outside the park northwest of Upper Greenwood Lake. Moraines are belts of till forming ridges and swales laid down along the front of the glacier. They mark the location of temporary stillstands of the ice margin as it retreated. The Cherry Ridge Moraine (fig. 16, Site A) extends discontinuously across the southern part of the park from Highland Lake to Lookover Lake and forms the southernmost shore of Wawayanda Lake. Cherry Ridge Road follows segments of this moraine. Most till is deposited as a layer on the bedrock surface, forming what is sometimes called ground moraine. Most of Wawayanda State Park, except for rock outcrops, is covered with a thin ground moraine. Soils in these areas are thin and rocky and are generally unsuitable for agriculture. Some north-facing slopes have a thicker, more continuous ground moraine than elsewhere because ice was under more pressure on those slopes and melted to release more sediment, forming thicker till. These areas of thicker till were easier to clear and farm and were commonly used for pastures and orchards. The fields along Warwick Turnpike and Barrett Road near the New York State border mark such ground moraine, as does the area around the historic High Breeze Farm (fig. 16, Site B).

As the glacier melted, it generated meltwater. This water flowed in channels beneath, or along, the edge of the glacier, and carried sand, gravel, silt and clay released from the melting ice. This sediment was laid down to form layered deposits known as stratified

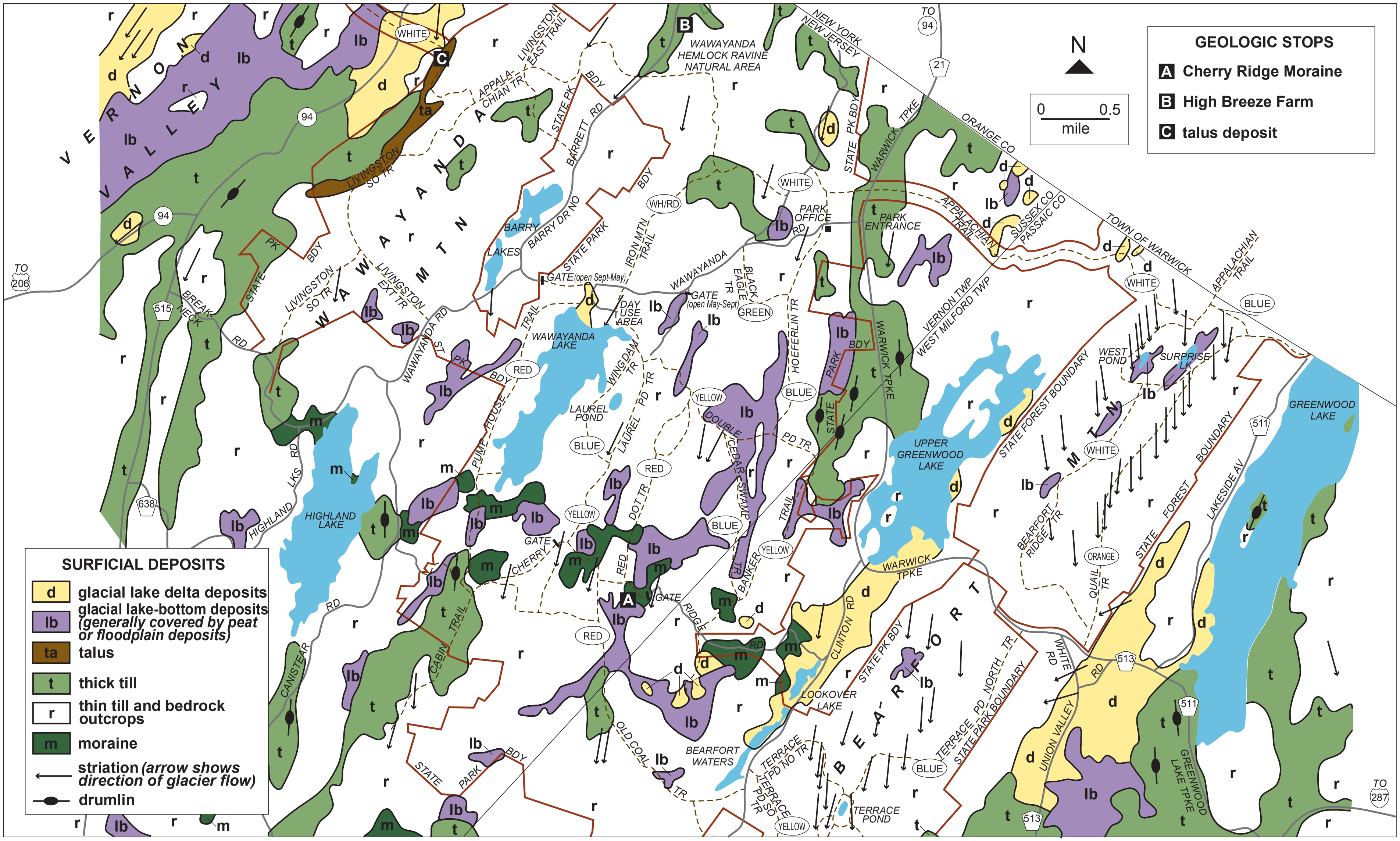


Figure 5. Surficial geologic map of Wawayanda State Park and surrounding area, New Jersey, generalized from Stanford (1991), Stanford (1992) and Stanford (1993).

drift. Stratified drift includes sediment laid down by rivers and streams flowing away from the glacier, and sediment laid down in glacial lakes that formed when valleys were blocked by ice or by other glacial deposits. Small deposits of both varieties of stratified drift are found in the park. Wawayanda State Park includes all or part of seven glacial lakes, which filled and drained sequentially from south to north as the ice margin retreated. The large wetland areas on Wawayanda Mountain south and east of Wawayanda Lake, as well as Wawayanda Lake itself (Double Pond), are vestiges of these formerly much larger glacial lakes. Small deposits of sand and gravel mark deltas built into these lakes at the former edge of the ice. For example, the beach and picnic area at the north end of Wawayanda Lake are on a flat-topped surface of one of these deltas (fig. 6, Stop 1). Meltwater that drained from the lakes, or that flowed away from the ice margin in valleys lacking lakes, carved channels into the ground moraine. Sand and silt were washed away by the meltwater, leaving concentrations of boulders known as boulder lags along the channels. Today many of the valleys in the park display these lags, an indication that they once served as meltwater channels or glacial-lake spillways.

As the glacier retreated northward out of New Jersey, the land slowly adjusted to the reshaped landscape and warming climate. Streams established new courses across the ground moraine and newly drained lake bottoms. The forests returned. Spruce trees, the earliest to arrive, gave way to pine and birch, which were then replaced by the present oak-maple-hemlock forest. Plant debris accumulated in the remnants of the glacial lakes to form swamps and marshes (fig. 6, Stop 7). This plant debris formed deposits known as peat. Peat is as much as 25 feet thick in some of the larger swamps and probably results from more than 15,000 years of accumulation of plant material. On cliffs and steep rock slopes, the slow action of water and ice pried away loose rock, which accumulated in aprons of debris at the base of the slope known as talus. One of the largest talus deposits in New Jersey is located beneath the cliffs on the west side of Wawayanda Mountain, overlooking Vernon Valley and crossed by the Appalachian Trail (fig. 16, Site C). These postglacial processes continue to slowly alter the present landscape of the park.

ECONOMIC DEVELOPMENT

Sussex and Passaic Counties have a rich and varied history, but people are commonly unaware of the role geology played in the development of this region. Among the early inhabitants, Indian tribes no doubt settled in the area to take advantage of the sheltered protection and the abundance of game offered by the mountainous terrain, as well as the rich, fertile soils and convenient transportation provided by the major streams and valleys.

From 1710 to 1966, a thriving iron ore industry hosted in Mesoproterozoic rocks flourished in northern New Jersey, which, during the early 19th century, led the nation in iron ore production by its mining of the mineral magnetite. During the Revolutionary War, some of this ore was forged into cannonballs and other weaponry for use by the Continental Army. More than 500 mines and prospects throughout northern New Jersey were worked, producing an estimated total of 50 million tons of iron ore by the time the industry closed. Mining activity contributed significantly toward economic growth in the Wawayanda area until its decline in about 1890.

Several abandoned iron mines are in, or close to, Wawayanda State Park (locations are not shown in this report). These include the Green, Wawayanda, Layton, and Parker Mines. The Welling and Carey Mines are located just off of park property. The following abbreviated information on each of these mines is mainly from Bayley (1910).

The Green Mines, worked intermittently from about 1853 until 1888, consisted of several shafts and prospect pits on the east-central part of Wawayanda Mountain. Despite the small size of an ore vein that ranged from 1 to 4 ft. thick, a large quantity of ore was mined, although the exact amount is unknown. The Wawayanda Mine is located directly north of the Green Mines. It was worked intermittently from about 1854 until 1891. Ore was mined from a vein that was 2 to 12 feet thick. About 5,200 tons of ore was removed from 1887 to 1891, although the overall total remains unknown. The Layton Mine, on north-central Wawayanda Mountain, was worked from 1878 until 1883. The ore was mined from several shafts in a vein 5 to 6 feet thick, the deepest of which was 128 ft. deep, and also from several prospect pits. The total amount of ore removed is unknown, but it is doubtful that it was large. The Parker Mine, on the west side of Wawayanda Mountain, was worked briefly in 1873. Two small prospect pits were dug, but only sparse amounts of ore were recovered and therefore, no actual mining started. The Welling Mine (known also as Ten Eyck's Exploration) is situated east of the Green and Wawayanda Mines. It was worked intermittently from 1855 until 1880 from several shallow shafts and prospect pits. The total amount mined is unknown, although 400 tons were removed during the last year of production. The Carey Mine is located on the east side of Wawayanda Mountain. It was worked for an undetermined number of years, but had closed by 1886. The ore vein was 7 feet thick and mined from a single shaft 27 feet deep and also from a shallow open cut. The total amount mined is unknown.

A minor industry developed in Sussex and Passaic Counties, New Jersey and southern Orange County, New York, involving the quarrying of rocks for use as crushed stone (granite and gneiss), agricultural product (limestone, dolomite, and marble) or roofing shingles and chalkboards (slate). None of the stone quarries are currently active. Of these, the largest quarries in the vicinity of the park are to the north on Mount Eve and Mount Adam. Some limestone and dolomite was also mixed with iron ore for use as a flux during the roasting of ore in furnaces such as the one at Wawayanda. Glacial sand and gravel deposits were mined locally for use as construction aggregate, especially along the west side of Wawayanda Mountain.

Since earliest colonial times, agriculture has been important in the area, especially in the valley north of Wawayanda State Park. The development of farms may not have been possible were it not for the geologic processes that created the rich, fertile soil that covers much of the valleys, particularly to the north in Orange County. This soil, known locally as "black dirt", was formed from organic-rich sediments that accumulated at the bottom of a glacial lake that formerly filled the valley.

Postglacial geologic conditions provided favorable sites for the location of reservoirs occupying the watershed area of the Newark Division of Water Supply. These include Canistear, Oak Ridge, Clinton, Charlotteburg, and Echo Lake Reservoirs, all south of Wawayanda State Park. Most of the bedrock contains enough groundwater in fractures to serve as an important source of supply for domestic, industrial, and public-supply water wells in the region. However, deposits of glacial sand and gravel and dolomite bedrock that overlie the Mesoproterozoic rocks in the valleys of the region are even more productive sources of groundwater.

FEATURES OF GEOLOGIC INTEREST

The varied areas of Wawayanda State Park provide an excellent opportunity to examine the diverse and interesting geology that has developed during the past 1,300 million years. The following stops shown on the map in figure 6 make it possible for a self-guided walking tour, starting at the beach area where a particular rock type, glacial feature, or other geologic feature may be easily observed. Geologic features along the trails in areas of the park that are more remote, or are off of park property, are shown on the map in figure 16 and described under "Additional Geologic Features".

Figure 6. Map showing surrounding trails of Wawayanda State Park self-guided tour. Numbers are keyed to descriptions of stops in the text.

Stop 1. Wawayanda Lake
(41° 11' 17.75" N, 74° 25' 42.55"W)

At the heart of Wawayanda State Park is Wawayanda Lake (fig. 7); a relic glacial feature having its origins in the Pleistocene Epoch (fig. 2). The original drainage consisted of two elongated ponds connected by a channel and formerly referred to as Double Pond. Dam construction in 1845 flooded both ponds, resulting in the formation of the present lake. Wawayanda Lake covers an area of 255 acres, has a maximum length of nearly 1.5 miles, and a maximum width of about 0.5 mile. The former northern pond has a depth of slightly more than 60 feet, whereas the former southern pond is somewhat deeper, at nearly 90 feet. The ponds are separated by Beech Island, near the center of the present lake.

Figure 7. Wawayanda Lake view looking south from the beach. Photo by R. Volkert.

Wawayanda Lake was created as a source of water power to service a variety of mills as well as the mining industry in the immediate area. The main dam, located at East Cove at the extreme northeastern end of the lake, was constructed over an outlet occupied by a stream flowing east past the old Wawayanda Furnace. This dam is 225 feet long, 13 feet high, and 24 feet thick at its maximum (Apffel, 1970). A smaller dam, roughly the same age as the main dam, was constructed over a stream flowing from Wing Dam Cove east to Laurel Pond.

The basin filled by Wawayanda Lake was scoured out of bedrock by the late Wisconsinan glacier about 22,000 to 18,000 years ago. It is one of many such basins on Wawayanda and Bearfort Mountains. As the front of the glacier melted back to the north about 18,000 years ago, its margin acted as a dam across these basins, forming a series of glacial lakes. The beach area at Wawayanda Lake is on a delta of sand and gravel that was deposited in the glacial lake that occupied this basin. The flat lawn around the parking lot at the beach approximates the surface of this glacial lake, which was about 10 feet higher than the present lake.

The many swamps and smaller lakes in the park, and man-made lakes near it, like Highland Lake and Upper Greenwood Lake, mark the location of these former glacial lakes, most of which were larger and deeper than the present lakes. As the glacier retreated, these lakes lowered or drained, and their remnants gradually filled with clay, silt and peat, forming marshes and swamps. These wetlands are crossed by the Double Pond and Cedar Swamp Trails, and may be seen from most other Park trails. Natural ponds like Laurel Pond and Terrace Pond in Wawayanda State Park, and Surprise Lake and West Pond in Abram S. Hewitt State Forest, are deeper and have less sediment washing in from streams, so they have yet to be converted to wetlands.

As you walk to Stop 2, note the smooth surface of the gneiss outcrops in the bed of the trail as you cross the hill east of the beach. The smoothing is from glacial abrasion, which we'll discuss at Stop 3.

Stop 2. Granite outcrop
(41° 11' 18.25" N, 74° 25' 37.63" W)

Figure 8. Outcrop of Lake Hopatcong granite. Photo by R. Volkert.

The outcrop in the hillslope behind the restrooms is Lake Hopatcong granite (fig. 8), named for Lake Hopatcong where it is best exposed. This granite is characteristically white to tan weathering, light greenish-gray on fresh surfaces, and medium- to coarse-grained with tight, interlocking mineral grains. The granite consists mainly of the minerals quartz (light gray) and feldspar (creme), and minor yellow to brown weathering pyroxene. Similar outcrops of this granite underlie nearly all of Wawayanda Mountain west of Wawayanda Lake. Lake Hopatcong granite is about 1,185 million years old.

Note the alignment of minerals into bands or parallel layers, known as foliation (fig. 9). Foliation forms during the high-temperature alteration of the original rock, in which the minerals recrystallize and separate because of differences in their density. The parallel alignment of the minerals is a result of compressional stresses on the rock during metamorphism that "squeeze" and flatten the layers.

Figure 9. Parallel alignment of minerals (foliation) in granite outcrop. Pencil for scale. Photo by R. Volkert.

Along Double Pond Trail, leading to the beach just west of this granite, are outcrops of rusty-weathering gneiss. Note the difference in grain size, color, and texture, between the granite and gneiss. This gneiss formed from sediments deposited in an ancient sea about 1,295 million years ago; therefore the granite is much younger and was intruded into the gneiss about 1,185 million years ago.

Stop 3. Glacially streamlined and polished bedrock outcrop (41° 11' 21.44" N, 74° 25' 32.71" W)

The pavement-like bedrock outcrops at the trailhead of the Iron Mountain Trail (fig. 10) were produced by glacial abrasion. Glacial ice moving against a knob or hill of resistant rock like granite will undergo increased pressure on the up-flow side of the obstacle and decreased pressure on the down-flow side. Increased pressure melts the ice, creating a thin film of water between the ice and rock. This water reduces friction and enables the glacier to slide on the rock surface. Sand and gravel particles in the ice scour and abrade the rock, eventually polishing it to a smooth pavement. Large gravel fragments may cut long, straight gouges known as striations that record the direction of ice flow. Striations in the park record ice flow slightly west of due south, reflecting flow of the glacier out of the Wallkill Valley and across the Highlands. Faint, fine striations may be seen on this outcrop where soil has recently been scraped away (white area on photo); elsewhere they have been weathered or obscured by lichen growth (gray area on photo). The striations here show that the glacier moved southward, toward the boat launch.

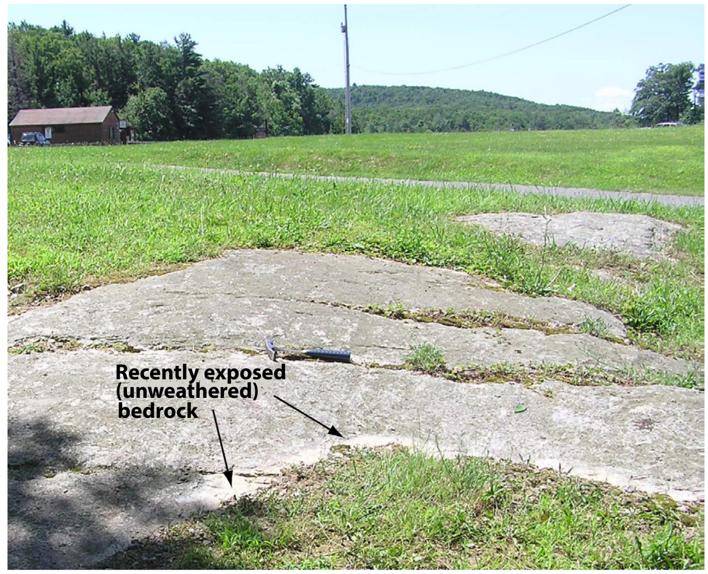


Figure 10. Bedrock pavement outcrop showing glacial features. Rock hammer for scale, center of outcrop. Photo by S. Stanford.

Abraded, pavement-like ledges of rock are common throughout the park on north-facing slopes, which faced advancing ice. On the down-flow side of hills and ridges, on south-facing slopes, glacial pressure dropped and the water generated by melting on the up-flow side migrated into joints and fractures in the rock and refroze. The growing ice expanded in the joints, prying out blocks of rock. As the ice mass continued to grow and freeze onto the glacier, the blocks of rock were detached and carried away by the moving ice, leaving cliffs. This process is known as quarrying, and it created the many small cliffs on south-facing slopes in the park. The small cliff at Stop 4, which is a south-facing slope, was probably created in part by glacial quarrying.

Stop 4. Joints in bedrock (41° 11' 15.85" N, 74° 25' 24.35" W)

An exceptional example of naturally occurring fractures, known as joints, that cut the granite bedrock can be seen here (fig. 11). Joints form as a result of extensional forces that split the rock along well-defined surfaces, partitioning the outcrop into blocks. This is one method by which rocks physically weather. As water in the joints freezes during cold weather, the rock is wedged apart along these fractures. During glaciation, subglacial water freezing in the joints during glacial quarrying has the same effect (see Stop 3). Blocks become dislodged

Figure 11. Joint surfaces in granite outcrop. Photo by R. Volkert.

and tumble or slide downward from the outcrop under the effect of gravity and glacial movement, which here was southward toward the lake. Note the accumulation of square to rectangular blocks at the base of the outcrop that have become dislodged.

Two well-developed joint sets are visible in the outcrop here. One set is parallel to the shoreline and Double Pond Trail and the other set extends into the bank, at a right angle to the shoreline. All of the joints here are spaced about one foot to several feet apart.

Stop 4A. Small abandoned rock quarry (41° 11' 14.18" N, 74° 25' 22.02" W)

The development of joints that partition the granite into blocks, such as those observed at Stop 4, create a natural quarrying process that was exploited locally by quarry workers. Here we see the worked face of a small, abandoned rock quarry (fig. 12). Note the smooth face at the back of the quarry on one joint set and the steep face along the right side of the quarry on another joint set. Separation along these joint sets enabled workers to dislodge the blocks with minimal effort, possibly using only pry bars and wedges. The accumulation of blocks at the base of the quarry face is excess material left from the quarrying process. Although the date of this quarrying is not precisely known, the rock was likely used very locally in the construction of the nearby blast furnace, the raceway situated upslope of the furnace, and the building foundations visible in the adjacent woods.

Figure 12. Worked faces along joints and loose, quarried blocks. Photo by R. Volkert.

Stop 5. Wawayanda Furnace (41° 11' 07.15" N, 74° 25' 18.50" W)

Figure 13. Wawayanda Furnace. Photo by R. Volkert.

Standing as a reminder of the mining heritage of the area are the ruins of the Wawayanda blast furnace (fig. 13). Constructed by William Ames in 1846 on the family property, the furnace was intended to process local iron ore extracted from the Green and Wawayanda Mines. It operated from 1846 until 1850 and then on and off from 1854 until it closed in 1867 (Dupont, 1993). The tapering appearance of this furnace, and its overall construction, are typical of such furnaces throughout the Highlands that were generally built near iron mines. The width of the Wawayanda Furnace ranges from slightly more than 30 feet at its base to 28 feet at its top, and its total height is 42 feet (Apffel, 1970).

Heat for the furnace was provided by burning charcoal, which was produced from local timber. The furnace was fed a mixture of charcoal, iron ore, and dolomite, which was used to assist the melting process and help remove impurities. The mixture roasted until the iron ore melted. According to Apffel (1970), producing one ton of pig iron required 160 to 200 bushels of charcoal, two tons of iron ore, and a quarter ton of dolomite.

Most of the iron from the Wawayanda Furnace was shipped by rail to Philadelphia for use in manufacturing steel (Apffel, 1970).

Stop 6. Water-worn outcrop
(41° 11' 07.53" N, 74° 25' 17.21" W)

Note: Outcrops may not be exposed during times of high water.

This outcrop is a glacially abraded pavement like that at Stop 3 (note that the hillslope here, as at Stop 3, is north-facing, facilitating abrasion) but with some additional erosional features carved by stream erosion. These smooth, furrow-like features are visible on the lower half of the outcrop along the stream (fig. 14). They were formed as sediment-laden floodwaters scoured feldspar-rich layers in the gneiss bedrock. Quartz-rich layers form the ridges and knobs between the furrows. Feldspar minerals are softer than quartz, and therefore abrade faster. The furrows probably represent several thousand years of stream erosion. The erosion takes place during floods when the depth, velocity, and sediment load of the stream are sufficient to initiate scour.

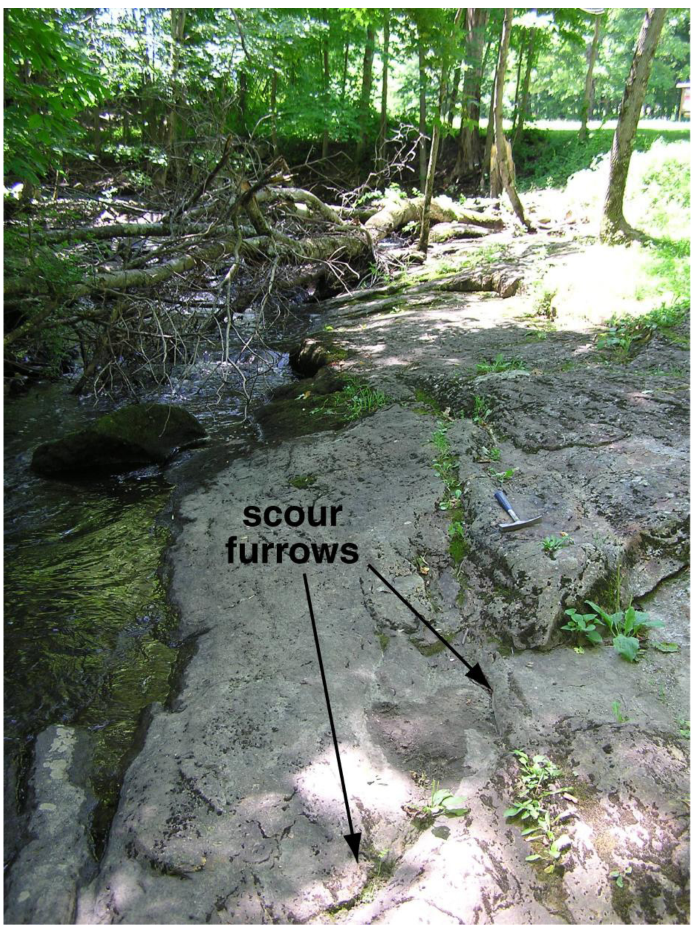


Figure 14. Water-worn outcrop near Wawayanda Furnace. Rock hammer for scale, center right of photo. Photo by S. Stanford.

Stop 7. Freshwater marsh
(41° 11' 02.66" N, 74° 25' 19.22" W)

The marsh visible here upstream from the bridge (fig. 15) extends about 0.25 mile up the valley to join Laurel Pond. It is one of the smaller of the many swamps and marshes on Wawayanda and Bearfort Mountains. These wetlands commonly occupy basins eroded in the bedrock by glacial plucking and abrasion. A few basins formed where moraines and drumlins blocked valleys. Most of the wetlands on Wawayanda Mountain, like the marsh here, occupy the floors of glacial lakes. Notice that the outlet stream for this marsh flows north (toward the furnace). The northward slope of most of the valleys on Wawayanda Mountain indicates that the margin of the retreating glacier acted as a dam, holding in a series of lakes that lowered and drained successively as the ice margin withdrew northward. The wetlands we see today were left in the lowest parts of those lakes that could not drain. Plant matter that falls into the marshes and swamps does not decompose as completely as it does when exposed to air, and instead builds up to form peat. Peat has been accumulating in these wetlands for the past 10,000 to 15,000 years, as forests became reestablished following deglaciation. In places, the peat is as much as 25 feet thick. Pollen extracted from vertical profiles of peat, obtained by coring the marshes, can be analyzed to provide valuable information on changes in

Figure 15. Marsh on west side of Laurel Pond Trail. Photo by S. Stanford.

vegetation and climate since deglaciation. It is from such evidence that we know that the vegetation in northern New Jersey has changed since the last glaciation from tundra, to boreal spruce and pine forest, to the present-day temperate hardwood forest.

Additional Geologic Features

A. Glacial Features

Till forms a thin veneer over the bedrock throughout most of the park. This bouldery, sandy sediment was deposited directly from melting glacial ice. It may be seen beneath the topsoil in trailbeds and cuts along the old roads in the park. In places, the till is thick enough to form low ridges called moraines. These were deposited along the edge of the glacier and mark temporary stillstands during glacial retreat. The Cherry Ridge Moraine traverses the park in several segments from the south end of Wawayanda Lake to the north end of Bearfort Waters. It is best seen on Cherry Ridge Road east of the junction with the Red Dot Trail (fig. 5 and fig. 16, Site A). Here it is a bouldery ridge about 20 to 50 ft. high that dams the large marsh south of the road.

On many ridges and steep slopes, till was not deposited and glacially-shaped bedrock is exposed as ledges and cliffs. Smooth, sloping ledges were formed by glacial scour; cliffs and blocky talus slopes were formed by glacial quarrying. These features can be seen along most of the park trails. Good examples of ledge-and-cliff outcrops are along the Laurel Pond Trail between the Wingdam Trail and Cherry Ridge Road, and along the Double Pond Trail just east of the group campground.

In addition to the glacial lakes on Wawayanda Mountain described on the geologic tour, there was a much larger glacial lake in Vernon Valley and the Wallkill Valley, north and west of Wawayanda Mountain. This lake, known as glacial Lake Wallkill, extended from Augusta, New Jersey (about 5 miles north of Newton) to the vicinity of Goshen, New York, about 50 miles to the northeast, and was as much as 250 feet deep. The Appalachian Trail crosses a delta between Route 94 and the base of Wawayanda Mountain that was deposited in this lake. The sand and gravel composing the delta has been mined in the pits on either side of the trail. The surface of the delta marks the approximate former water level of the lake. The expanse of the lake, which was as much as 15 miles wide in New York State, can be visualized from the viewpoints at the top of Wawayanda Mountain.

B. High Breeze Farm
(41° 13’ 6.49” N, 74° 25’ 5.13” W)

The historic High Breeze Farm (fig. 16) dates back to the early 19th century, and today is the only remaining farm on Wawayanda Mountain. It was acquired by the state in 1981 and preserved largely through the efforts of the Vernon Historical Society. At present, the farm is part of Wawayanda State Park.

Bedrock is not exposed around the farm, but crops out farther uphill, and also downslope near Route 94, where various gneisses may be observed. Looking north from the farm is a view of Mount Eve and Mount Adam; prominent peaks that rise above the surrounding area. Both peaks are underlain by the 1,020-million-year-old Mount Eve Granite, unique to northern Sussex County, New Jersey and southern Orange County, New York. Mount Eve Granite was emplaced into the enclosing Mesoproterozoic rocks shortly after their metamorphism about 1,050 million years ago. Because of its massive and homogeneous texture, this granite was quarried for use as dimension stone. The more subdued areas surrounding Mount Eve and Mount Adam are underlain by Franklin Marble and various gneisses, all of which are less resistant to erosion.

Bedrock is conspicuously absent at the farm because the north-facing slope of Wawayanda Mountain is covered by thick, extensive glacial till. These areas of thick till were easier to clear and farm and were commonly used for pastures and orchards. The fields along Warwick Turnpike and Barrett Road near the New York State border mark such ground moraine, as does the area around the historic High Breeze Farm.

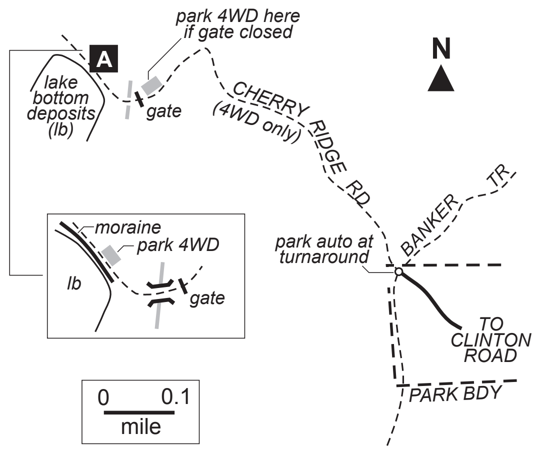
C. Talus Deposits
(41° 12’ 57.89” N, 74° 26’ 54.47” W)

Climbing the Appalachian Trail from Route 94, on the west side of Wawayanda Mountain (fig. 16), the abundance of very large to large, angular blocks of granite that drape the base of the mountain are a conspicuous feature. These blocks are an early stage in the erosion of bedrock outcrops by the process of physical weathering. Note the extent to which joints are developed in the bedrock. During cold weather, water that collects in the joints freezes and acts like a wedge to pry the joints apart. With repeated cycles of freezing and thawing, the blocks of rock detach and slide downhill, aided by gravity. They collect along the base of the mountain, forming an apron of rock debris known as talus. Note the sharp edges of the blocks and their rectangular shapes where they have become detached along joint surfaces from the bedrock outcrops upslope.

D. Bedrock Outcrops

Most of Wawayanda Mountain north and west of Barry Lakes and Barrett Road, as well as the Appalachian Trail from Route 94 east to Barrett Road is underlain by granite. The rest of the park, from the Hemlock Ravine Natural Area to the north, to the park boundary south of Lake Lookout and the Old Coal

Directions to Geologic Site A



1) From Wawayanda State Park Office, travel to main entrance.

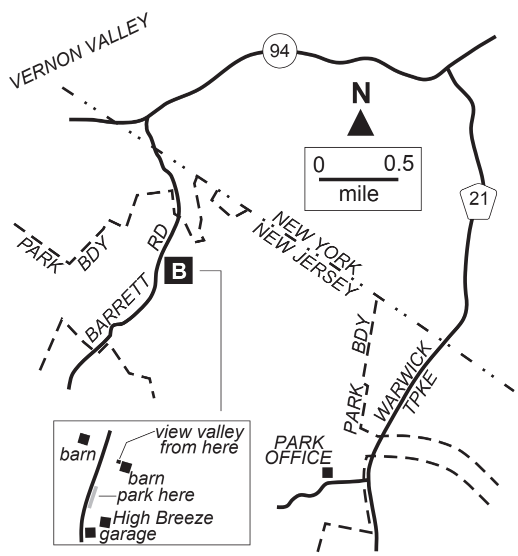
2) Turn right onto Warwick Turnpike and travel 2.3 miles.

3) Turn right onto Clinton Road and travel 0.8 miles to Lake Lookover.

4) Turn right onto Cherry Ridge Road and travel 1.1 miles to turnaround (see map).

5) Park and walk 0.6 miles to moraine on left. ***Or travel with high clearance 4WD vehicle.***

Directions to Geologic Site B



1) From Wawayanda State Park Office, travel to main entrance.

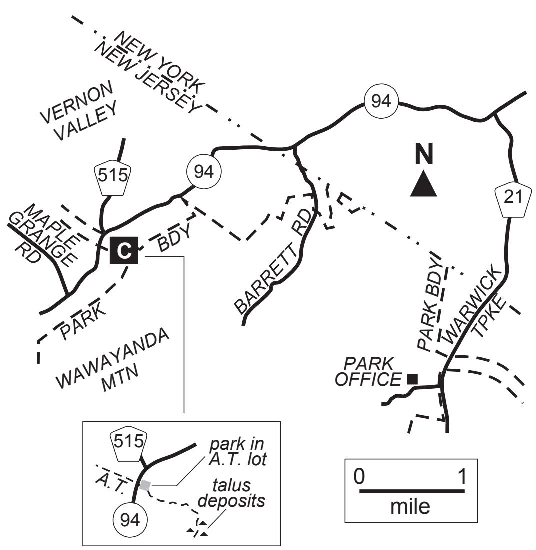
2) Turn left onto Warwick Turnpike and travel 3.0 miles.

3) Turn left onto NY 94 and travel 2.1 miles.

4) Turn left onto Barrett Road and travel 1.1 miles to historic High Breeze Farm on left.

5) Park and view Vernon Valley (see map).

Directions to Geologic Site C



1) From Wawayanda State Park Office, travel to main entrance.

2) Turn left onto Warwick Turnpike and travel 3.0 miles.

3) Turn left onto NY 94 and travel 4.3 miles.

4) Turn left into Appalachian Trail (A.T.) parking lot.

5) Park and walk A.T. (white trail) toward Wawayanda Mountain to talus deposits at base of mountain (see map).

Figure 16. Directions to Additional Geologic Features. Sites are keyed to features in the text.

Trail to the south, is underlain by gneiss. Throughout the area, outcrops of granite and gneiss trend mainly toward the northeast. Therefore, one generally stays on a single type of rock while walking on the north-south trails, but crosses over to other rock types while on the east-west trails.

E. Bearfort Mountain

Bearfort Mountain is underlain by sedimentary rocks, of which the most abundant are reddish-purple conglomerate and quartzite of the Skunnemunk Formation (fig. 4). The extreme western edge of Bearfort Mountain, along Clinton Road, and the eastern edge of the mountain, are underlain by Bellvale Sandstone. Most of the trails in the Abram S. Hewitt State Forest and the Bearfort Mountain Natural Area traverse the Skunnemunk Formation. The high resistance of this rock to erosion causes the overall high relief of Bearfort Mountain, whereas the variation in resistance from bed to bed creates the rugged terrain that consists of the numerous close-spaced, narrow valleys that one crosses in walking from west to east.

The effects of glacial erosion are particularly well displayed on Bearfort Mountain. The resistant layers of quartzite and conglomerate, which have been tilted to steep angles by tectonic forces, form the many long narrow ridges on the mountain. The tops of these ridges typically are glacially scoured ledges, where glacial striations may be seen. Glacially quarried cliffs form the sides of many of the ridges. Layers of less resistant sandstone interbedded with the quartzite were more deeply eroded by the ice, forming the numerous intervening valleys. Many of these small valleys contain swamps and marshes. Scenic ponds, like Terrace Pond, Surprise Lake and West Pond, occupy basins in the small valleys where erosion was deepest and where there was little to no sediment influx.

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