FIELD GUIDE TO THE GEOLOGY OF WEST POINT

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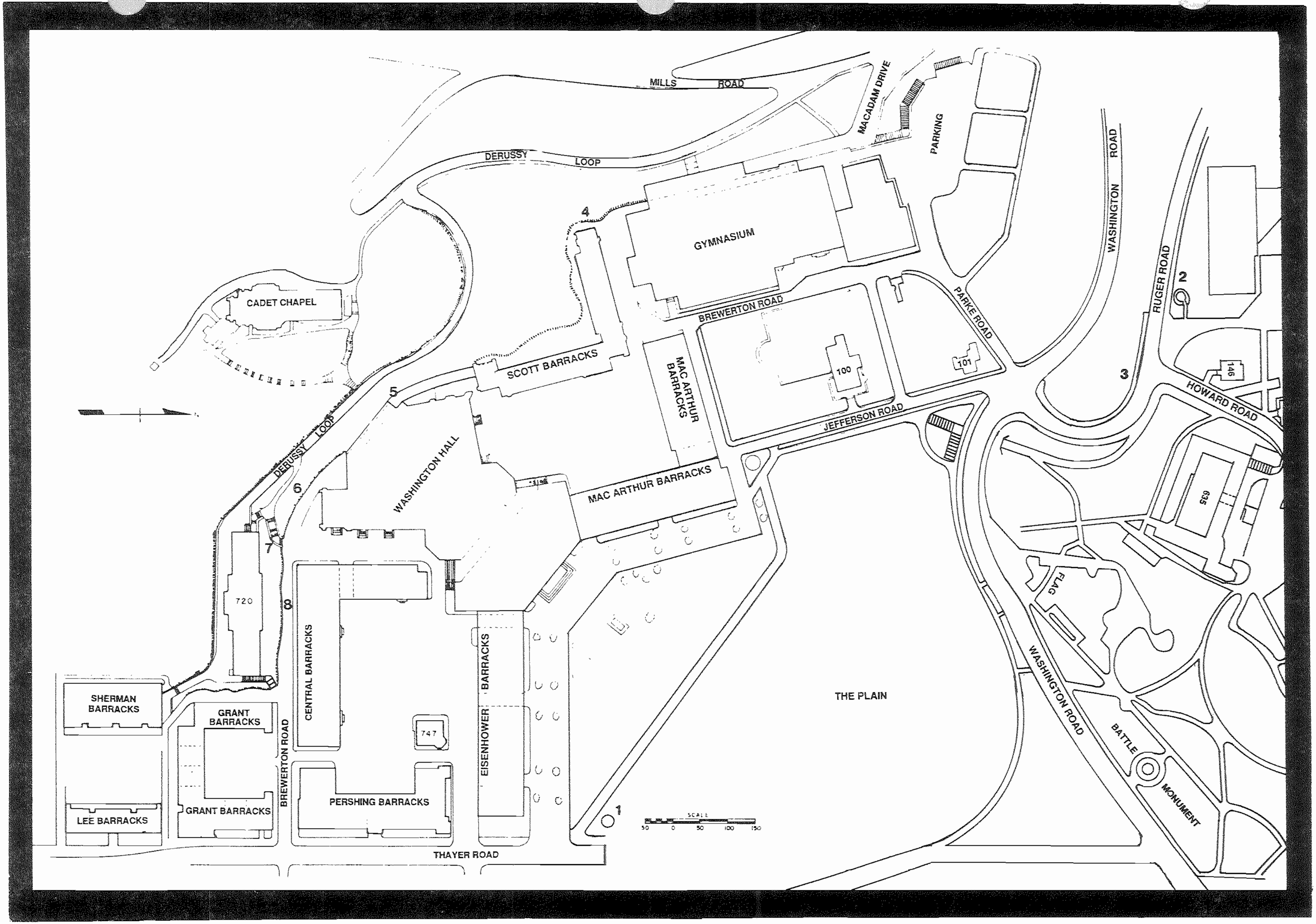
GEOLOGY WALK



MILLS ROAD
MACADAM DRIVE
PARKING
DERUSSY LOOP
WASHINGTON ROAD
RUGER ROAD
GYMNASIUM
CADET CHAPEL
BREWERTON ROAD
PARKE ROAD
SCOTT BARRACKS
MACARTHUR BARRACKS
100
101
146
HOWARD ROAD
JEFFERSON ROAD
WASHINGTON HALL
MAC ARTHUR BARRACKS
635
FLAG
720
CENTRAL BARRACKS
EISENHOWER BARRACKS
THE PLAIN
WASHINGTON ROAD
BATTLE MONUMENT
SHERMAN BARRACKS
GRANT BARRACKS
BREWERTON ROAD
747
GRANT BARRACKS
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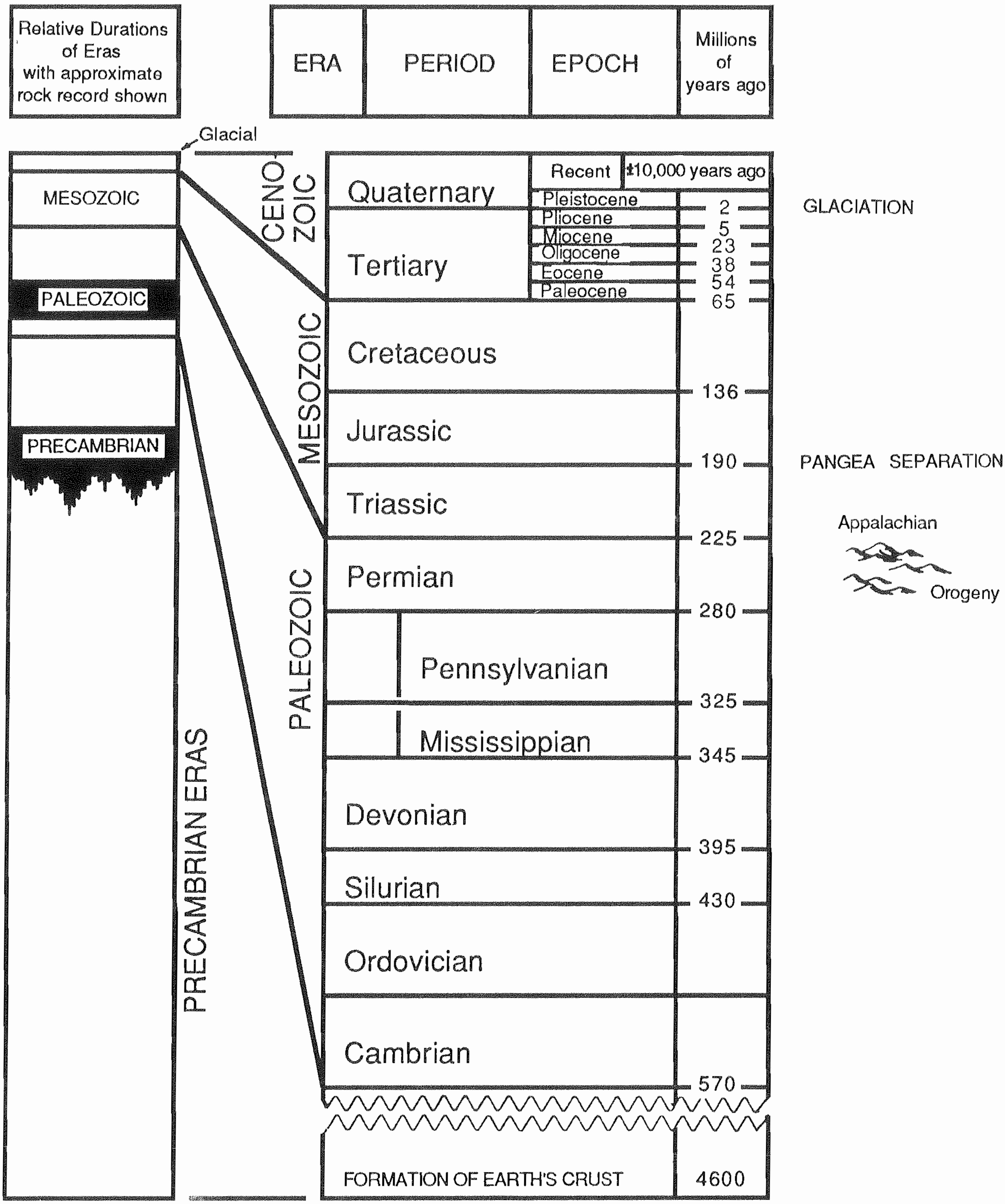


Figure 1. Geologic time scale

INTRODUCTION

GEOLOGIC HISTORY

The present topography and landscape at West Point are an expression of the underlying rock type and structure, as shaped by surface erosional forces. Rock exposures in the West Point area reveal its geologic history, which includes compressional and tensional tectonic forces as well as evidence of glacial erosion and deposition. Although the age of some rocks exceeds one billion years, they may have been folded and faulted 300 million years ago and more recently eroded by glaciers 10,000 years ago (Figure 1).

West Point is located within the Hudson Highlands, which connects the southwest trending Reading Prong with the main part of the New England physiographic province. The Hudson Highlands section of the New England Province consists of a rugged, dissected, and glaciated upland underlain by a complex sequence of Precambrian metamorphic and igneous rocks which extend from Reading, Pennsylvania through West Point and into New England where the Hudson Highlands become the Housatonic Highlands of Western Connecticut, the Berkshires of Massachusetts, and the Green Mountains of Vermont (Figure 2).

North of West Point, Newburgh is located in a valley near sea level (Hudson River surface). This valley was eroded from soft 400 million year old sedimentary rocks (shales and limestones). The valley extends from the Canadian border through New York, Pennsylvania, and Virginia (where it is known as the Shenandoah Valley) to Alabama (Figure 3).

The rocks in the West Point area are thought to have originally accumulated adjacent to a volcanic island arc. These sediments were severely deformed and experienced regional metamorphism at depths of 15-25 km and temperatures of 650-725 degrees Centigrade. Large magmatic intrusions accompanied this tectonic activity. The average radiometric age for the igneous intrusions is approximately 1.15 billion years. These igneous and metamorphic structures evolved into the present northeast coast of North America.

Figure 2. Northeast portion of Landforms of the United States by Erwin Raisz annotated with physiographic divisions according to Fenneman.

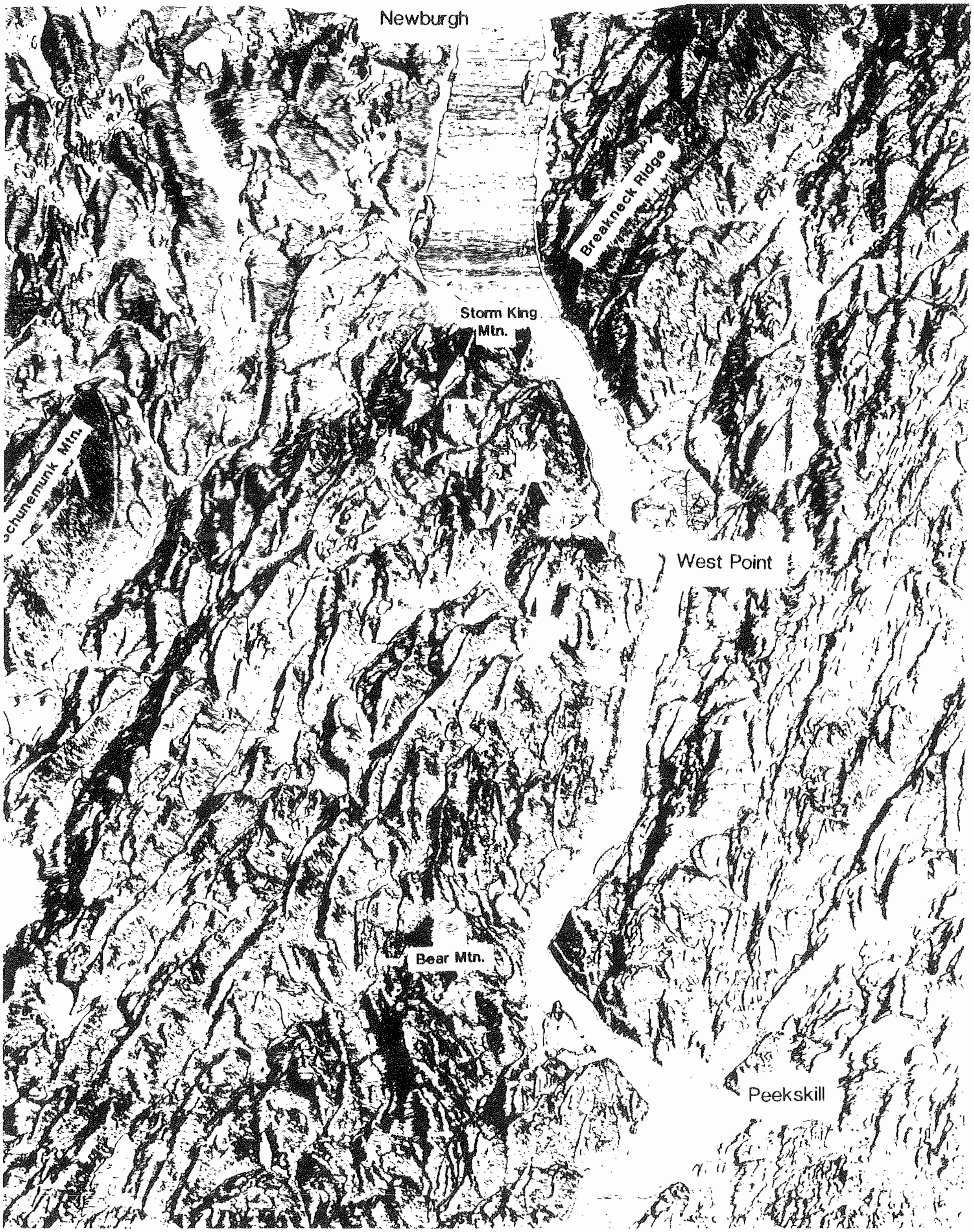


Figure 3. Terrain Diagram of the West Point Area, printed by Army Map Service, Corps of Engineers, 1959. The appearance of perspective is obtained by shifting all features northward by 1 inch for every 600 feet of relief.

By the end of the Precambrian era (around 600 million years ago) these complex crystalline rocks had been deeply eroded to expose large masses of plutonic rock. During the Paleozoic era, this area experienced several sedimentary episodes as ancient North America and Africa moved slowly towards one another in an enormous continental collision (Figure 4).

Compression between the North American and African plates occurred two or three times during this period. Each compressional event squeezed up sediments from the small oceans between them. These sediments, and the intense crustal deformation of continental margins formed high mountains similar to the Alps or Himalayas.

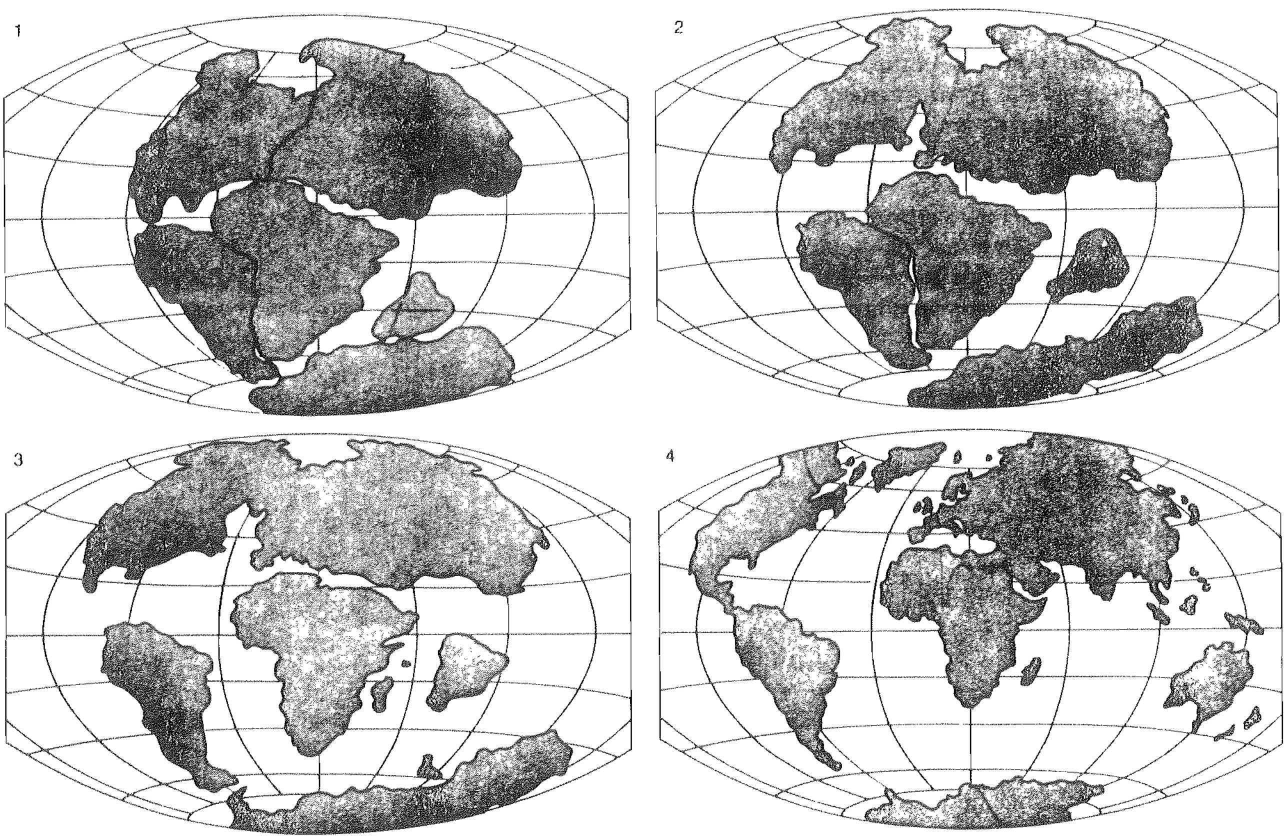


Figure 4. How Pangea may have broken into separate continental masses. Each diagram represents about 65 million years from the preceding one. The series starts about 200 million years ago and ends with the present geographic arrangement.

During the Mesozoic Era, the area was above sea level, but eventually beveled to a low altitude. As the North American and Eurasian/African tectonic plates began to separate in the early Triassic (about 200 million years ago), the associated tension produced graben structures, mafic intrusions and lava flows south of the Hudson Highlands along the Palisade Sill (Figure 5). The rocks of the Palisades were deposited, intruded, or extruded during the last separation of the American and African continents and the opening of the present Atlantic Ocean.

The tensional forces of that event created basins (grabens) along normal faults that filled up with sandstones derived from the adjacent ridges (horsts). While the grabens were above sea level, the sandy sediments deposited in the valleys were oxidized in the atmosphere to their reddish color. The reddish sedimentary sandstones used on the Superintendent's doorsteps, the brown-stones used as facing on some Colonels' housing, and the well known Brownstones of New York City are contemporaneous with this event. Dinosaurs trod across these sandy valley floors 200 million years ago, leaving many footprints which can be seen today in places such as Dinosaur Park in Connecticut. Eventually, the graben dropped low enough to be inundated by the sea. When the Atlantic Ocean began to form, oceanic sedimentary rocks were deposited, including limestones, such as those used as building facings (often mistaken for concrete) at West Point. These limestones consist of finely ground marine organisms, some of which can still be clearly made out (including fossil forms such as crinoids -- circular stem fragments are often clearly visible). The cap rock used on top of Thayer Hall (parking lot) is an excellent example of this type limestone.

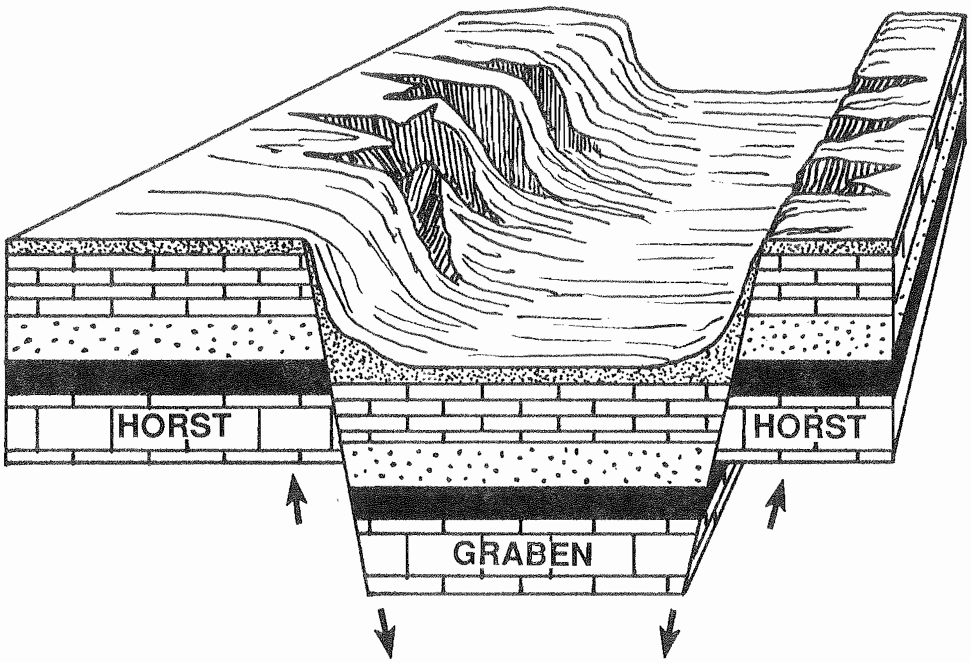


Figure 5. Horst and Graben topography resulting from tension and normal faulting.

The Tertiary history of the area is difficult to describe because it was largely an erosional interval. There is no evidence of marine submergence during the Tertiary; therefore the land surface has been above sea level for the last 100 million years and subject to subaerial weathering and erosion. This indicates that the present landscape was "etched out" by erosion on much older rock structures. As a result, uplands, plateaus, and ridges are found to be supported by strong rock units. Where weaker formations are exposed, they have been eroded to form lowlands or valleys. Furthermore, jointed or faulted structural zones in the bedrock have produced corresponding clefts or notches in the topography. In the process of landform development, the Hudson River became situated at an oblique angle to this part of the Reading Prong.

It may be important to note that within the water gap, the Hudson River seems to follow fault zones. At West Point, the southeast trending section bounded by angular bends concides with: (1) southwest and northwest dipping joints, (2) northeast dipping lineations in the Storm King Granite and foliation of metamorphic rock, and (3) more easily weathered dikes that parallel joints and foliation . This close alignment between structure and channel course suggest that the river is, to some degree subsequent in nature. It does not, however, explain the original establishment of the river across this section of the Reading Prong.

Whatever the cause, the Hudson River water gap through the "Highland" is apparently preglacial because of its profound and deep modification by ice in a fashion not approached elsewhere in the area. The smoothed, striated, quarried uplands; asymetrically eroded hills; and oversteepened, fiord-like walls on the river valley are all evidence of significant modification of the landscape by Pleistocene glaciation. Known centers of ice accumulation to the north and sequential drift sheets to the south indicate that this area must have experienced repeated glacial events even though only Wisconsinan drift is known in the area.

Most of the landscape shows erosion to be the major glacial effect, but during deglaciation some depositional features of special note formed in the West Point area. The most conspicuous formed from glaciofluvial sediment deposited between stagnating glacial ice within the valley and the bedrock valley walls. The result was a number of kame terraces. One of the largest formed The Plain and the site of the cemetery at West Point.

Post glacial modification of the area is largely the result of streams and mass wasting, but their effect has been minor, as evidenced by the modest amount of erosion achieved by the nearby "hanging" tributaries to the Hudson River.

Station 1

Military History of West Point Area

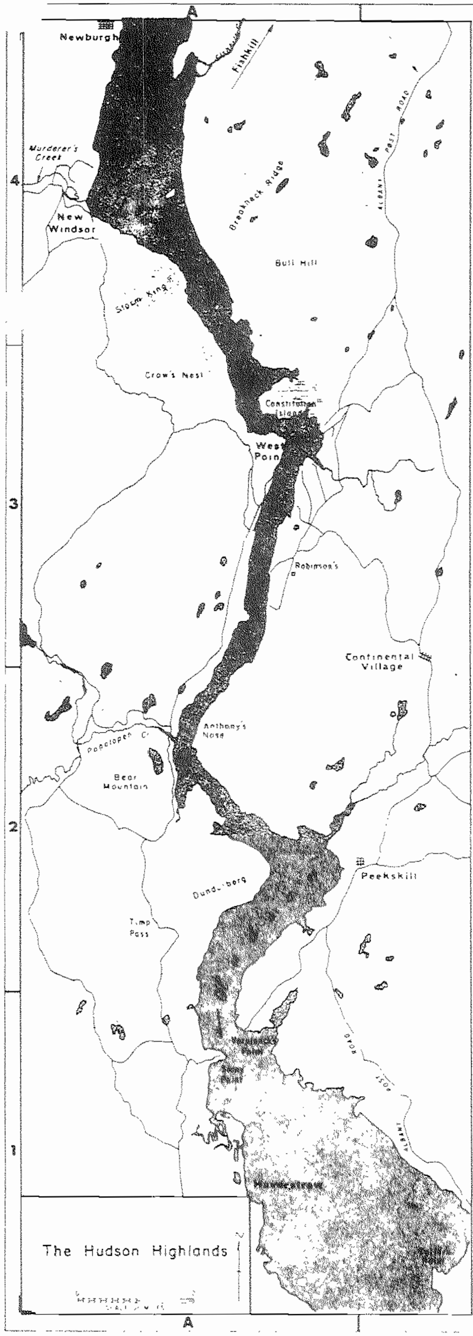
Eisenhower Statue to MacArthur Statue

The Military Academy at West Point owes its superb location to a series of geologic events going back over one billion years in time. These include volcanism in an island arc; metamorphism and granitic intrusion deep in the earth's crust; folding and faulting; erosion by the Hudson River; and sculpting of the landscape by glaciers. This combination of events created a strategic location noted by Washington during the American Revolution (Figure 6).

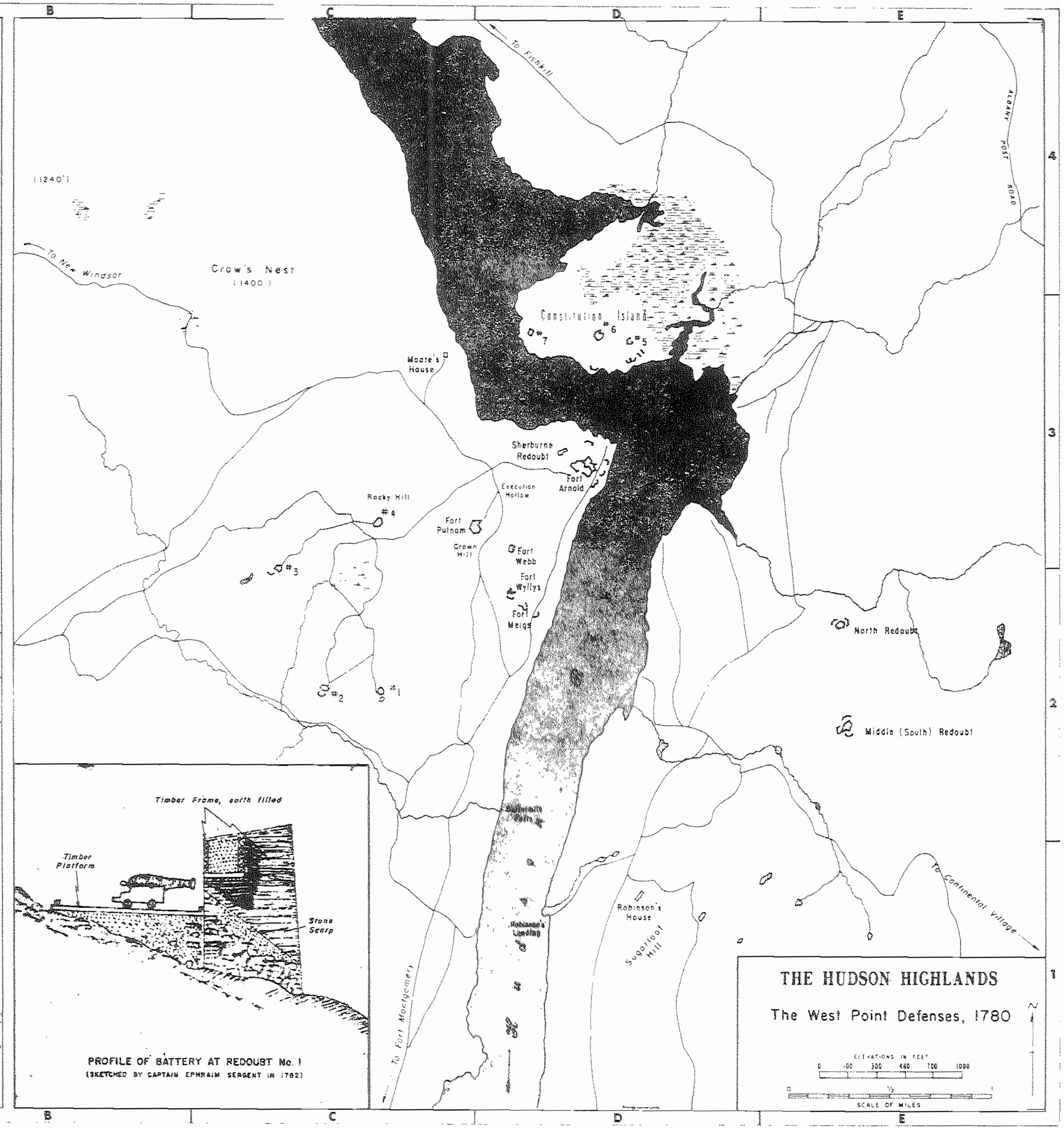
Despite what would appear to be the obvious strategic value of West Point, the early fortifications in the Hudson Highlands initially were concentrated elsewhere. In August 1775 construction began on Constitution Island and supporting positions on the east bank of the Hudson. In March 1776 work began on Fort Montgomery at Popolopen Creek about 9 km south of West Point. While construction was underway, the soldiers discovered a better location just across Popolopen Creek on the south bank. This site was also fortified (Figure 7).

In the fall of 1777 the British mounted a three-pronged attack to divide the colonies along the Hudson River. As part of this effort, Sir Henry Clinton attacked north from New York City. The twin forts of Popolopen Creek fell after a bitter battle, and the British sailed as far as Kingston-60 km north of West Point. They burned Kingston and destroyed the American fortifications throughout the Hudson Highlands. But the British victory was short lived, for the capture of General Burgoyne and the British at Saratoga forced Sir Henry Clinton to abandon the Highlands after twenty days occupation and return to his base in New York City.

Following Clinton's withdrawal to New York City, General Washington performed a more thorough terrain evaluation and recommended that West Point be defended as the key to the Hudson Highlands. Soldiers crossed the ice separating West Point from Constitution Island in January 1778 to begin work on a series of batteries, forts, and redoubts, and on a chain across the river. The last British attack against the Highlands came in May 1779 when they seized the fort at Stony Point at the southern end of the Highlands. General "Mad Anthony" Wayne ended this threat when he recaptured Stony Point in a daring night attack two months later. Thereafter the intrigues of General Benedict Arnold in 1780 provided the only danger for the West Point defenses.



MAP 2



MAP 3

Figure 6. Revolutionary War era maps of the Hudson Highlands.

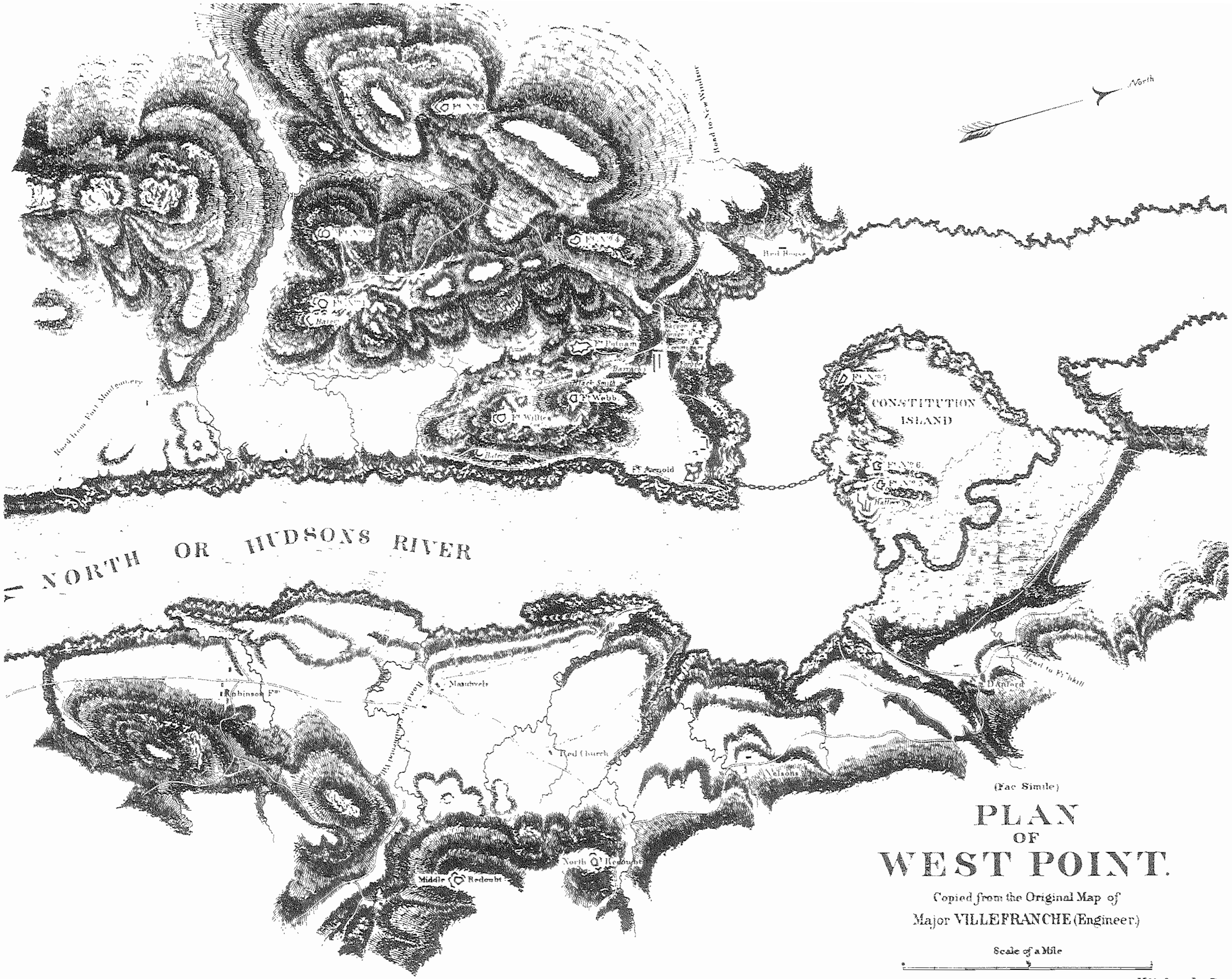


Figure 7. Detailed defense plan of West Point and Hudson Highlands.

The strategic importance of the Hudson River and the Highlands, particularly near West Point, during the Revolution rested on the following factors:

1. The Hudson River was and still is a major line of communication, open to sea-going ships as far north as Albany.

2. The width of the river channel narrows by approximately two-thirds when it enters the Highlands.

3. The tidal current flows more swiftly through the narrow river bends, than it does in the under upstream or downstream of sections.

4. The Hudson makes several right angle turns in the Highlands, which require sailing ships to tack. Slowly tacking ships provide outstanding targets.

5. The high relief of the Highlands provided good sites for fortifications overlooking the river and for supporting fires.

Station 2

Glacial History of West Point Area and Outcrop Demonstrating Glacial Erosion

Eisenhower Hall Clock Tower

During the last 2 million years, great ice sheets periodically moved south on the North American continent in response to changes in the earth's climate. Since water in the ice originally came from the oceans, as the glaciers grew sea level dropped approximately 200 feet. Thus surface erosion agents, such as streams and glaciers, could incise channels about 200 feet deeper than is presently possible. Glaciers flowed over the Highlands, scraping off soil and exposing bedrock. The glacier followed the Hudson's course, gouging a deep fiord-like channel 700 feet deeper than the present river level (to the depth of sea level at that time). The last glacial advance, 18,000 years ago, went as far south as Long Island and Staten Island (Figure 8). At that time, these islands were terminal moraines consisting of unsorted glacial drift deposited by the glacier when sea level was hundreds of feet below its present elevation.

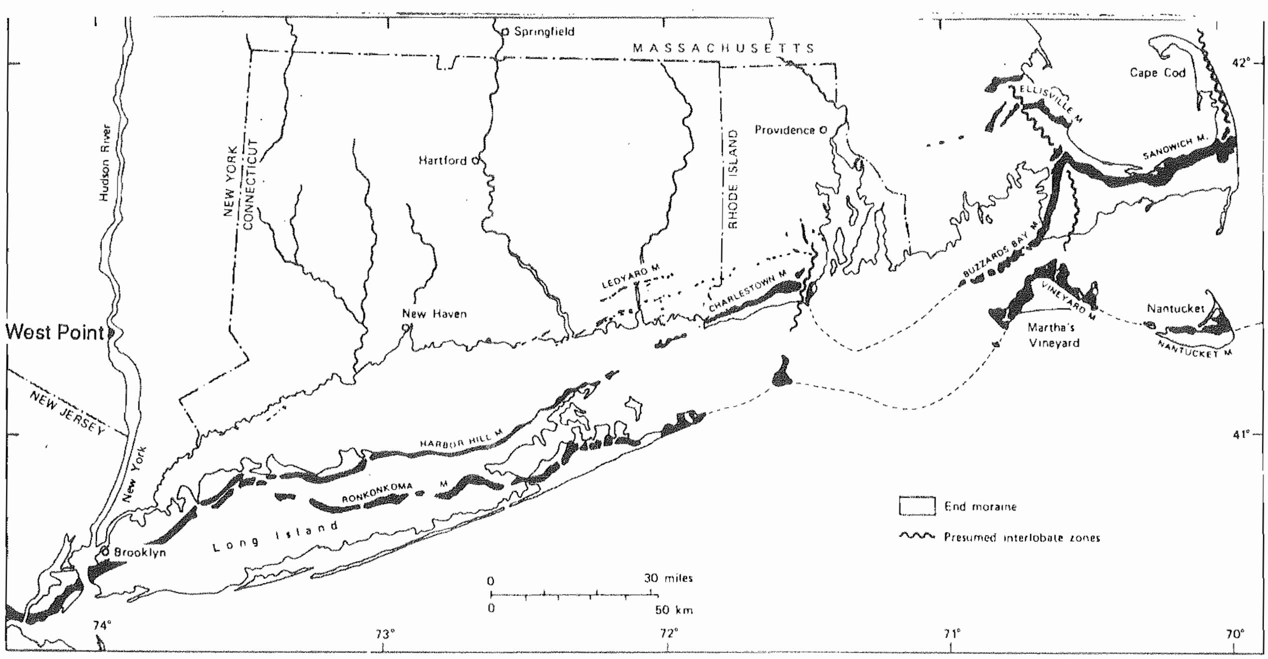


Figure 8. Map showing the relationship of glacial end morains and present geography of the northeast coast. The advanced position of end morains indicates that, at one time, the margin of a large ice sheet lay on the continental shelf beyond the present east coast.

Emanating from the glacier behind these terminal moraines, the Hudson River flowed for another 200 km over what is now the continental shelf to the ancient shore of the Atlantic Ocean (Figure 9). The glacier at West Point could not negotiate sharp turns where the river followed geologic joints and faults. Consequently, it carved a new channel west and south of Constitution Island. The old channel is now a swamp being filled with silt.

As glaciers began to wane about 10,000 years ago, sea level began to rise, creating islands from the terminal moraines, the Hudson River became a tidal river (difficult sailing) and raging streams began to flow off the ice sheets (Figure 9). Glacial retreat produced depositional features along the valley walls adjacent to the ice margin (Figure 10). The most prominent are the kame terraces that underlie North Athletic Field, Buffalo Soldier Field, and at least a thin veneer on the Plain (Figure 11). These sediments, deposited by braided streams, are stratified but poorly sorted, with fine sediments (silts and clays) irregularly interbedded with sands and gravels. The textural changes represent changes in stream energy due to shifts in channel position and seasonal variations in glacial runoff.

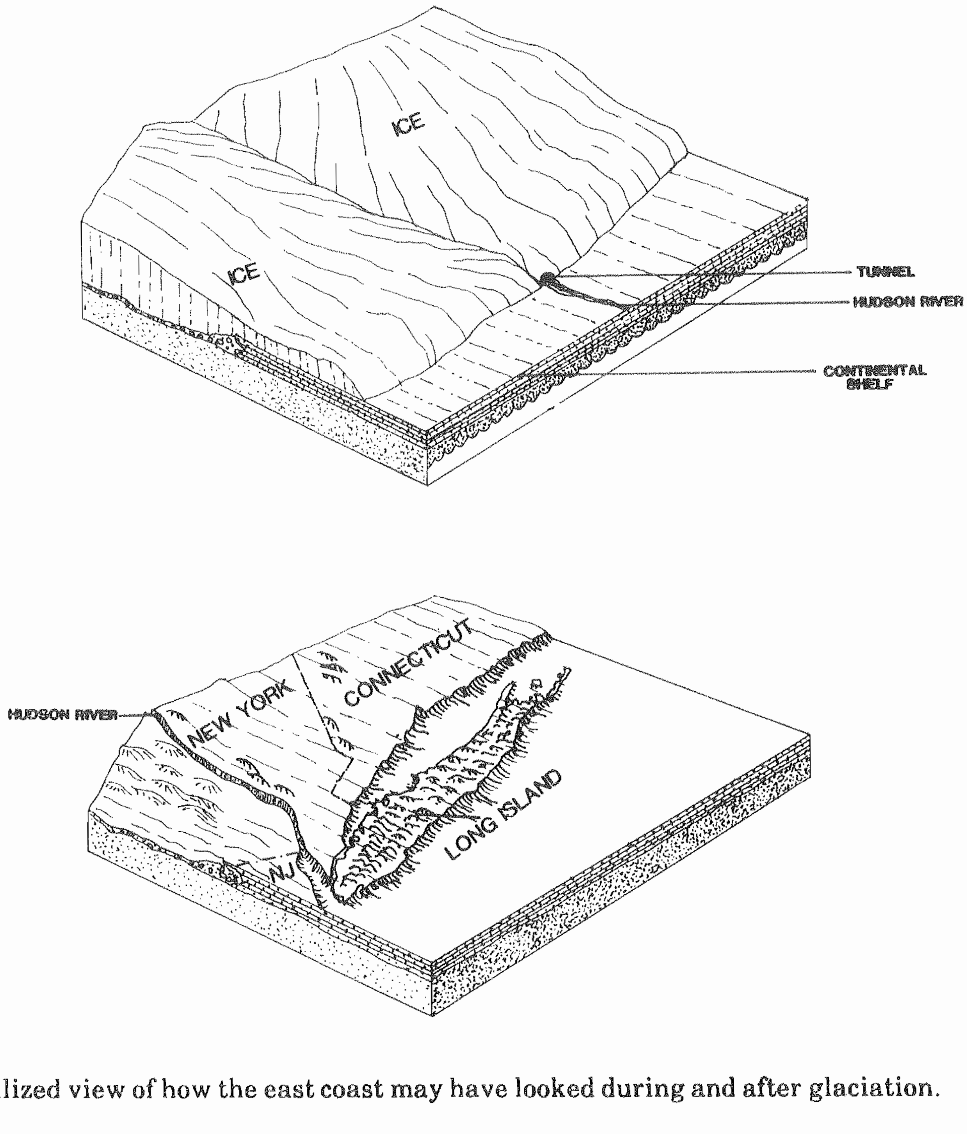


Figure 9. Idealized view of how the east coast may have looked during and after glaciation.

Maps from the Revolution show a depression on the Plain known as Execution Hollow. This was probably a kettle, formed by a block of ice left amid the sediments. When the ice melted it left a depression, which has since been artificially filled to make room for formations and parades.

The river channel of the Hudson has received 500 ft of sedimentation since the glacier finally retreated. Presently, the channel is 200 ft below sea level in some areas. Channel sediment has been sorted by size and weight in response to river velocity (Figure 11).

Outcrop Demonstrating Glacial Erosion, Abrasion and Plucking

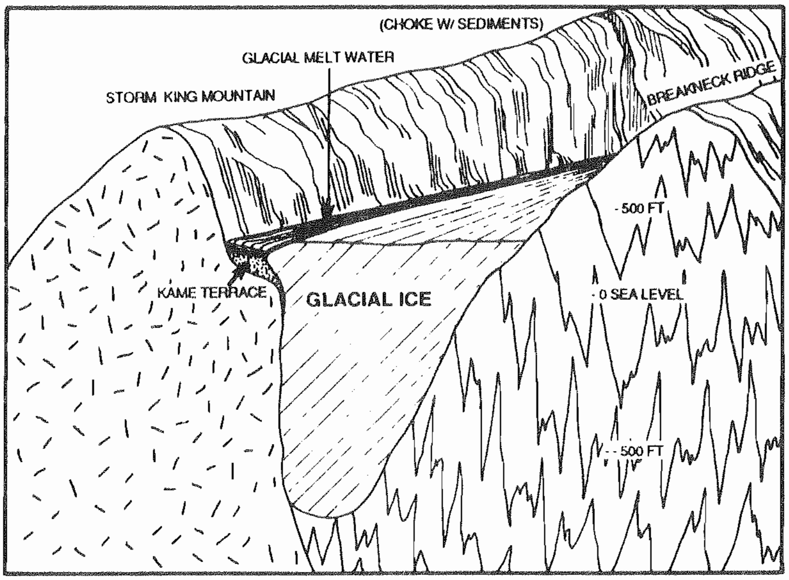


Figure 10. As the great continental ice sheet began to wane, the valley remained filled with flowing, or stagnant ice. In some areas, meltwater deposited sediments along lateral margins.

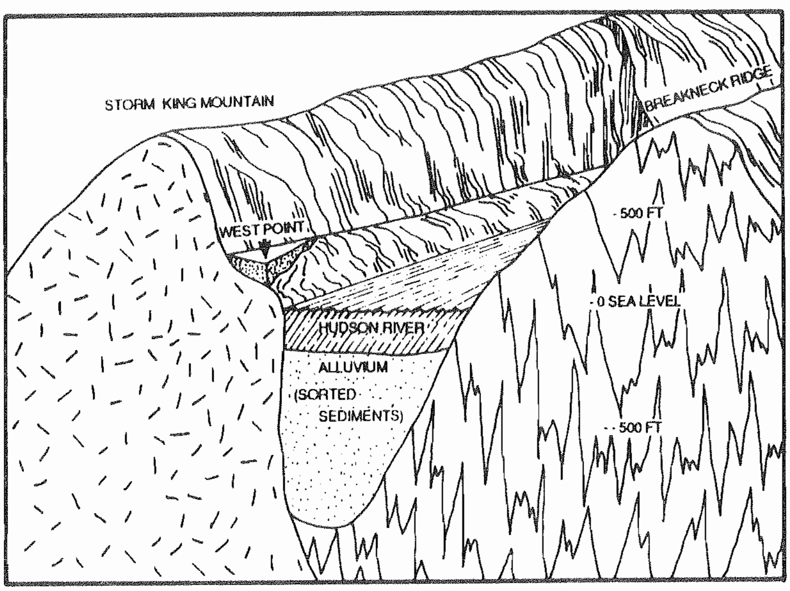


Figure 11. As the glaciers disappeared, sea level rose and the deeply incised channels filled with sediment. The kame terrances at West Point, perched high above the present river level are evidence of glacial run off when ice filled the valley about 18,000 to 10,000 years ago.

The outcrop just north of the clock tower.

This outcrop has been abraded and plucked by glacial processes (Figure 12). The up-ice side (toward the north) has been abraded and is smooth and gently sloping; the down-ice side (to the south) has been plucked and is steeper and more irregular. Plucking often occurs along joints or fractures in the rock, which are encountered by the glacier in its advance. This outcrop's shape and polish suggest a glacier flowing from north to south down the Hudson Valley (Figure 13).

Figure 12. Rock outcrop at Eisenhower Hall Clock tower shows evidence of glacial polish on the north side.

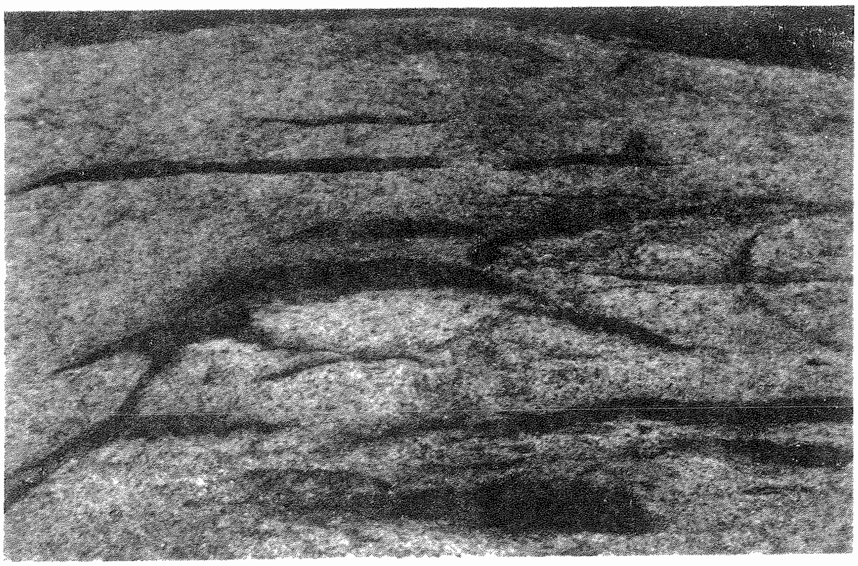


Figure 13. This granite on top of Bear Mountain (about 6 miles south of West Point) shows cresentic shaped gouges called Chatter marks. Chatter marks are thought to be formed when ice in contact with the rock surface moves suddenly forward, tearing or chiseling out portions of rock. Note the camera lens cover for scale.

The Hudson Valley is surrounded by evidence of the great size of this ice sheet. A view to the north across the river provides an excellent perspective of the effects of large scale glacial scour and quarrying on Breakneck Mountain and the nearby hills. These present the classical profile of a roche moutonnee (Figure 14/15). Granite on the top of Bear Mountain, six miles south of West Point, displays examples of glacial chatter marks and polish. These and other evidence indicates that the glaciers may have been over one mile thick at West Point. The tributary valleys on each side of the river appear to be "hanging" and may provide a partial basis for determining the amount of deepening of the Hudson River gorge by glacial action; there is more than 765 feet of sediment accumulated above bedrock in the river channel.

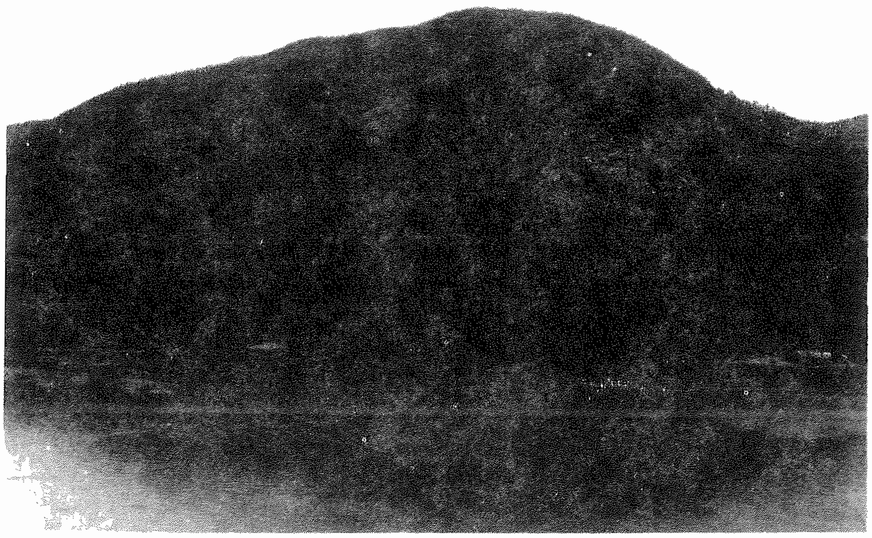


Figure 14. A view looking east toward Breakneck Ridge, which displays the classic profile of a roche moutonnee.

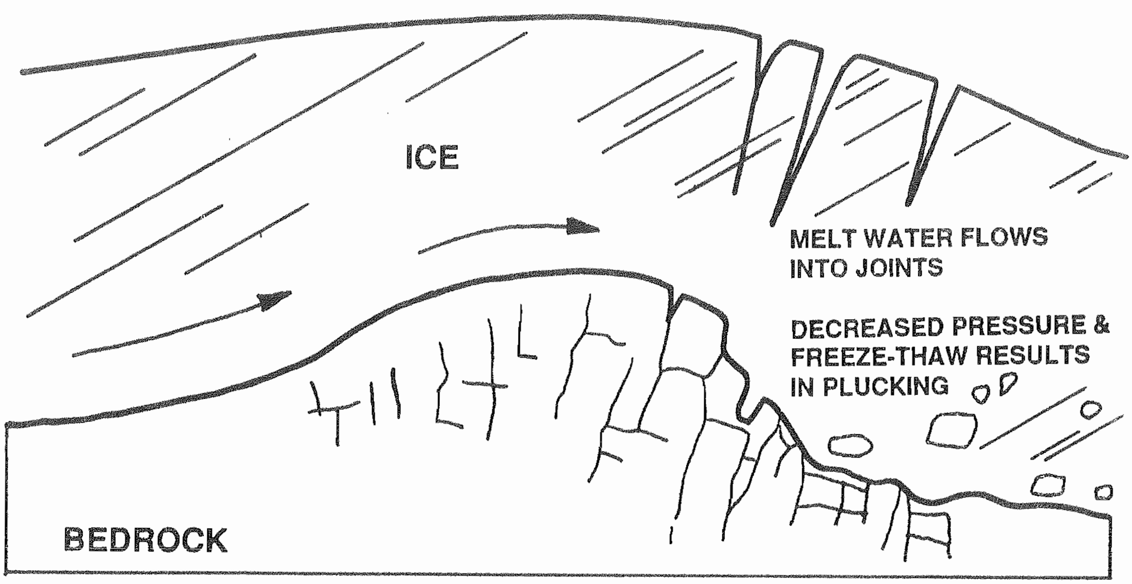


Figure 15. Differential pressure on the up- and down-ice side of terrain cause glacial ice to thaw and refreeze in joints and crevices. As the glacier moves, rocks and boulders are "plucked" from the down-ice side.

Station 3

Bedrock Geology Outcrop

West of the Ruger Road -- Howard Road Intersection

This outcrop is typical of the bedrock at West Point (Figure 16). It consists of gneiss, amphibolite, and pegmatite. The rocks with alternating bands of light and dark colored minerals are metamorphic rocks known as gneiss. The more massive dark rock is a metamorphic rock called amphibolite, after its primary constituent mineral, amphibole.

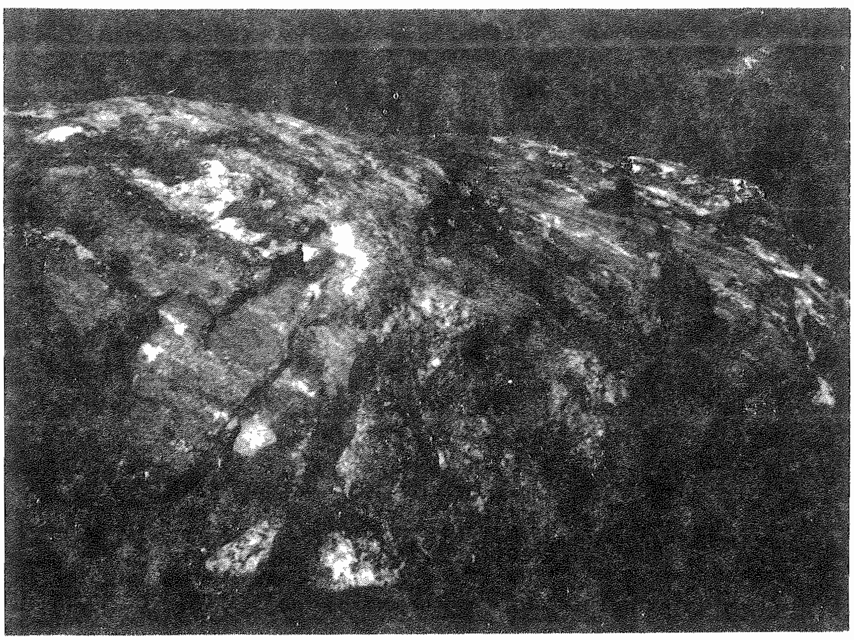


Figure 16. Typical bedrock exposure at West Point consists of gneiss and granitic pegmatite.

At about the middle of the outcrop, there is a one meter thick pegmatite sill composed of quartz, feldspar, and mica. Pegmatites are igneous rocks (rocks formed from a liquid, or molten rock mass injected as a "vein" into the other rocks). Pegmatites are extremely coarse-grained. A majority of pegmatites are felsic (SIAL) with very large crystals of orthoclase feldspar, sodium-rich plagioclase feldspars, and quartz. Hence, the term pegmatite generally implies that a rock is of granitic composition.

The extremely coarse texture of pegmatites is attributed to both slow cooling and low viscosity of the magma from which they formed. Under normal circumstances, the magma solidifying to granite is thought to be very viscous. What probably makes the magma of a pegmatite quite fluid is water held in under high pressure. After magmatic intrusion into a rock structure, if no fracture allows the gases to escape, they become sealed in, as in a pressure cooker. This makes the pegmatite magma very fluid (nonviscous). When a crystal starts to form during slow cooling, the appropriate atoms within the melt are able to move freely and become part of the growing crystal. As the crystal adds more and more atoms, it becomes very large. This pegmatite was intruded as a liquid solution into the other rocks, probably some time during their metamorphism.

There are also many maroon, almost rusty garnets in some of the rocks of this outcrop. The significance of garnets is that the mineral can only be formed during metamorphism. Garnets in a rock indicates that it was subjected to heat and pressure at some stage in its history; but not enough to cause it to melt and crystallize as an igneous rock.

On top of the outcrop, about two meters south of the pegmatite dike, are a number of augenite. These light-colored, eye-shaped, minerals reflect smearing of the rock during its metamorphism.

These metamorphic and igneous rocks comprise most of the Hudson Highlands bedrock on which West Point is located. They are typically very hard and have resisted erosion -- by water, wind and ice -- more effectively than rocks of the surrounding area. Consequently they are known as "Highlands", and of course, were key terrain during the Revolutionary War.

Station 4

West Point Geologic Setting and Outcrops Demonstrating Rock Jointing

Return from Ike Hall Area to south end of Gym Tunnel

The Hudson Highlands are part of a larger geologic province of similar rocks (billion year old metamorphics and granites) which extend from Reading, Pennsylvania through West Point and into New England (Figure 17). North from West Point Newburgh is located in a valley, near sea level (river surface). This valley was eroded from soft 400 million year old sedimentary rocks (shales and limestones). The valley in which Newburgh lies can be traced from the Canadian border thru New York, Pennsylvania, and Virginia to Alabama.

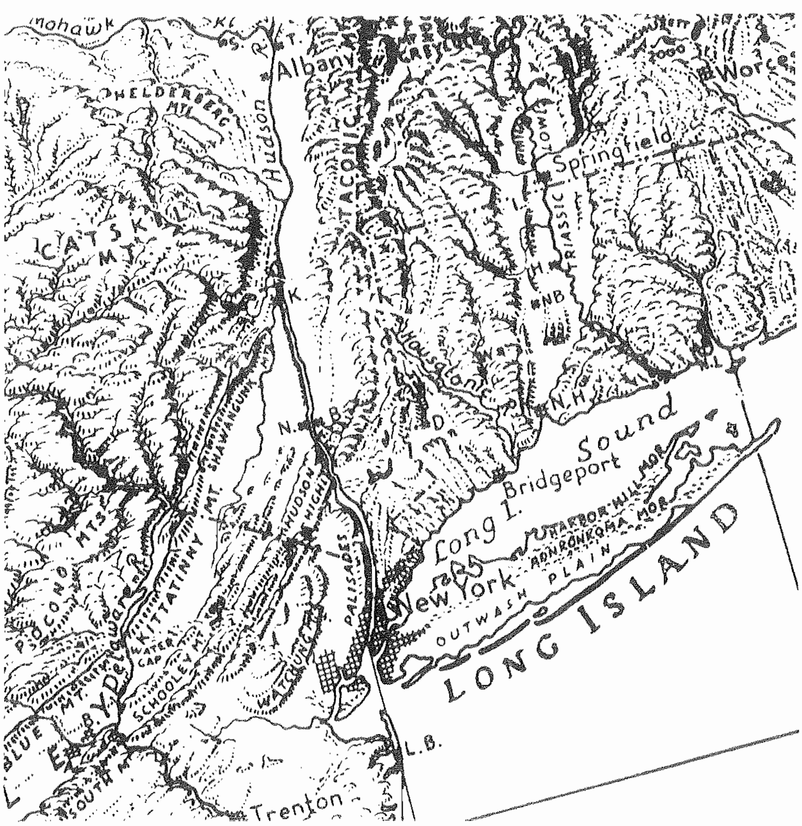


Figure 17. A portion of Landforms of the United States by Raisz shows the physiography surrounding West Point.

On a clear day it is also possible to see the Shawangunk Mountain ridge above the town of Newburgh, which consists of another very resistant rock known as conglomerate (Figure 18). This conglomerate was deposited about 300 million years ago. The Shawangunk ridge can be traced down the Appalachians through New Jersey, Pennsylvania, and into Tennessee.

Figure 18. A view north up the Hudson Valley fiord toward Newburgh and Shawangunk Mountain.

These mountains are the result of compression between the African and American Plates about 300 million years ago. The collisions between these continents squeezed up sediments from the small oceans between them into high mountains. The mountains were subsequently eroded, providing the sandstones and conglomerates of the Shawangunks and Catskill Mountains.

South of the Hudson Highlands is the Palisade Sill. The Palisades include volcanics, intrusive igneous rocks, and reddish sedimentary sandstones (Figure 19). These rocks were deposited, intruded, or extruded during the last separation of the African and American continents, at the birth of the present Atlantic Ocean 200 million years ago.

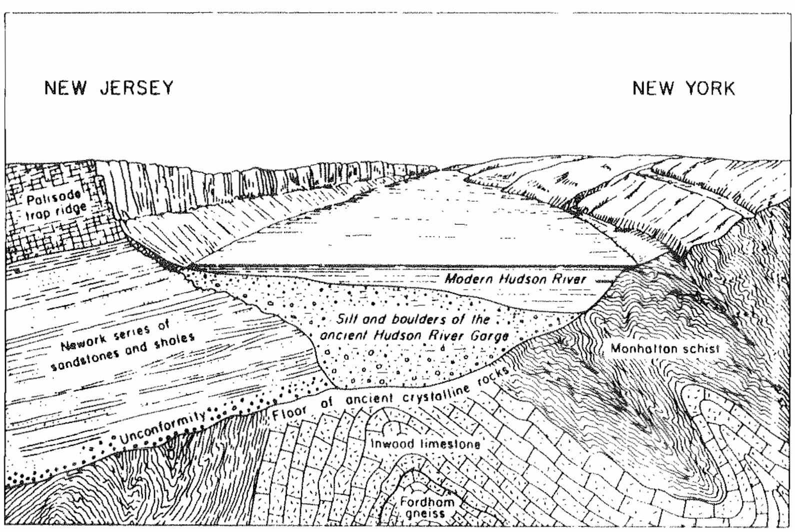


Figure 19. Geology and structure under the Hudson River, at the Palisades (south of West Point). From Thornbury, 1965, p. 98.

Outcrops Demonstrating Rock Jointing

At South end of Gymnasium Tunnel

Rock in this outcrop displays the ninety degree jointing and fracturing also characteristic of this area. Of particular interest are the vertical faces of some joints. Jointing is a common feature, especially in rocks that were once buried at great depth and have subsequently been moved to the surface, where the pressure is greatly reduced (Figure 20). Rocks begin to crack when pressure is released -- (related to exfoliation) (Figure 21). A crack along which no movement has occurred is a joint. If movement accompanies the crack, or occurs during some later time, the crack is referred to as a fault. The outcrops behind Washington Hall show further evidence of both joints and faults.

Figure 20.
A joint in the rock where apparently no movement has taken place.

Jointing and faulting is also related to large scale topography and geomorphology at West Point. Glacial plucking often occurs along joint planes as seen on Crow's Nest Mountain. The sharp bends in the Hudson River at West Point demonstrate erosion and stream cutting along faults and joints in the rocks of the Hudson Highlands.

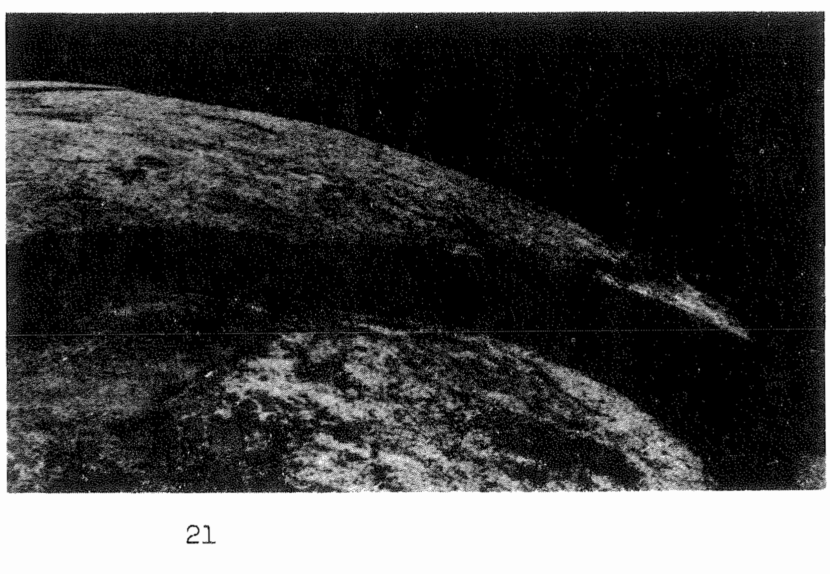


Figure 21.
Exfoliating granite on top of Bear Mountain results from pressure release.

Station 5

Faults Joints, and Weathering

Opposite 44th Division, just before 2d tunnel

Smooth surfaces inclined toward Brewerton Road represent fault planes that have been polished and scratched by friction during motion (producing slickensides).

The rocks have many joints that are more roughly textured than the faults. Both faults and joints are stained by rusty iron oxides deposited by flowing groundwater which seeps continuously. In winter this entire outcrop is covered with ice. Ice wedging and the steep slope create potential rock falls; the joints and faults define the potential failure blocks. Thin soil supports plants in many of the joints where root wedging and chemical reactions enhance weathering.

South of tunnel, between 43d Division and Washington Hall

This outcrop is jagged and irregular because (a) joints occur in three major sets or directions, and (b) rock shattering around some drill holes. The gneiss here has good folilation from the segregation of light and dark minerals. A pegmatite from one to three feet thick, intrudes the gneiss opposite the stained glass window (Figure 22). Primarily quartz and feldspar, with some dark mafic minerals, the pegmatite has characteristics of both dikes and sills. The shiny minerals are mica. Groundwater has left white powdery deposits and iron oxide coatings. Plants grow on ledges and in joints throughout this formation. The smooth vertical fault plane at the top of this outcrop adjacent to the tunnel under the mess hall is of particular interest (Figure 23). It goes diagonally up the outcrop, and is marked by a zone of crushed rock.

South end of tunnel

Opposite the south end of the mess hall loading docks, there are some small folds in white bands within the gneisses. One of these folds has a small, prominent fault offsetting it. Inside the southeastern end of the wet-walled tunnel, there is a nearly vertical, smooth, wet rock face. While not the same surface as on the other side of the tunnel it is the same type of fault surface. This face suggests horizontal slickensides. A fair amount of ground water is discharged along this wall through the faults and joints.

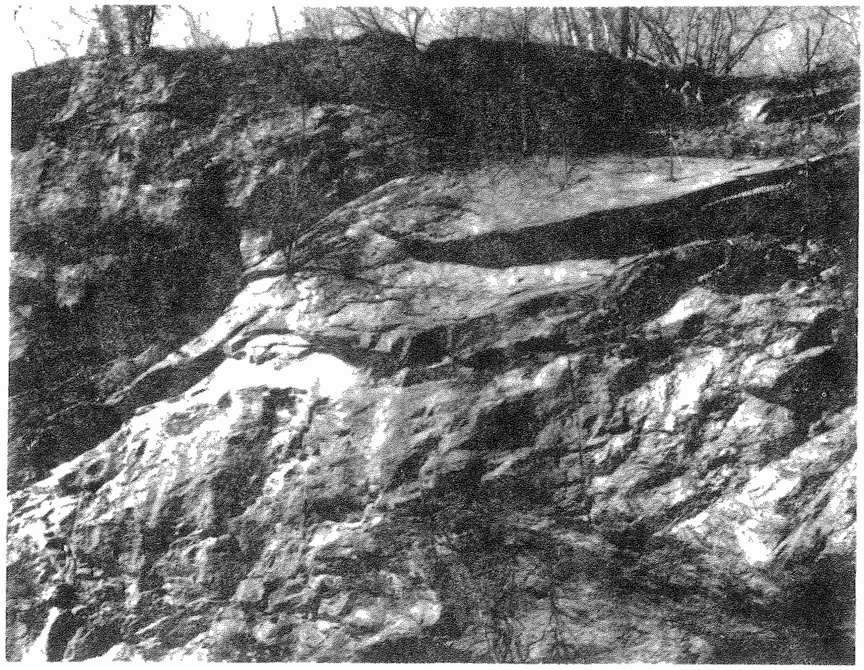


Figure 22. Exfoliation is evident from the sheets or slabs of gneiss and granite near the top of this outcrop.

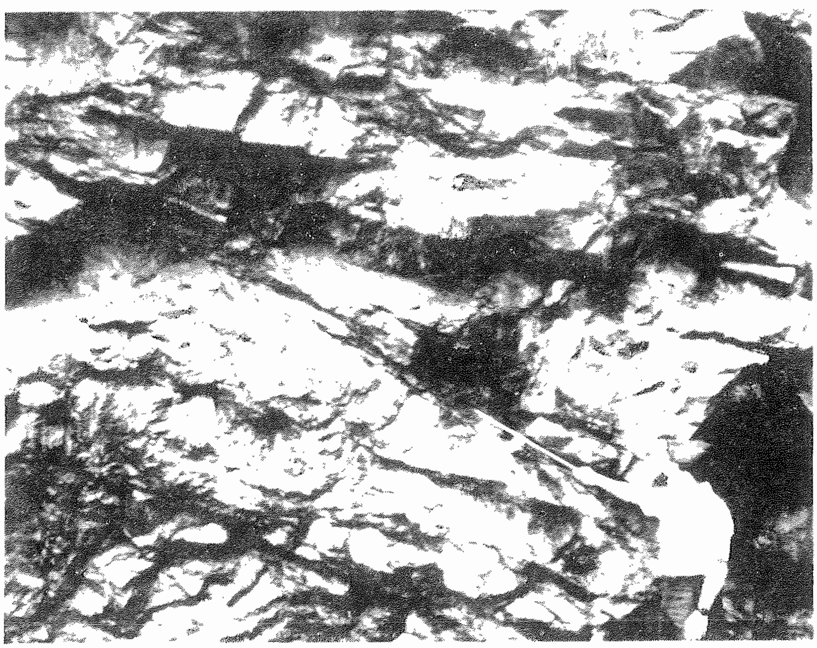


Figure 23. A fault running diagonally up through the rock along the axis of the pointer. Crushed, jagged rock indicates movement along the crack.

Foot of metal stairs

At the foot of the metal stairs adjacent to the tunnel entrance, the rock face is planar and vertical but not as smooth as the fault exposed in the tunnel. This is probably a joint along which movement did not occur. Groundwater preferentially moves along one sloping fracture plane 2-5 feet above the ground which ascends toward the staircase (Figure 24). Water constantly flows along this surface, as shown by well-established liverworts and mosses growing on the bare rock surface just below the fracture plane.

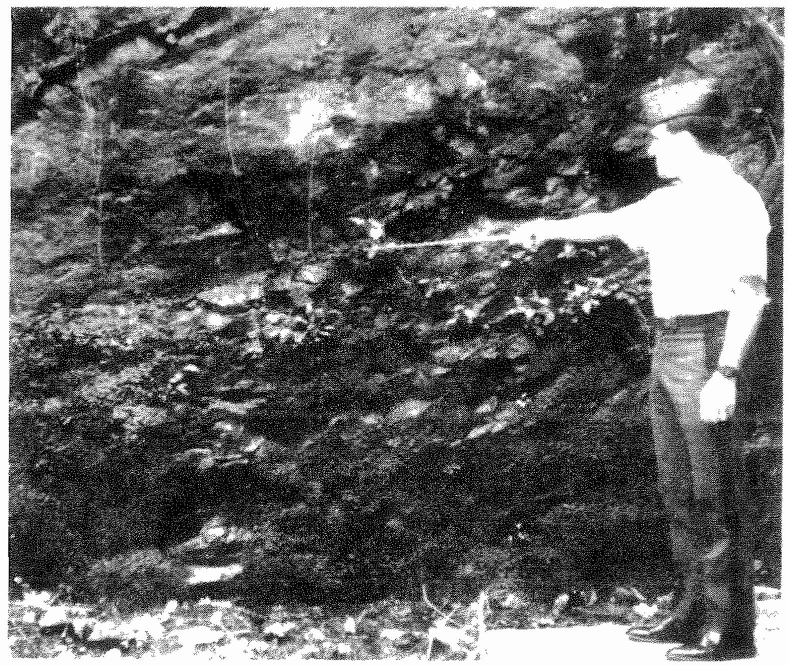


Figure 24.. Groundwater seeping along this prominent joint supports a thriving liverwort community below the joint. Above the joint the rock is baren.

Just beyond station metal stairs

This exposure demonstrates a jointed, foliated gneiss inclined toward the Hudson River. The gneiss blocks in the retaining wall on the east side of the road (opposite the outcrop) contain small garnet crystals. Southeast from this corner of Washington Hall there are thin pegmatite dikes, pink feldspar crystals, and folds.

Station 6

Normal Fault and Plate Tectonics Outcrop

Opposite fire plug

A fault occurs about 60 feet northwest of the "Stairs to Nowhere". It is a normal fault inclined away from the Hudson River, and offsets two parallel pegmatite sills by about 15 inches (Figure 25). Without the pegmatites for reference, the fault could easily be overlooked (Figure 26a). This is a normal fault because the hanging wall has moved downward relative to the footwall, resulting in an extension of the Earth's crust. Slickensides may be present along the fault at about head height (Figure 26b). Some joints are covered with the green mineral epidote and crystals of quartz and feldspar. The fault developed after the folding (because it is not folded) and after the pegmatite intrusion (because the pegmatite is faulted). The fault does not intersect joints, so it could be either older or younger than the joints. The grassy surface at the top of the outcrop continues straight across the fault, so the fault is older than the Pleistocene glacier which smoothed the top of the outcrop (Figure 26c).

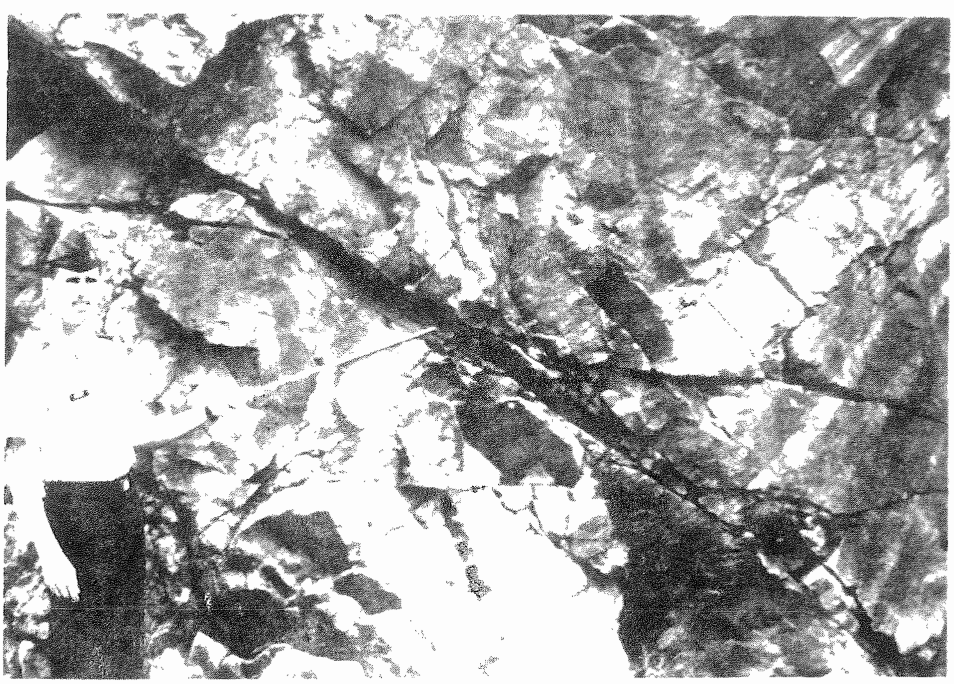


Figure 25. Fault offsetting a pegmatite sill.

Normal faulting results from tensional forces associated with plate divergence. The greatest divergent episode along the East coast was the break up of Pangea, when North America and Africa split creating the Atlantic Ocean. This fault may be related to that period of divergence and tension 200 million years ago, since the rocks are about 1.2 billion years old.

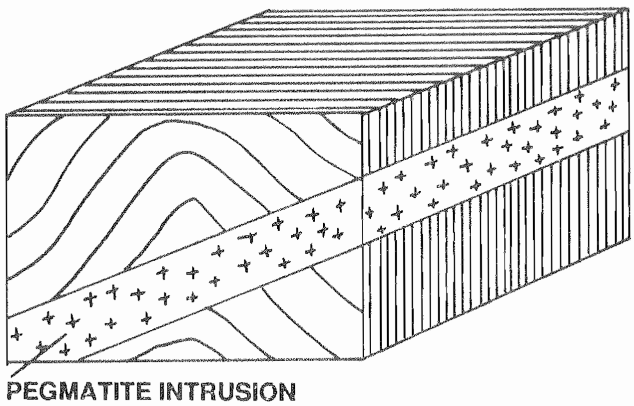
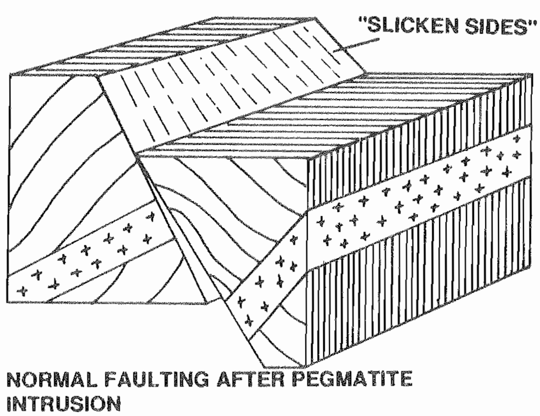
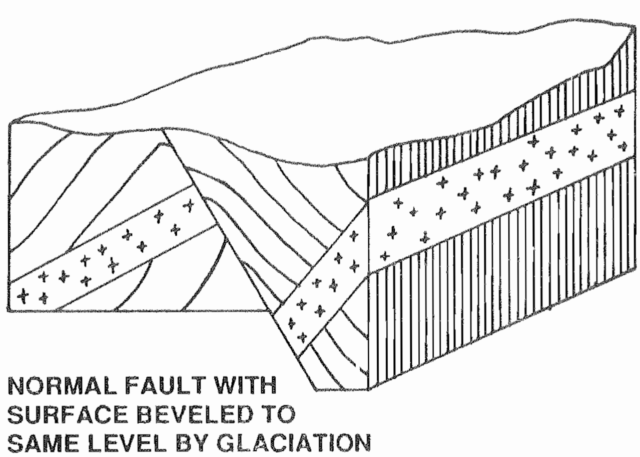


Figure 26.
a. Country rock is intruded by pegmatite. The pegmatite cuts across folds in the rock and is therefore younger or occurred after folding.



b. Tensional forces cause the rock to break and downward movement of the headwall in relation to the footwall identify this as a normal fault. The polished rock surfaces along the fault, exposed on the footwall, are called slicken sides.



c. After years of erosion, the surface is beveled to the same level, hiding evidence of the fault except in side view in some outcrops.

Station 7

Petrology and Plate Tectonics Outcrop

Stairs to Nowhere

The outcrop at head height, adjacent to the stone staircase, has a zone of large pink feldspar crystals and many coarse, black biotite flakes (Figure 27). The pink and white feldspar have an elliptical shape known as augen (eyes).

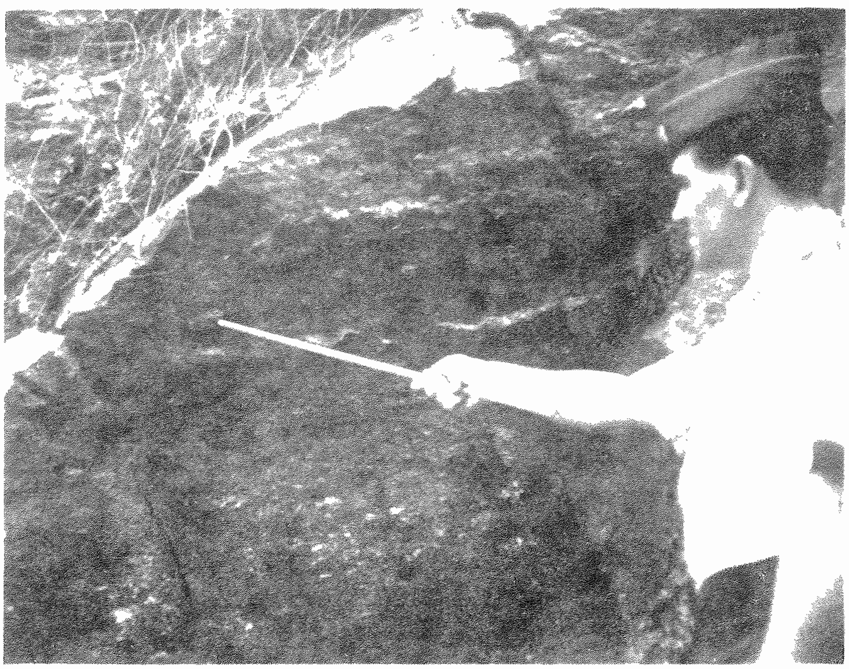


Figure 27. Augen indicative of metamorphic conditions.

Conditions to metamorphose these rocks have been duplicated experimentally. Temperatures must be in the range of 650-725 degrees Centigrade, with pressures of about 4000-6500 atmospheres. Since the geothermal gradient is about 30^{o}C/km, it can be inferred that these rocks were metamorphosed about 20km beneath the Earth's surface.

The geothermal gradient and its consequent heat is caused radioactively within the earth's crust. As radioactive elements decay into smaller daughter atoms, mass becomes energy through fission which heats the interior of the Earth. Some of these daughter products accumulate as gases in the atmosphere, including Argon (1% of earth's atmosphere) and Radon. Decay rates of the radioactive elements in the earth (K, U, Sr) are known and facilitate calculating the age of the rocks at West Point as 1.2 billion years.

Heat generated by nuclear fission keeps the outer core molten and permits convection cells to transfer heat through the mantle to the lithosphere, where crustal plates move (divergently/convergently/laterally). The continents, composed primarily of sialic crust, float on the denser oceanic crust (sima). The rocks at West Point are continental (sial).

These rocks were metamorphosed at depths of 20 km in the Earth's crust, producing garnets and elliptical augen - a result of tremendous compressional force. Most of this rock was formed about 1.2 billion years ago in the convergent boundary and subduction zone associated with the collision between North America and the Eurasion/African continents which formed Pangea.

Station 8

Weathering

Opposite 4th buttress on Central Bradley Barracks

In general, mechanical weathering is the predominant process reducing these massive, consolidated rock outcrops to boulders and smaller rock fragments. Evidence of root wedging, a mechanical weathering process, is apparent near the stairs leading to building 720 (Figure 28). Tree roots grow into the cracks along joints or fractures where there is water moving through the cracks, and mineral nutrients released by weathering. As the roots grow, they may exert pressure on the rock and wedge open fissures. Wet areas on the rock face identify groundwater seepage along cracks and crevices that expand and contract as water freezes and thaws to further promote mechanical weathering.

Figure 28. Root wedging is considered to be a form of mechanical weathering.

Although mechanical weathering seems dominate, there is subtle evidence of persistent chemical weathering. A joint face at shoulder height has well developed quartz crystals (Figure 29). These line a joint or fracture in the rock that at one time was filled with groundwater. The groundwater carried dissolved silica, probably from the chemical weathering of feldspar which decomposes to form clay minerals and silica. Feldspar is a common mineral constituent of the granite, gneiss, and schist in the West Point area.

Hydrolysis. In hydrolysis, ions derived from one mineral react with water to produce a different mineral.

$2KAISi_3O_8$	+	H_2CO_3	+	H_2O	->	K_2CO_3	+	$AI_2Si_2O_5(OH)_4$	+	$4SiO_2$
(K-feldspar)		(carbonic acid)		(water)		(potassium carbonate- readily soluble)		(a clay mineral)		(soluble hydrated silica or finely divided quartz)

This hydrolysis could have been accelerated by physical weathering produced by glacial abrasion (rock flour) which increases the surface area available for chemical reactions. The development of naturally acid forest soil profiles, as plant communities revegetated the area, would further enhance chemical weathering.

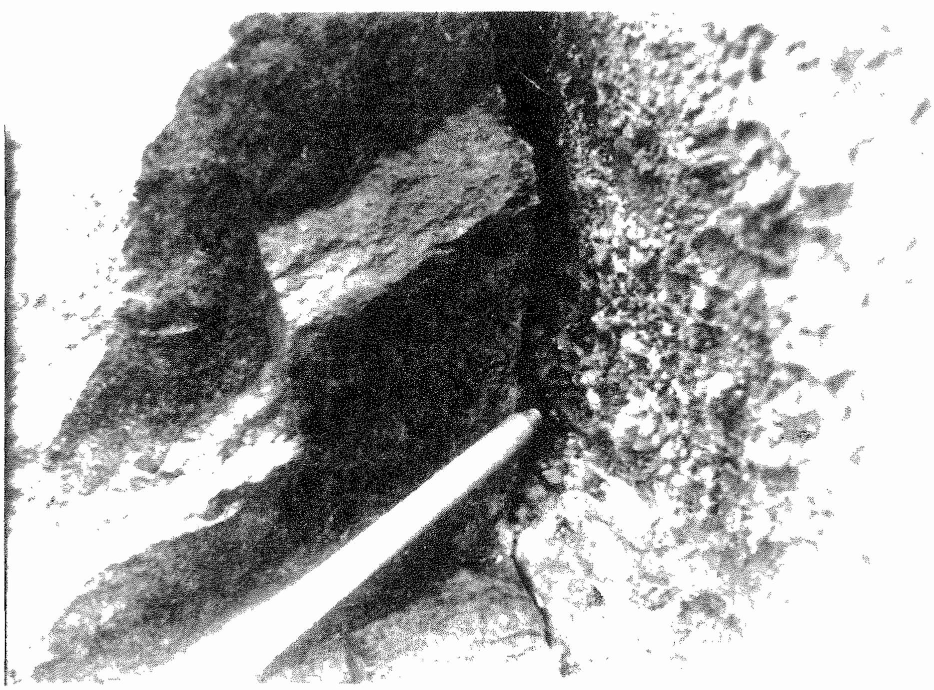


Figure 29. Quartz crystals formed by solution from the chemical weathering of feldspar a common mineral in granite.

Another chemical weathering process known as oxidation is evident in the rust stains on some academy walls. Garnets within the gneiss are partially composed of iron minerals which oxidize, or rust, in the environment.

> Oxidation. The reaction of free oxygen with metallic elements is perhaps more commonly known as rust. Oxidation affects rock containing iron (Fe) and other metallic elements. In this oxidation reaction, iron atoms contained in minerals lose one or more electrons each to oxygen and then precipitate as different minerals or amorphous substances.

$4FeO$	+	$3H_2O$	+	O_2	$\rightarrow$	$2Fe_2O_3$	*	$3H_2O$
(ferrous oxide)		(water)		(oxygen)		(ferric oxide bound with water)		

White, powdery deposits below some of the mortar in the buildings may be gypsum or calcite being redeposited after leaching from the mortar. The mortar, comprised of calcium (Ca), is susceptible to carbonation, as are the limestone window facings on Washington Hall.

> Carbonation. Carbonic acid is formed either in the atmosphere or in the ground water by dissolution of carbon dioxide in water. Carbonic acid readily combines with calcium carbonate to produce calcium bicarbonate, a salt that is easily soluble in water.

H_2O	+	CO_2	$\rightarrow$	H_2CO_3
(water)		(carbon dioxide)		(carbonic acid)

$CaCO_3$	+	H_2CO_3	$\rightarrow$	$Ca(HCO_3)$
(calcium carbonate in limestone and mortar)		(carbonic acid)		(calcium bicarbonate; water soluble)

Station 9

Discussion of Rock Cycle

From stairs to Bldg 720, past Bldg 747 to MacArthur Statue

The topography and landscape of West Point, which proved to be key terrain during the Revolutionary War and make it such a scenic location today, is a result of constructional and destructional processes over a billion years of geologic history.

The difference between granite and gneiss is easily discerned. Gneiss is foliated (banded) with alternating layers of light and dark colored minerals (Figure 30). Gneiss may also have garnets, minerals that form only under metamorphic conditions. In contrast, granite has more of a salt and pepper (homogeneous) distribution of light and dark minerals. Granite may also have a grey, white or pink appearance depending on its constituent minerals. It will not be banded or contain garnets.

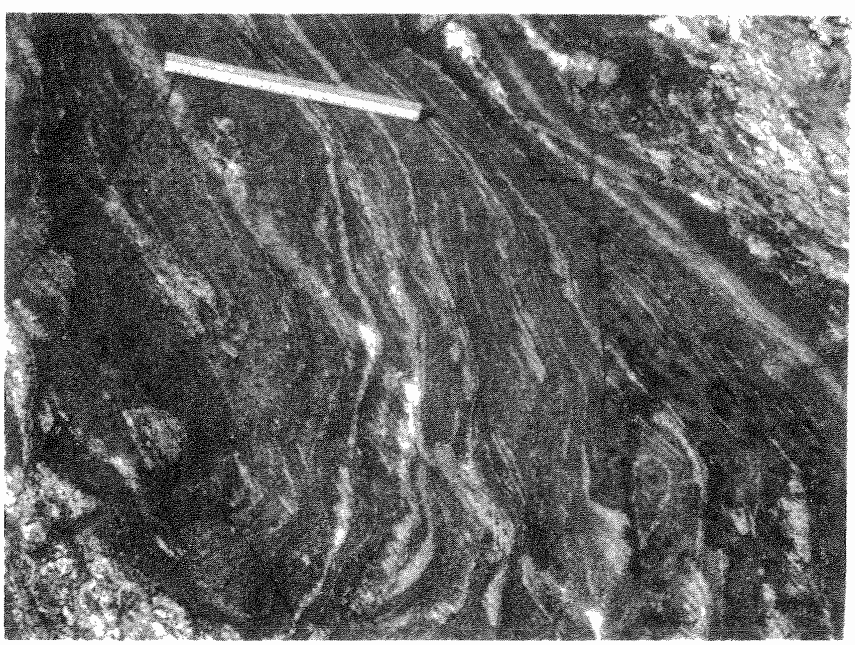


Figure 30. Foliation or the segregation and banding of dark and light minerals in the metamorphic rock gneiss.

The bedrock at West Point is approximately 1.2 billion years old. Prior to becoming gneiss, these rocks were normal seafloor deposits of shale, sandstone and limestone resting on the simatic ocean crust, they were then metamorphosed by heat and pressure. Therefore, these rocks were created at great depth in the earth's crust. In order to attain these depths (20 kms) the rocks must have been dragged near the bottom of an ancient subduction zone. The limestone metamorphosed to become marble which outcrops and forms the bridge at Camp Natural Bridge. Gneiss is the last metamorphic stage of shale before the rocks melt and yield an igneous rock. If the shale were subjected to more heat and pressure, than it took to form the gneiss, it would have melted and recrystallized as granite (hence the juxtaposition of gneiss and granite). As the granite weathers, it becomes sandstone and shale, making the rock cycle complete (Figure 31).

Weathering of the present day gneiss and granite continues to reduce these massive outcrops. The rocks are producing sand and clay size sediment and chemical products. The sand will become sandstone (such as the brownstone seen in Bldg 747 or in the pavement at the Eisenhower statue), the clay will become shale, and the chemicals will provide calcium for sea creatures that will die and accumulate to form limestones (like those used in the building facings).

The weathered sediments will eventually form rocks on the seafloor, where they will ultimately find their way into subduction zones to be metamorphosed or melted and return as igneous intrusives (Palisade sill) or extrusives (volcanoes).

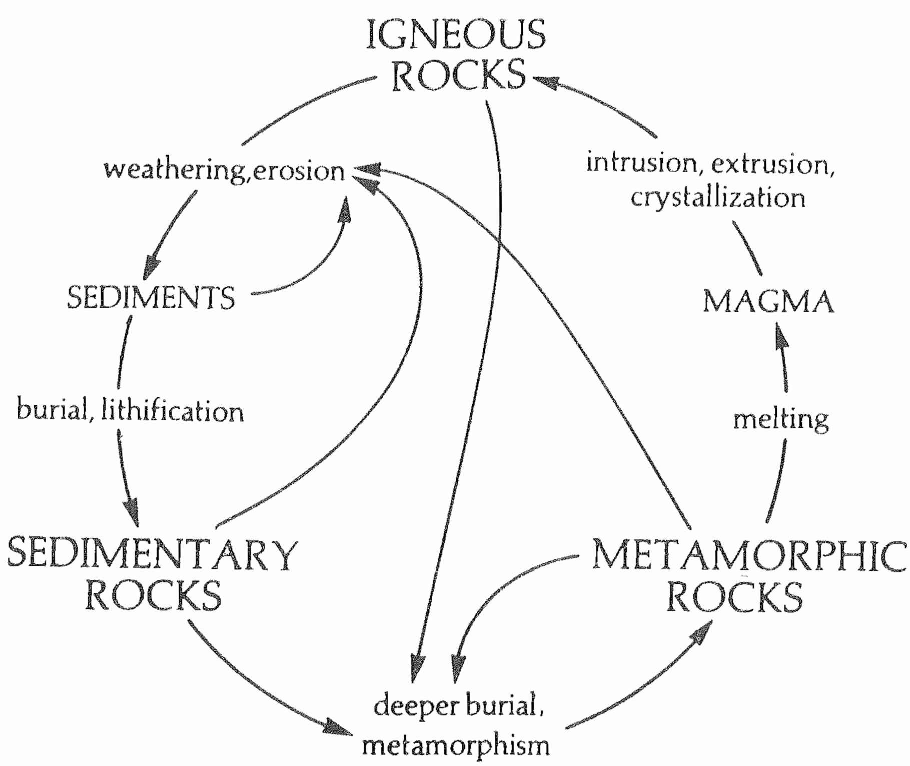


Figure 31. The rock cycle

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