

2 The Hudson River Valley: Geological History, Landforms, and Resources

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ABSTRACT The course and character of the Hudson reflect its underlying geological structure and the modifications of Pleistocene glaciations. Radiating drainage out of the Adirondacks is transformed into a broad meandering pattern in its tidal reaches below Troy. The river's course then cuts through the Hudson Highlands in a fjord-like gorge. A broad curving path takes the river along the Triassic, Palisades Escarpment following the juncture with the older rocks of Manhattan. The bedrock foundation of the Hudson was established in three mountain-building episodes beginning over a billion years ago. Most recently, the entire region has been glaciated and the course of the Hudson takes it through relic beds of glacial lakes and several ice margin deposits of glacial sediment. After the deglaciation of the region, estuarine conditions were established in the Hudson beginning about 12,000 years ago. The Hudson briefly crosses the coastal plain breaching the Wisconsin terminal moraine at the Narrows. On the continental shelf, the course of the ancestral Hudson is marked by the Hudson Submarine Canyon.

Introduction

The source of the Hudson River was discovered in 1872 by the naturalist and surveyor, Verplanck Colvin. It is a pond on the western slope of Mt. Marcy, the highest peak in the Adirondacks at 1,629 m. Colvin, an ardent supporter of preserving the mountain forests and watershed, referred to the pond as 'tear of the clouds' (Schneider,

1997). He recognized that the many springs, ponds, bogs, swamps, and other wetlands provided the water flowing from the mountains to create the Hudson watershed. To Colvin and like-minded associates, these wetlands and their encompassing forests were a resource worth protecting. They lobbied the New York State Legislature to establish parkland for this purpose. By the late nineteenth century, the state began to set aside tracts of land and to preserve forested lands that otherwise would have reverted to the timber industry. Today these lands are the Adirondack Park.

During the colonization and growth of eastern and central New York, the Hudson River watershed supplied water for agriculture. A network of streams enabled lumbermen to drive logs from high mountain valleys to sawmills in the valleys beyond the Hudson gorge. Taking advantage of spring snow melt, water was stored in natural and man-made lakes in these tributaries and then released after the ice was out of the channel to drive rafts of logs down the river. The Hudson's water powered mill wheels, ore processing plants, and later, hydroelectric turbines. It provided potable water for communities on the river. Today, this watershed provides water for recreational boating as well as for snow making at ski resorts during the winter. Although the Hudson was not the true northwest passage sought by European entrepreneurs, the river made a major contribution in supplying water, timber, and mineral resources to the nation's economy and in opening up the routes of its westward expansion.

The Hudson River is over 500 km long from Lake Tear in the Clouds to the Narrows (between Brooklyn and Staten Island). The Hudson estuary is tidal and navigable upsteam for nearly 240 km to the dam in Troy and the locks that join the river to the barge canal system. In the Adirondacks, the watershed drains a region with 1,200 m peaks into a lowland less than 125 m above sea level. The Mohawk drains central New York into the Hudson. The watershed is also supplied by rivers that rise in southwestern Vermont. South of Albany, tributaries flow westward to the river from the Taconic mountain range and eastward from the Catskills Mountains (Fig. 3.1, Chapter 3). Many of the Catskill streams, such as Esopus, Neversink, and Rondout creeks, fill freshwater reservoirs for New York City.

¹ Deceased

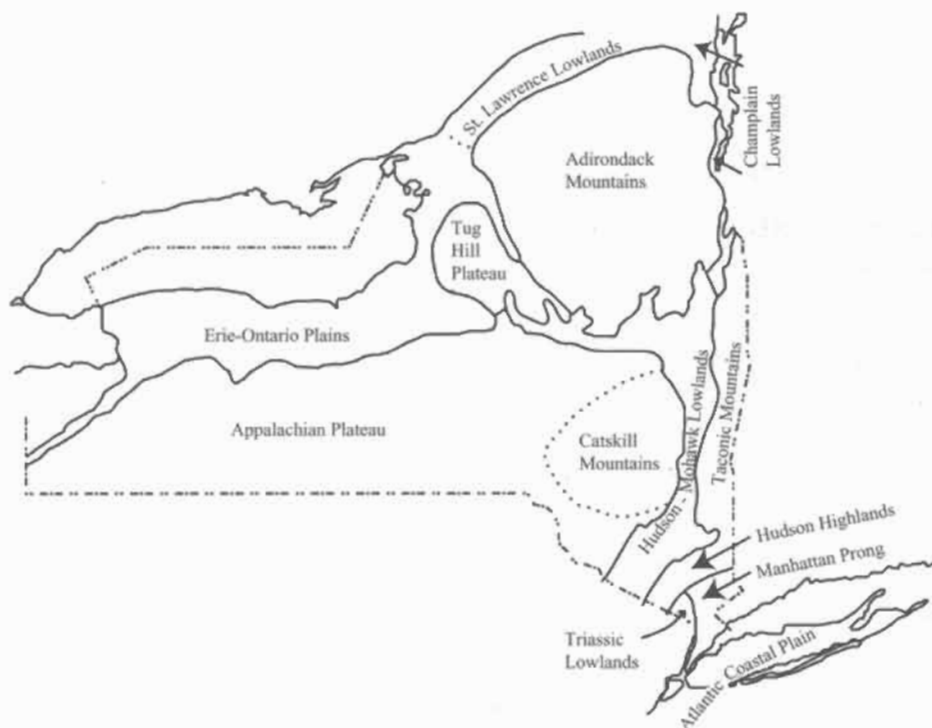


Figure 2.1. Principal physiographic provinces in the vicinity of the Hudson River (after Dineen, 1986).

The northern third of the Hudson's drainage radiates from the high peaks of the Adirondacks. Southward, the Hudson's tributaries appear rectangular, some following the trend of northeast to southwest faults and ridges, and others joining at right angles to the faults along joint planes. The river occupies its bedrock gorge, flowing over rock ledge rapids and coarse cobble point bars (from Mt. Marcy to Glens Falls), until partly blocked by mountains, it turns abruptly to the east through the Luzerne Mountain gorge. It then emerges onto glacial lake sediments and forms a broad, meandering pattern on lowlands underlain by shale for nearly 210 km (from Glens Falls southward to near Newburg).

From the Hudson's lowlands (70 km south of Glens Falls), the river is a tidal one (Fig. 2.1). For the final 240 km, it drops only about a meter to sea level, its course confined to a narrow meander band in this reach. Even though tidal, the Hudson behaves like any river at base level, depositing its bed load and some of its fine-grained suspended load in the form of sand bars.

Further southward, the river cuts laterally through the hard crystalline rocks of the Hudson Highlands (Fig. 2.1). Even here it has an entrenched meander pattern, shifting back and forth in its valley until it emerges from the mountains. Through the highlands the river exhibits characteristics typical of a fjord within towering rock walls. The river's course gently curves in front of the Palisades escarpment, which towers more than 100 m above the water's surface. At the Narrows, the Hudson has breached its final barrier, the terminal moraine of the last glaciation, before it reaches the Atlantic Ocean. On the continental shelf the ancestral course of the river is marked by a subsea canyon.

Geologic History

The Hudson Valley region has experienced three mountain-building episodes that punctuated prolonged intervals of subaerial erosion and periodic invasion by epicontinental seas (Seyfert and Sirkin, 1979). Late in this history, glacial erosion reshaped the peaks and ridges, and deepened valleys.

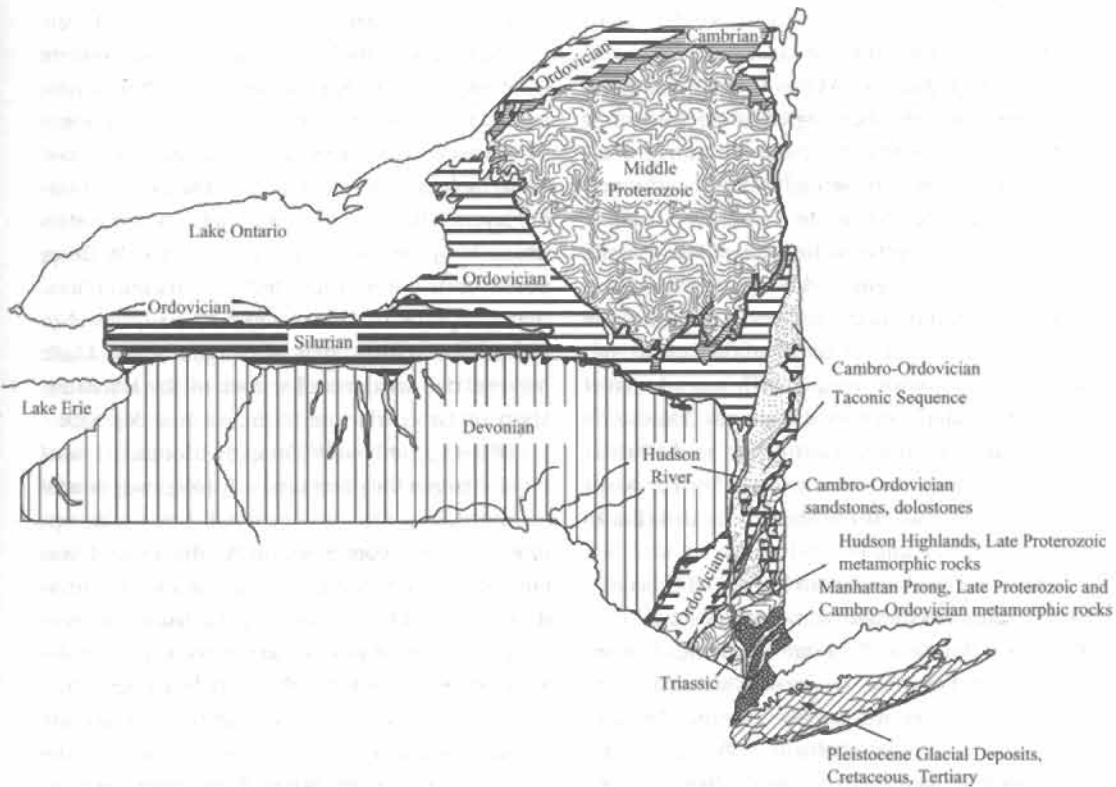


Figure 2.2. Generalized bedrock geology map of the New York State region. Modified after Geological Survey, New York State Museum, geological map, 1989.

The oldest bedrock in the Adirondack headwaters of the Hudson is an anorthosite of mid-Proterozoic age, dated at about 1.4 billion years (Fig. 2.2). Anorthosite originated as igneous rock intruded into sedimentary deposits, mainly sandstone and limestone. After mountain-building episodes, the sedimentary rock units were folded, faulted, and metamorphosed to quartzite, gneiss, and marble. The first major mountain building episode, the Grenville Orogeny, began around 1.2 billion years ago. This event affected a broad region along the margin of ancestral North America, from maritime Canada to northwestern Mexico. The mountain system created by the Grenville Orogeny is believed to have rivaled the Himalayas, driven by a collision in which Laurentia (North America) was overridden by Gondwana (Africa). The deep burial of Laurentia resulted in the first episode of metamorphism, partial melting of rock, and separation of light and dark minerals of the Adirondack gneisses. As the continents subsequently rifted in the late Proterozoic Period, basaltic volcanic rocks

were intruded into the mountains, cutting across the anorthosites and gneisses.

The Hudson Highlands gneisses and the lowest unit, the Fordham gneiss, of the New York Group rocks of the Manhattan Prong in southern New York (Fig. 2.2) are late Proterozoic in age. In both cases, the gneisses were probably derived from sedimentary rocks during the Grenville event. These gneisses have been dated at around one billion years, although the Highlands gneisses may be somewhat older and the Fordham somewhat younger. Long episodes of erosion of the Grenville mountains and subsequent crustal uplift have brought this once-deeply buried crust to the surface. Late in the Proterozoic, erosion of the Grenville mountains provided a source of thick sedimentary deposits that partly engulfed the upland, but while these deposits are found elsewhere in the Appalachians, almost all were removed from the Hudson Valley.

In the early Paleozoic, sand and gravel eroded from the mountains became basal sandstone and

conglomerate (e.g., the Potsdam Sandstone of northern New York and the Lowerre Quartzite of the Hudson Highlands). As the epicontinental sea inundated the mountain region, a thick cover of marine limestone and shale was laid down in an elongated trough that formed on the continental margin where the mountains had once prevailed. Limestone was deposited in shallow water along the continental margin, and shale solidified from muds carried into the deeper, seaward part of the basin. The shale bedrock between Glens Falls and the Highlands is what remains of thousands of feet of sediment deposited in the trough. Limestone strata found north and west of the mid-Hudson valley represents the carbonate, platform deposits thought to be similar to the Modern Bahama Banks (Isachsen, Fisher, and Rickard, 1970).

In the late Cambrian Period (ca. 500 million years ago), Laurentia collided with the ancestral core of Europe, Baltica and a large fragment of continental crust known as Avalonia. This mountain-building event, known as the Taconic Orogeny, lasted throughout the Ordovician Period and resulted in the new supercontinent called Laurasia. While much of the subduction, metamorphism, and volcanism took place well to the east, island arc volcanic structures (such as the Cortland Complex) have been identified in the vicinity of the Hudson Highlands. To the north and west in the mid-Hudson Valley, the sedimentary rocks were folded and faulted, with the trend of the folds parallel to the southwest to northeast Appalachian structures. Closer to the margin, thin sheets of rock were thrust dozens of kilometers westward, known as the Taconic thrusts. Fine-grained shales were crumpled and thrust into the narrow seaway west of the mountains. Blocks of limestone slid into the trough and were incorporated in the *mélange* of jumbled, shale masses. Today the river flows past the western edge of the thrusts and cuts into the *mélange deposits*.

Sandstone, limestone, and shale, similar in age to the mid-Hudson strata, and Proterozoic bedrock from the Highlands south and east in the Manhattan Prong, were deeply buried as the continent's margin was subducted near the zone of plate convergence. The rocks were partially melted and metamorphosed to gneiss, marble, and schist, and folded into the typical Appalachian alignment.

(The New York Group consists of the Proterozoic Fordham Gneiss and the early Paleozoic Lowerre Quartzite, Inwood Marble and Manhattan Schist; Isachsen and Fisher, 1970, Isachsen, 1980). Streams in the metamorphic lowlands follow valleys formed along fault lines or on the softer, more soluble marble layers. Metamorphosed oceanic crust borders the rocks of the New York Group to the east. Deep, ocean-basin volcanic and sedimentary sequences, that is, ophiolites, have been metamorphosed to greenstone schists, that is, serpentinites. Mafic mineral-rich metamorphic rock of the Hartland-Harrison Group represents the oceanic deposits.

Following the Taconic Orogeny, a long interval of erosion began the process of stripping away crustal overburden as the new continent was slowly uplifted by plate compression. As the upland was eroded, the epicontinental sea gradually inundated the Hudson Valley region from the low-lying continental interior to the west. During the Silurian Period and into the early Devonian, shallow seas covered the region, and tropical calcium carbonate-rich sediments were deposited. In the early Devonian, rivers flowed from the eastern uplands, carrying sediment westward into the sea to form layers of marine sandstone. At the shoreline, a large coastal delta formed over the marine beds. By the mid-Devonian an alluvial plain extended westward across the Catskill region; the shoreline had shifted to the west. At this time, thousands of meters of mid-Paleozoic sediment were piled over the Hudson Valley; continental red sandstones from the east interfingered with gray, marine sandstone to the west. The compressive force overturned folds to the northwest (Schunemunk Mountain along the New York State Thruway near Highland Mills is an example of folded early Devonian limestone and sandstone).

Renewed plate compression, and the resulting uplift of the eastern ranges, marks the beginning of the *Acadian Orogeny*. This mountain building episode was associated with collision of the North American continent, Laurasia, and the southern supercontinent, Gondwana. Acadian volcanic arcs and granitic intrusions of Devonian age were located east of the Hudson Valley near the continental margin. One granitic pluton, a possible volcanic arc remnant, was intruded just east of Peekskill (Isachsen, 1980).

By this time, the sea was retreating from east to west, exposing great thicknesses of sedimentary rocks from the Acadian Mountains across the Catskill Delta. The final compression of the converging Paleozoic Era continents, the Alleghenian Orogeny, began late in the Permian Period. All of earth's landmasses were now joined to form the supercontinent, Pangaea. Pulses of this orogeny had folded and uplifted the Paleozoic rocks of the Appalachians, forcing the epicontinental sea from the Catskills to the Pocono Plateau in northeastern Pennsylvania to western Pennsylvania. In the east, only relict marine embayments, like that in Rhode Island, persisted into late Paleozoic time when the sandstone, conglomerate, and coal deposits were metamorphosed.

Once above sea level, the Devonian strata of eastern New York were subjected to over 250 million years of subaerial erosion. At some point during this time span the drainage reoriented from west to southward aligning the ancestral Hudson River along a north-south trend. Perhaps this redirection of the drainage took place as the upslope edge of the deltaic beds on the east side were eroded from the mountain front during the late Paleozoic and early Mesozoic. Streams would have followed the tilt of the land and the resistant edge of the strata, both to the south, gradually capturing the headwaters of the west-flowing streams. As the bedrock was worn away, the boundary of the Paleozoic strata migrated westward so that only small outliers of mid-Paleozoic rock units would remain east of the Catskill Front. With the more resistant, metamorphic Taconic Mountains to the east and the Catskill Mountains to the west (Fig. 2.1), the river system in the mid-Hudson Valley worked its way down through softer sedimentary layers, leaving behind the slopes of the mid-Devonian Hamilton Shales and the limestone benches of the Onondaga and Helderberg formations, east of the Catskill Mountains, before reaching the Ordovician age Canajoharie Shale of the current bedrock surface (Isachsen and Fisher, 1970).

The break-up of Pangaea followed in the Triassic Period. Large rifts and grabens stretched from northeast to southwest. In the lower Hudson region, a Mesozoic rift basin known as the Newark Basin of the Triassic Lowlands (Fig. 2.2) covers much of southern New York south of the Hudson

Highlands, west of the river and continuing into east central New Jersey. This basin received thousands of meters of Hudson Valley sediment, much of it colored red by oxidized iron minerals from Proterozoic and Paleozoic metamorphic rocks or re-deposited from the Catskill red beds. The Mesozoic red beds show flow patterns emanating from the Highlands as indicators of north to south drainage.

Concurrent with graben formation, basaltic magmas were intruded along fault lines and into the red beds of the basin between 200 and 190 million years ago. The magmas formed the Palisades Sill. Today, the more resistant Palisades stand as ridges above the softer red beds of the Newark Basin. The tabular Palisades Sill slopes to the west, and the eastern edge forms the escarpment, or 'palisade' of vertically jointed basaltic rock so recognizable from the New York side of the Hudson.

In late Mesozoic times, igneous intrusions were emplaced along a northwest to southwest trend across southern Canada and northern New England, and the mountains were uplifted. The linear trend of the intrusions aligns with a chain of younger seamounts, or subsea volcanoes, across the continental shelf and into the ocean basin, reaching as far as the mid-Atlantic rift. As the North American continent moved away the midocean ridge and over a source of high heat flow embedded in the earth's mantle, the hot spot generated intrusions and volcanoes. It may also have been responsible for uplifting the northern, or higher section of the Appalachian Mountains, thereby reactivating erosion in the mountains and doming up the Adirondack anorthosites. The lower-lying mountains of southern New York experienced uplift to a lesser degree, but the thick, overlying sedimentary cover was eroded to expose the deep-seated, high-temperature metamorphics of the Highlands and the New York groups.

Deposition in the Newark Basin ended in the early Jurassic Period. The Hudson became entrenched into its flood plain and began carving its gorge into the resistant gneisses of the Highlands and southern New York. Relict meanders of the channel may date from this time. With the widening of the Atlantic, river sediment was carried to the new continental margin to form the coastal plain and continental shelf. By late Cretaceous time, the eastern rivers were depositing alluvial and deltaic

sediment over marine strata on the continent's margin from Long Island to Virginia. The Hudson drainage carried upland sediment to a new sea level close to the edge of the metamorphic upland, about twenty kilometers inland from the present shoreline.

Uplift of the Long Island platform and embayment in the Raritan region to the south, coupled with lower sea level, allowed deposition of the younger, Tertiary-age sediments on the seaward margin of the Cretaceous delta. Lower sea level may also have enabled the river to begin excavating the Hudson Canyon into the continental shelf both by subaerial erosion and turbidity currents below sea level (Shepard, 1963). In the late Tertiary Period, the river turned toward the southwest as a tributary to the Delaware River in central New Jersey (Stanford, 2000). This drainage carried fluvial sediments along the inner margin of the coastal plain, over Cretaceous strata in southern New Jersey, and into the Delmarva region (Owens and Minard, 1979; Owens and Denny, 1979). Tertiary fluvial sediments interfingered with marine strata in the coastal plains and the offshore shelf of New Jersey and the Delmarva Peninsula.

PLEISTOCENE GLACIATION

Although there is no definitive evidence of earlier Pleistocene glaciation, the Hudson River Valley was the arena for the last two advances of Laurentide glaciers, the older during the Illinoian glacial stage and between 140,000 and 200,000 years ago and the younger in the later part of the Wisconsinan stage ending 22,000 years ago. Regional topography enabled the glacier to form a lobate ice margin, as the ice thinned over the Catskill and Taconic uplands (Fig. 2.1) and thickened and expanded southward down the valley. The older drift on western Long Island appears to contain more rock debris from Highlands and Hartland gneisses and less material from the northwest side of the Valley. The lower, U-shaped tributary valleys and bedrock gorges may be related to the last ice advance and postglacial rivers, while more open upland topography might have originated during the earlier advance.

Pollen analysis and radiocarbon dating indicates much warmer conditions than the present during the last interglacial following the Illinoian glaciation. At that time, forests like those of the present, southeastern coastal plain grew in the Adirondacks

and as far north as Toronto (Muller et al., 1993). Sea level rose several meters higher than today's sea level. During the last advance glaciers expanded in the early Wisconsinan (60,000 years ago) as far as the St. Lawrence valley, and cold conditions, along with boreal forests, persisted in the northeast prior to 34,000 years ago when a warming trend began. This warm interval, called the Portwash-tonian warm interval, peaked around 28,000 years ago, at which time oak and hickory forests prevailed and sea levels rose from glacial lows around 100 meters below to within 20 meters of the present level (Sirkin and Stuckenrath, 1980; Sirkin, 1986). As cooling resumed, boreal forests migrated back into the region. By 26,000 years ago, the Laurentide Glacier covered the Ontario and St. Lawrence lowlands. Subsequently, an ice lobe advanced into the Champlain Valley and over the Adirondacks and Green Mountains. At the height of this glacial advance, the ice may have overtopped the High Peaks region by as much as 300 meters (Flint, 1971). The south-flowing glacier deepened the Hudson gorge guided by the softer, metamorphic rock, such as the marble on the west side of the Crane Mountain near Warrensburg.

South of Glens Falls, the ice deepened the channel of the river, and, at the Highlands, cut the fjord, leaving Storm King, Beacon and Bear mountains over 400 m high above the present water level and the river's thalweg over 250 m below sea level (Flint, 1971). With glacial sea level depressed over 100 m, the bedrock was lowered to over 80 m below present sea level near Manhattan and 60 m near the Verrazano Narrows as the river cut its way down to the lower base level. The pre-existing Hudson Canyon was also more deeply entrenched in its new subaerial reach by glacial meltwater flow, and, possibly, eroded below the glacial sea level to the continental rise by turbidity currents.

The Hudson-Champlain Lobe of the Laurentide Glacier reached its southerly boundary 22,000 years ago. The position is marked by the terminal moraine, which stretches from Long Island across Staten Island and New Jersey to Pennsylvania (Sirkin, 1986; Stanford, 2000). The terminal moraine of this lobe, known as the Harbor Hill Moraine (Fig. 2.3, after Long Island's Harbor Hill in Roslyn), impounded glacial meltwater resulting in large proglacial lakes, such as Lake Hackensack in New Jersey, Glacial Lake Hudson and Glacial Lake

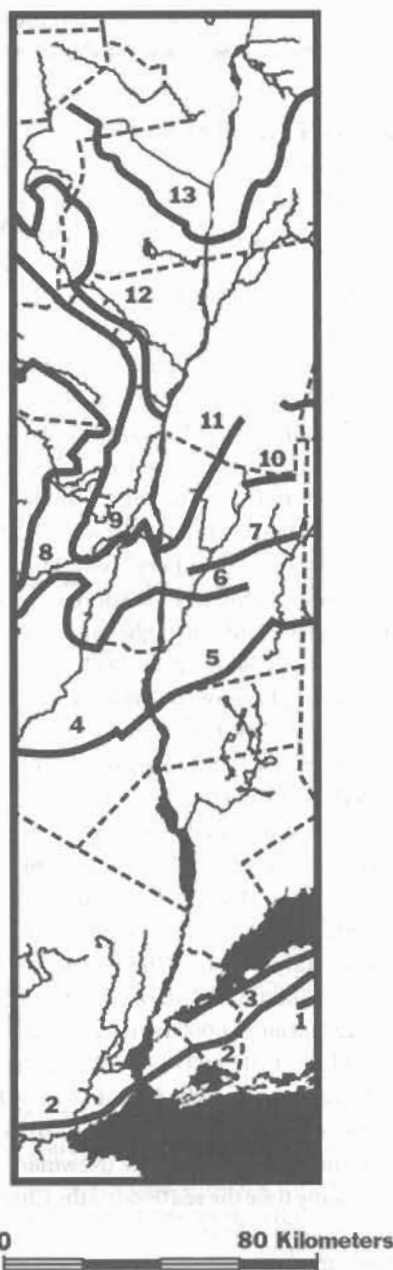


Figure 2.3. Major recessional ice margins. (1) Manetto Hills, (2) Harbor Hill Moraine, (3) Sands Point, (4) Pellets Island, (5) Shenandoah, (6) Poughkeepsie, (7) Hyde Park, (8) Wallkill, (9) Rosendale, (10) White Plains, (11) Red Hook, (12) Middleburg, and (13) Delmar. (After Cadwell, 1986; and Connally and Sirkin, 1986).

Connecticut whose basin is now occupied by Long Island Sound. Thick deposits of lake clay overlap bedrock along the Staten Island and Manhattan shorelines and into the low topography in

mid-Manhattan (Cadwell and Pair, 1989). Meltwater drainage blocked by the moraine flowed eastward into the Glacial Lake Connecticut, in the current basin of the Long Island Sound.

Recession of the Late Wisconsin Ice Sheet

Shortly after deposition of the terminal moraine, the ice front began to recede northward. In less than 2,000 years, Long Island and Staten Island were icefree. The ice front first receded from the terminal moraine to a new ice margin a few kilometers to the north. Here, a recessional moraine was deposited with a lineation of ice contact features, such as proglacial lakes and deltas, lateral meltwater channels, and kames. The ice front of the Hudson Lobe retreated northward from the Harbor Hill Moraine and formed the ground moraine terrain of the Oyster Bay Moraine. The ice stood long enough at the next northerly position, the Sands Point Moraine (Fig. 2.3), to develop an ice margin that cuts across the necks of western Long Island. This position is documented by the Sands Point and College deltas, the Kings Point bog, now dry land over thick peat deposits, and a lateral, west-to-east meltwater channel, that now separates Lloyd Neck and Eatons Neck from older glacial topography to the south.

As the ice front crossed the East River lowland, it deposited a minor recessional moraine at the City Island-South Bronx position, traceable at least to Central Park. By 19,000 years, the ice front reached the White Plains-Dobbs Ferry margin, where a delta of ice-contact sand, gravel, and till nearly 25 m thick was deposited into the eastern shore of Glacial Lake Hudson. Subsequently, the ice receded to a still stand along the present Croton River-Croton Reservoir Valley. Here, meltwater flowing into Lake Hudson deposited the prominent Croton Delta, a remnant of which still protrudes into the Hudson.

At the next ice margin, a delta, now concealed by downtown Peekskill, completes the northward recession of the ice to the southern edge of the Hudson Highlands and the opening of the fjord (Sirkin et al., 1989; Sirkin, 1999). Here, the ice simultaneously downwasted over the mountains and through the gap to establish an ice margin and a moraine, the Shenandoah Recessional Moraine,

along the northern edge of the Highlands (Fig. 2.3; Connally and Sirkin, 1986). As the ice withdrew, further Glacial Lake Hudson expanded northward through the fjord to become Glacial Lake Albany.

The pattern of formation of ice margins, recessional moraines, and deltas continued into the mid-Hudson Valley where deltas were deposited into both sides of the lake (at Cold Spring, Moodna Creek, Marlboro, Milton, Hyde Park, Rhinebeck and Red Hook). About 17,200 years ago, the receding glacier stood long enough to build the Walkill-Poughkeepsie Moraine (Fig. 2.3) and then the Hyde Park, Pine Plains, and Red Hook moraines (Fig. 2.3), and the Rhinebeck and Red Hook deltas at an elevation of 60 m. Identification of ice margin position on the west side of the valley corresponding to the Red Hook stand is complicated by the first reversal in the trend of recession, the Rosendale readvance. The ice readvanced several kilometers, deforming lakebeds and depositing till around 16,100 years ago.

Glacial Lake Albany continued to expand and deepen behind the ice, leaving lake clays and shoreline deposits at elevations around 100 m (Dineen, 1986), although the stagnating glaciers in Catskill valleys dammed meltwater as high as 400 m. Ice margins formed at Woodstock, Cairo, and Middleburg (Fig. 2.3) before a second readvance of the glacier, around 15,500 years ago, overrode minor recessional moraines to form drumlins. The higher lakes drained into Lake Albany at an elevation of 100 m through a succession of tunnels in the stagnant ice; the meltwater depositing esker-like ridges (LaFleur, 1979). Later, ice margins developed at Ravena and Altamont before a final readvance in the Albany basin that overrode and deformed lakebeds near Delmar. At the next stand at the Schenectady ice margin, with the lake level at about 95 m, a delta nearly 20 m high was deposited from the west by the Mohawk River drainage. In all, up to 100 m of laminated lake silts and clays now fill the basin of Lake Albany (Cadwell and Dineen, 1987).

As the ice front receded and Lake Albany expanded northward toward present day Lake George, melt water was impounded in tributary valleys of the Adirondack foothills by both ice and moraines (Connally and Sirkin, 1971). Proglacial lake sediments and morainal segments cut across

the valley and occur along several tributaries of the Hudson north and west of Warrensburg.

Postglacial Environments

Sediment cores taken from several bogs between Long Island and the Champlain Valley recorded the northward migration of eastern forests following the shrub-tundra and park tundra zones over deglacial terrain (Sirkin, 1977). In the vicinity of the terminal moraine, spruce forests replaced tundra around 18,000 years ago, as climate changed from very cold to cold and moist. Spruce forests reached the mid-Hudson Valley only 2,000 years after the ice left, the northern Hudson Valley less than 1,000 years after the ice, and the Champlain Valley only a few hundred years later. Between 11,000 and 9,000 years ago, warm and dry conditions favored the succession of pine forests. Spruce species migrated northward and into higher and wetter habitats, while pine colonized the well-drained outwash and lake plains of the valley. From 9,000 to 7,000 years ago, oak forests associated variously with pine, hemlock, and hickory overtook the pine-dominated forests as climate cooled.

Sea level rose to establish estuarine conditions in the Hudson. Around 12,000 years ago, the sea flooded into the Hudson Valley through a gap eroded into the terminal moraine across Long Island and Staten Island. The post-Lake Albany lakes in the Champlain Valley must have drained between 12,000 and 11,000 years ago. The river was tidal to Peekskill by 12,000 years before present and estuarine conditions reached Manhattan by 10,280. Salt marsh deposits in the Hudson estuary date from around 11,000 years ago (Newman, 1977), about the same time the sea flooded the Champlain and St. Lawrence valleys.

The estuary retreated slightly around 9,000 years ago but by 7,000 years before present estuarine conditions had reached as far north as Nyack. The estuary reached its maximum northern extent at Peekskill about 6,000 years ago. It has been receding since, perhaps due to sedimentation or continued climate change.

Postglacial Geologic Processes

After the Laurentide ice receded north of the St. Lawrence lowland over 12,500 years ago and local

ice melted out of the cirques, very cold conditions, along with high winds and permafrost, persisted in the northern Hudson region. Ice still gripped the glacial soils and wedged into joints in the bedrock, loosening shed-sized angular blocks. The homogeneous, anorthosite domes developed curved sheets of rock decimeters thick at the surface. The sheets cracked into large angular plates along joint planes perpendicular to the surface, in a process known as exfoliation. The rock slabs continue to be prime candidates for sudden rockslides, and the ground-level bases of the domes are surrounded by this very coarse debris strewn over the talus slopes.

Ice-wedging is a common cause but earthquakes are also causative factors in debris slides, and they may be connected to groundwater problems. Earthquakes occur along ancient faultlines and trigger failure of unstable slopes and slumping of coastal plain sediments far from any earthquake's epicenter. Renewed movement and seismic activity in recent times has been linked to postglacial rebound in which stresses in the differentially rising crust are relieved along faults. In addition, industrial and suburban development along fault lines has led to increased use of groundwater and disposal of wastewater into the ground, as well as destabilization of slopes and excavation of bedrock for superhighways and residential and industrial construction sites. All of these factors can have a negative impact on fault line stability and lead to increased activity.

Rock and Mineral Resources

For over 250 years, the Valley has been exploited for earth materials, dating from the incipient iron industry of the early 1700s in the Hudson Highlands to the present need for aggregate and building materials (Hartnagel, 1927).

Of the metallic minerals, iron was the first to be mined from early scrapings of bog iron in wetlands to exploiting concentrations of magnetite, found mainly in veins cutting through the Proterozoic metamorphic rocks of the Hudson Highlands (Hurlibut, 1965). Iron was important to the Colonial economy as early as the 1750s. During the Revolutionary War, iron mines like the Sterling mine in Orange County supplied the forges of the American Army with the raw material for cannon

and ball, as well as the links for a chain to span the Hudson at West Point and block British naval advances (Isachsen, 1980). The emery is used for abrasives, and pyrite, an important source of sulphur, came from mines in the lenses and veins in the mafic Cortlandt complex rocks near Peekskill.

Magnetite mines opened in the Adirondacks in the early 1800s (Schneider, 1997). The northern mines became major sources of iron and titanium derived from magnetite and ilmenite deposits. While magnetite supplied the steel for heavy industry, ilmenite, limonite and other iron compounds were used mainly for paint pigment. Limonite, found as an iron oxide crust, was mined in Dutchess and Columbia counties early in the 1700s.

Other minerals associated with metamorphic rocks are graphite, garnet, and zircon. Graphite is mined in the Adirondacks near Ticonderoga and is used in making 'lead' pencils. Real lead is found in disseminated masses in sedimentary rocks in the Shawangunk Mountains southeast of the Catskills.

Garnet has been mined since the nineteenth century from the mountains bordering the Hudson gorge near North Creek in the Adirondack Town of Johnsburg (The Editorial Committee, 1994). It occurs as large, attractive, dark reddish-purple crystals accented by a halo of white feldspar in a matrix of black hornblende schist. While enticing in their size and color, the crystals are generally fractured, and only occasionally are gem-caliber specimens encountered. Garnet has been quarried for use in industrial abrasives. Zircon of gem quality is found in Orange County mines.

A great variety of whole rock products have been exploited in the Hudson watershed, taken from the earth where found or wherever convenient. Granite and gneiss have been quarried in the Highlands and Adirondacks, and anorthosite in the northern mountains. Quarried blocks were used as riprap on steep slopes, and glacial boulders support earthen walls and line roadways. Stonewalls were built of cobbles hauled from cornfields, while crushed rock is used for road fill and in gabions. Large-sized crystals of feldspar and mica have been taken from coarse-grained pegmatite dikes that cut across the metamorphic rocks of the Highlands: the feldspar is used in insulators and the mica formed the 'isinglass' windows in furnace doors. Crushed basaltic rock, mainly from quarries in the Palisades and the

Cortlandt Complex rocks, is the 'trap rock' in most railroad beds, selected for its crushing strength and durability. The product continues to be in demand.

Of the metamorphic rocks, the Inwood Marble and the Fordham Gneiss were quarried in Westchester County for facing stone to adorn high-rise buildings in Manhattan. White marble also comes from the marble belt east of Albany. Lower grades of marble wind up in sacks of ground and slaked lime for lawns and agriculture soil enrichment. The slate belt of eastern New York's Taconic range parallels the marble trend in Washington County. European slate miners crafted an enduring industry in slate products for roofing, walkways, and floor tiles.

Sandstone slabs and blocks are derived from beds of the Cambrian Period, Potsdam Sandstone, that border the Adirondacks. Taking advantage of the natural rectangular jointing of the bedrock, sandstone could be readily worked into facing and foundation stone. Red sandstone from the Newark Basin also shows up in older structures in the southern part of the valley, and crushed red sandstone gravel decorates creative gardens and driveways. Devonian-age flagstone, a uniformly fine-grained gray sandstone (a variety of which is the Catskill 'bluestone') was quarried and split into thin slabs for the sidewalks of northeastern cities.

While many mineral mines have closed, the sand and gravel and limestone-marble quarries prevail. The limestone formations, the Ordovician Trenton limestone, Silurian-Devonian Helderberg Formation, and the Devonian Onondaga limestone of the escarpments of the mid-Hudson region (Isachsen et al., 1970) became the walls of many colonial homes, such as the Huguenot cottages near New Paltz. The chemical nature of the Silurian-Devonian rock provided a basis for the Portland cement industry that flourished in the valley. Coal was not available as a local commodity. Colonial iron had been concentrated with charcoal because the thin coal seams in the Catskill delta, evidence of small Devonian swamps, were not enough to sustain smelting. Similarly, peat was not a major energy source.

Special use sediment of different grades supplied other building industries. Fine sands were used for molds, pure quartz for glass, and clay for bricks and ceramics. The brick industry thrived in scores of factories turning clay, from the Cretaceous-age

Raritan clays of Staten Island to Glacial Lake Hudson and Albany clays all the way to Glens Falls, into stone-hard building blocks.

All of these rocks and minerals, are, or have been, essential to the economy, but mining of earth materials has created a number of environmental hazards ranging from the variety of excavations – gapping and hidden holes in the ground, hollowed-out mountains, and forgotten subsurface rooms – to waste products, such as mine tailings, slag dumps, acid waters, acid rain, and air pollution, as well as sediment clogged streams. It was not until the 1970s that State and Federal environmental agencies began to require mine restoration and clean up and closure plans. But by then, many mines were grandfathered or abandoned, went out of business, or were converted into landfills. Today, the New York State Department of Environmental Conservation issues mining permits and monitors development, changing use, and closure plans.

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