DUKE GEOLOGICAL LABORATORY

Web: www.dukelabs.com
E-Mail: CharlesM@dukelabs.com

TRIPS ON THE ROCKS

Guide 02: Hudson Highlands and Bear Mountain, New York

Trip 02: 22 October 1988; Trip 14: 28 October 1990; Trip 30: 21 May 1994

Figure 1 – Physiographic sketch map of the Hudson Highlands and the Newark Basin showing the course of the Hudson River. (Drawn by Jack Fagan.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

CONTENTS

DUKE GEOLOGICAL LABORATORY

TRIPS ON THE ROCKS

Guide 02: Geology of the Hudson Highlands and Bear Mountain, New York

Trip 02: 22 October 1988
Trip 14: 28 October 1990
Trip 30: 21 May 1994

INTRODUCTION

The Hudson River and its surrounding valley have long been enjoyed by writers, artists, historians, naturalists, and vacationers whose accolades have spread far beyond the course of the majestic waterway. Named after the explorer Henry Hudson, the river divides the eastern edge of New York State from its headwaters in the Adirondack uplands southward more than three hundred miles to its mouth in Upper New York Bay (Figure 1). The locus of dramatic battles that turned the tide of the American Revolution, the Hudson harbors a deep, rich military history. Of scientific interest, the river cuts southward through a series of geologically distinct belts or physiographic provinces (Figure 2). Our field trip along the Hudson River valley will take you back in time across terrains that formed as recently as 10,000 to 18,000 years ago, upon those that were formed more than a billion years ago! During the trip, we will point out the evidence geologists use to explain the presence of former oceans and mountain ranges in the region. So sit back, relax, enjoy the view, and look through this guidebook which will unravel the complex geology and history of the Hudson River valley.

Part 1 of this guidebook details the rich pre-Revolutionary and Revolutionary War history of the Hudson River valley in a series of summaries, maps, and charts. Some of the forts and battlegrounds mentioned in the following pages will be seen or visited today.

Part 2, which concentrates on the geology of the Hudson River Valley, is arranged to discuss the geologic background of the region and provide a road log and descriptions of the six planned sites (called stops) we will examine in detail. Through the aid of sketches, index maps, geologic maps and cross sections (collectively called figures in the text), you can follow the field trip along each step of the way. The diagrams herein have been collected from numerous articles, books, and field-trip guidebooks published by us, our geological colleagues, and also by historians.

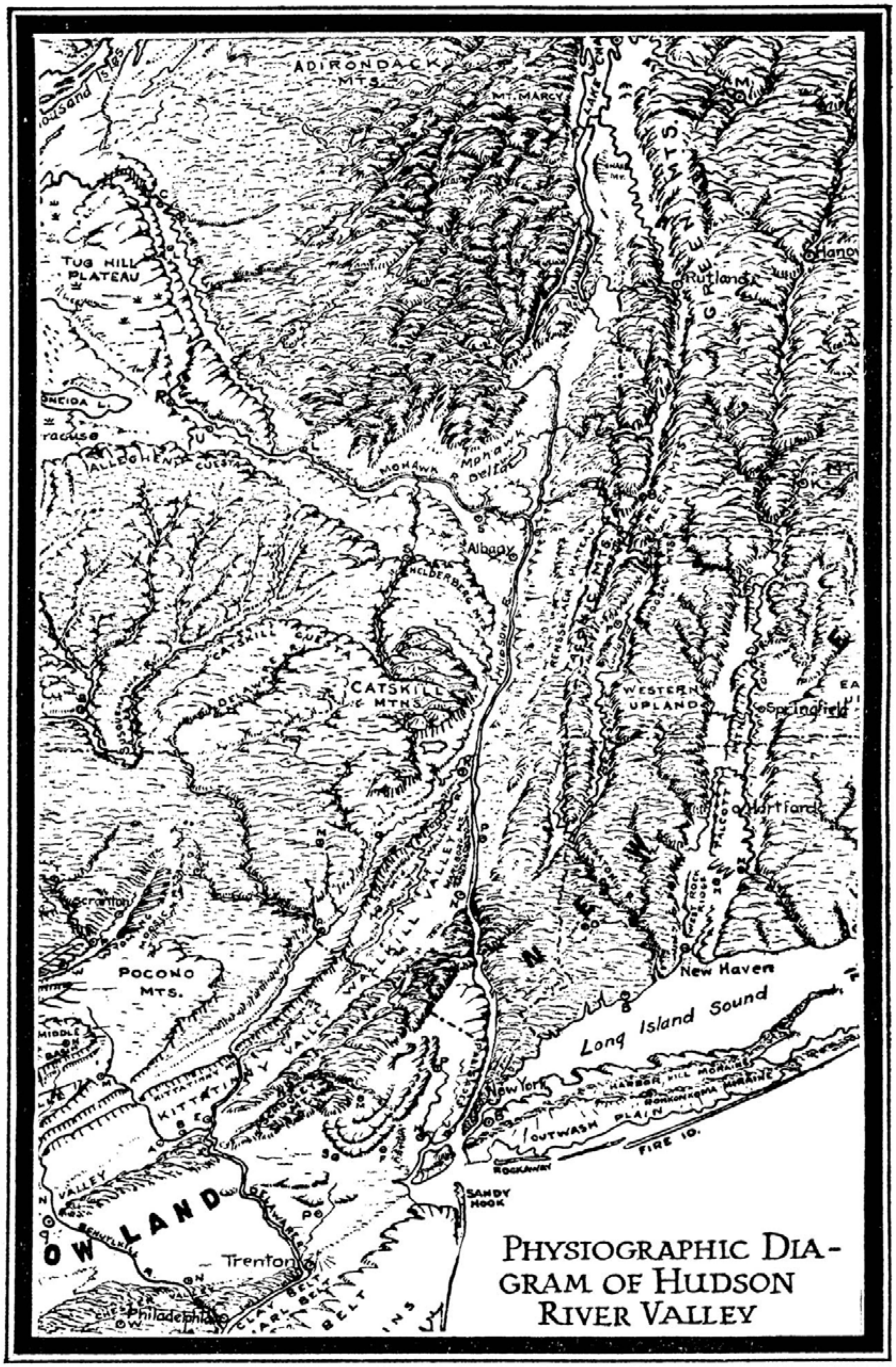


Figure 2. Physiographic diagram of the Hudson River Valley. (Drawn by E. Raisz).

PART 1 - HISTORICAL BACKGROUND

FACTS ABOUT THE HUDSON RIVER BASIN

EARLY EXPLORATION: What we now refer to as the Hudson River was known to Indians living along its shores as "Shatemue" (meaning the river that flows in two directions). European peoples first became aware of this magnificent river in 1524, when Giovanni di Verrazano, an Italian explorer who sailed under the flag of Francis I, King of France, found its mouth. On 03 September 1609, Henry Hudson, an English sea captain, working for the Dutch East India Company, sailed his vessel the "Half Moon," into lower New York Harbor. Hudson navigated and explored upstream as far as present-day Albany--the first European to explore the river upstream. (That same summer, Champlain was working southward through Lake Champlain and Lake George. They never met, but at one point were within a day's journey of each other.) On 04 October, the "Half Moon" set sail for its base in Texel. Hudson called the river the "Great River of the Mountains." His Dutch employers named it officially "River of Prince Mauritius"; later it bore the name "North River." Eventually, it was named Hudson after Henry Hudson. [On 07 November 1609 Hudson returned to England at Dartmouth, where his ship "was seized and detained by the English government, Hudson and the other Englishmen of the ship being commanded not to leave England, but rather to serve their own country"--In 1610, Hudson was back again on this side of the Atlantic, exploring Hudson Bay in the "Discovery." They became wintered in in the SW corner of James Bay. Early in the spring of 1611, under the prodding of Henry Greene, a mutiny took place and Hudson and 8 others, including the sick men, were left ashore to shift for themselves; the "Discovery" headed back to England. "During the voyage home Greene and several others were killed in a fight with the Eskimo, while (sic) others again died of starvation, and the feeble remnant which reached England in September were thrown into prison. No more tidings were ever received of the deserted men."--EB 11th ed.) A summary of Henry Hudson's voyage is presented in the 11th edition of the Encyclopedia Britannica and in Diamant (1983).

HEADWATERS: The highest source of water into the Hudson network comes from Lake Tear of the Clouds, high on the slopes of Mount Marcy, in the Adirondack Mountains, Essex County, New York (Figure 2). Water from Lake Tear of the Clouds flows into Feldspar Brook, which drains into Opalescent River. About 10 miles from Lake Tear, the Opalescent River joins what the maps show as the Hudson River, a stream coming from Sanford and Henderson lakes (Boyle, 1969, p. 69-71), on the Santanoni 15-minute quadrangle.

MOUTH: Upper New York Bay at 40°42'N latitude, and 74°02'W longitude.

MAJOR TRIBUTARIES: Sacandaga, Mohawk, and Wallkill Rivers. The Sacandaga, which has been dammed to form the large Sacanda Reservoir, enters at Luzerne. Starting at Corinth, about 4 miles S of Luzerne is Palmer Falls Dam, the first of series of 10 dams that have been built on the upper river for water power and/or navigation. The largest tributary is the Mohawk, which joins the Hudson at Cohoes, just upstream from the Federal Dam and lock at Troy. From Fort Edward to Troy are 7 dams and locks that form part of the Champlain Barge Canal system built and maintained by the State of New York. (New York is the only state with its own private canal system not operated by the U. S. Corps of Engineer as are interstate navigable waters.) The major tributary in the lower Hudson basin is the Wallkill River, a remarkable barbed tributary that flows northeastward from northern New Jersey and enters the Hudson at Kingston.

SMALLER TRIBUTARIES: In the upper Hudson basin, the Schroon and Hoosic Rivers; and in the lower Hudson basin, the Schoharie, Kinderhook, and Rondout Creeks.

COURSE: From its source, 4,322 feet above sea level, in the wildest part of the Adirondacks, the river winds for more than 100 miles in an irregular south-southeasterly direction to Corinth, then east to Glens Falls and neighboring Hudson Falls. Starting at Glens Falls the river passes many industrial facilities. Two of these, one at Hudson Falls and the other at Fort Edward, are capacitor-manufacturing plants of the General Electric Company, from which PCBs were flushed into the river during the period 1950 to 1977. From Hudson Falls to Fort Edward, the river occupies a narrow, steep-sided gorge, which is a retreat track formed by the upriver migration of Bakers Falls. From Bakers Falls, the river flows almost directly south for 45 miles to the head of the tide at the Federal Dam at Green Island, Troy, 150 miles above its mouth.

South of Troy, the river passes through farming- and industrial areas. About 60 miles south of Albany, it enters the colorful Highlands region at Storm King. For 16 miles, it zig zags through a narrow valley with high and rocky shores of great beauty. The river is sometimes called the "Rhine of America," because the rocks of the Highlands resemble the huge castles on the banks of the Rhine. The Hudson leaves the Highlands at Peeksill. Farther south, along its west bank, the river is bordered by majestic cliffs, known as the Palisades, which it follows from Haverstraw to Hoboken, New Jersey. From Palisades, New York, southward to Staten Island, the west shore of the river is no longer territory of New York, but of New Jersey. At Hoboken, the Hudson bends to the south, away from the trend of the Palisades, passes Jersey City, New Jersey, and then, opposite the southern tip of Manhattan Island, widens into upper New York Bay.

LENGTH: The river travels 306 miles, almost entirely within New York State. Of 135 U. S. rivers that are more than 100 miles long, the Hudson ranks 71st in length.

WIDTH: The maximum is about 3.5 miles at Haverstraw Bay; seldom more than 1,000 feet near midpoint at Troy; approximately 1 mile at its mouth.

DEPTH: Deepest point -200 feet near West Point; navigable channel depth of 32 feet is maintained by U. S. Army Corps of Engineers in the 143-mile tidal section between Albany and New York City; the Hudson-Champlain division of the New York State barge canal is designed to accommodate barges 43.5 feet wide, 300 feet long, and having a maximum draft of 12 feet.

RATE OF FLOW: At Waterford, just north of the confluence with the Mohawk, the mean flow is about 7500 cubic feet (250 cubic meters) per second. At Green Island, Troy, just south of the confluence with the Mohawk, the mean flow is about 15,000 cubic feet (425 cubic meters) per second, about 6 million gallons per minute. At the mouth, 9 million gallons per minute.

HIGHEST AND LOWEST FLOW: In 1913, greatest flood since 1846 at Albany; lowest annual flow in at least 44 years occurred in 1965. The value of the 100-year flood is 50,000 cubic feet per second at Fort Edward, about 110,000 cubic feet per second at Waterford, and about 220,000 cubic feet per second at Green Island (Darmer, 1987 ms.)

WATER QUALITY: The Hudson estuary is defined by most as extending northward as far as Troy, the tidal reach. But the northern tip of the saltwater wedge ranges back and forth between Poughkeepsie, at low flows, and the Tappan Zee Bridge, in floods. A typical position for this wedge is near Peekskill. North of Poughkeepsie, the Hudson's water is generally soft and slightly alkaline. In upper basin, north of Luzerne, the Hudson's water is potable even with minimum treatment. Cities that tap into the Hudson for drinking water are Waterford and Poughkeepsie; they are obliged to give it full treatment. The water is brackish below Poughkeepsie and saline below Peekskill.

In 1975, New York State Department of Environmental Conservation Commissioner Ogden Reid responded to the high levels of PCBs found in the fish by closing the entire fishery in the upper river and the commercial striped-bass fishery in the estuary. Although PCB values in fish declined in the interval 1977 (when the General Electric Company stopped its PCB discharges, and after New York State carried out two massive dredging operations near Fort Edward in 1975 and 1978) through 1982, the level in the striped bass still exceeds 2 parts per million, the amount above which the U. S. Food and Drug Administration bans fish in interstate commerce. Since 1982, the levels of PCBs in the striped bass have fluctuated with water discharge. (For a history of the PCB problem up to August 1989, see Sanders, 1989a.)

In 1990, the US EPA Region II began its thorough re-evaluation of its initial Superfund finding in which the eating of PCB-contaminated fish was declared not to be a human-health hazard. This first finding has now been reversed, and EPA is nearing completion of its total scientific re-analysis of the problem of PCB-contaminated sediments in the upper river. The General Electric Company has capped the remnant deposits, going well beyond the strictures laid on by EPA's Superfund I findings. In the summer of 1993, GE's monitoring contractor discovered that what had been referred to as the "mystery source" of PCBs north of Fort Edward was coming from parts of the GE properties that had never been cleaned up from their PCB-spillage days. New York State DEC and GE have reached a settlement about GE's remedying this newly discovered source of PCB's from GE to the river. It will be interesting to see how the river reacts after this new GE cleanup has been completed. For 17 years, everybody thought that GE's PCBs were no longer continuing to enter the upper Hudson River. In 1994, that condition may finally be attained.

DAMS, RESERVOIRS, AND CANALS: Croton, Rondout, Ashokan, Schoharie, Sacandaga, Hinckley, Delta, and Indian Lake Reservoirs; Federal Dam at Troy. Erie Canal still used between Rome and Albany and the Champlain Canal between Albany and Fort Edward near Glens Falls (both are part of the New York Barge Canal).

GEOLOGIC SETTING: The Hudson River Basin lies in six physiographic provinces; Piedmont, New England, Valley and Ridge, St. Lawrence, Adirondack, and Appalachian Plateau. The entire Basin has been covered one or more times by continental glaciers and the valleys are floored with deposits of glacial sand, -gravel and -clay. The northern part of the Basin is densely forested and contains many lakes and streams. Several of the Adirondack Mountain peaks are more than 5,000 feet high. Below Albany, the land becomes open country except where the rugged hills of the Catskills and the Hudson Highlands cut across the Hudson Valley. South of the Highlands, the Basin is again open country, except along the outcrops of igneous rocks that form the high cliffs of the Palisades. The geologic history of the Hudson Estuary has been summarized by Sanders (1974a).

A PLAGIARISED HISTORY OF FORT MONTGOMERY AND FORT CLINTON, NEAR BEAR MOUNTAIN, NEW YORK

Forts Montgomery and Clinton were erected to stand guard in the Hudson River Highlands 45 miles north of New York City, five miles south of West Point. These two forts, called the Twin Forts of the Popolopen, were constructed during 1776 and 1777 (Figures 3, 4). The strategic importance of the Hudson River was recognized early in the conflict between the American colonies and Great Britain. Every road connecting New England with the other colonies crossed the Hudson River at some point. The Hudson River was also important as a means of transportation from the St. Lawrence through Lake Champlain and southward to the Atlantic Ocean at New York City (Figure 3). The colonists realized the necessity of keeping control of the river and preventing the separation of the colonies by the British.

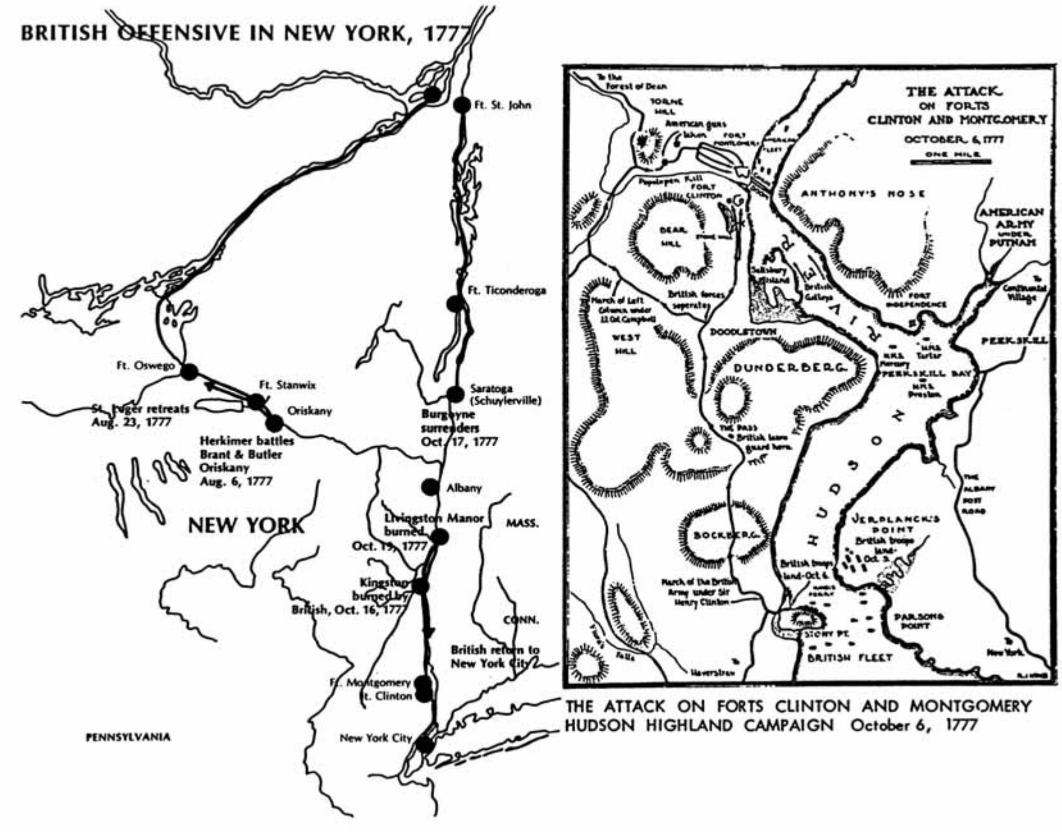


Figure 3. Sketch maps showing the three-pronged British offensive of 1777 and the attack on Forts Clinton and Montgomery.

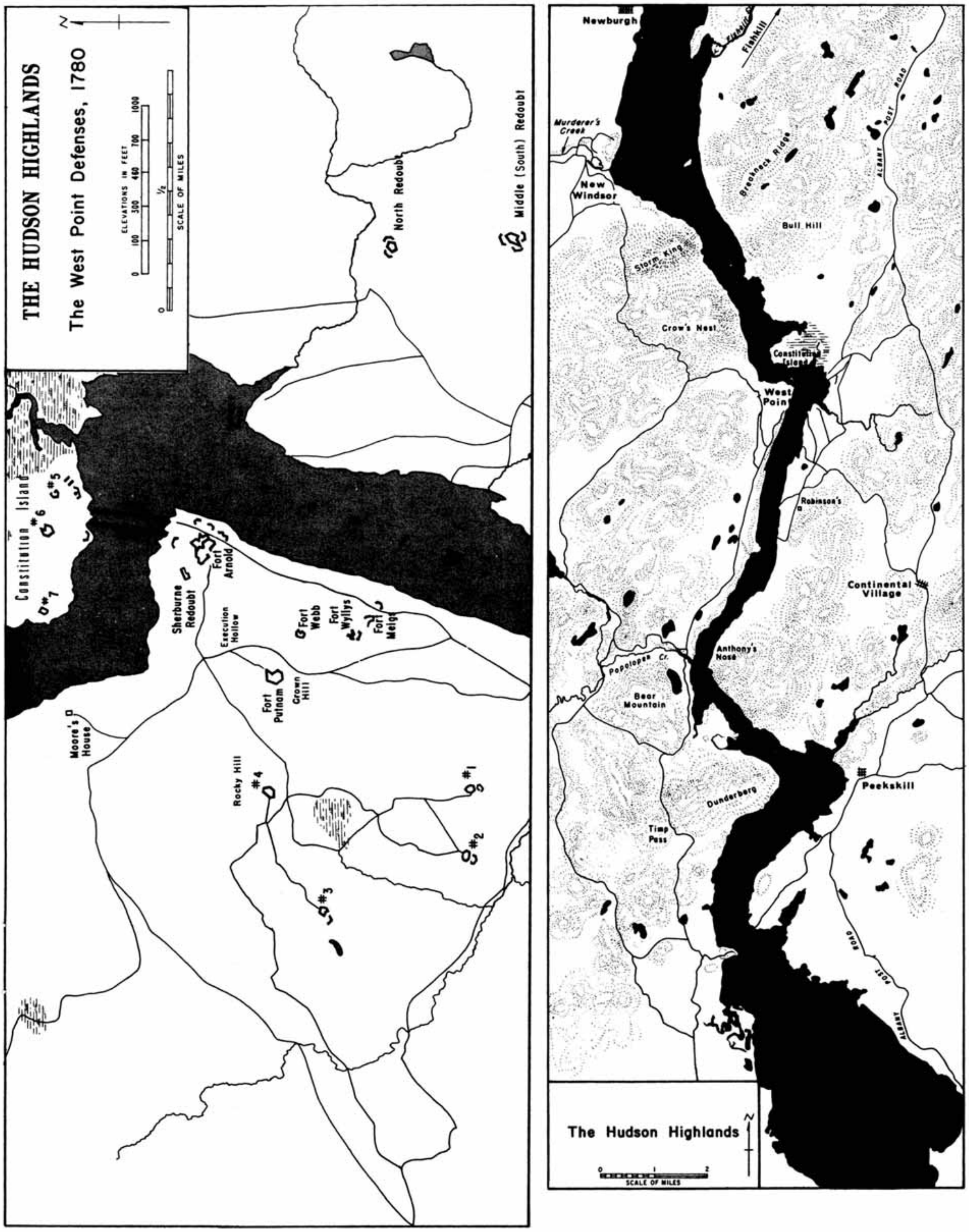


Figure 4. Sketch maps showing the West Point defenses of 1780 and the course of the Hudson River through the Highlands.

On May 25, 1775 the Continental Congress in Philadelphia ordered the erection of fortifications in the Hudson River Highlands and directed Colonel James Clinton and Christopher Tappan to report to the Congress upon such fortifications. Clinton and Tappan recommended the erection of fortifications of the east and west sides of the river in the vicinity of West Point and Constitution Island (Figure 5). Fortifications were begun on Constitution Island, but later the commissioners recommended placing a strong battery five miles to the south at Popolopen Creek. Thus, in March 1776, construction of Fort Montgomery was begun because of its strategic location where it "would command the reach of the river downward to the point of the Dunderbarragh, being the distance nearly three miles, and from the same point the reach upwards may be commanded as far." As work on Fort Montgomery progressed it became obvious that the higher land on the south side of Popolopen Creek had an even greater strategic location and work was begun on a fort in that location.

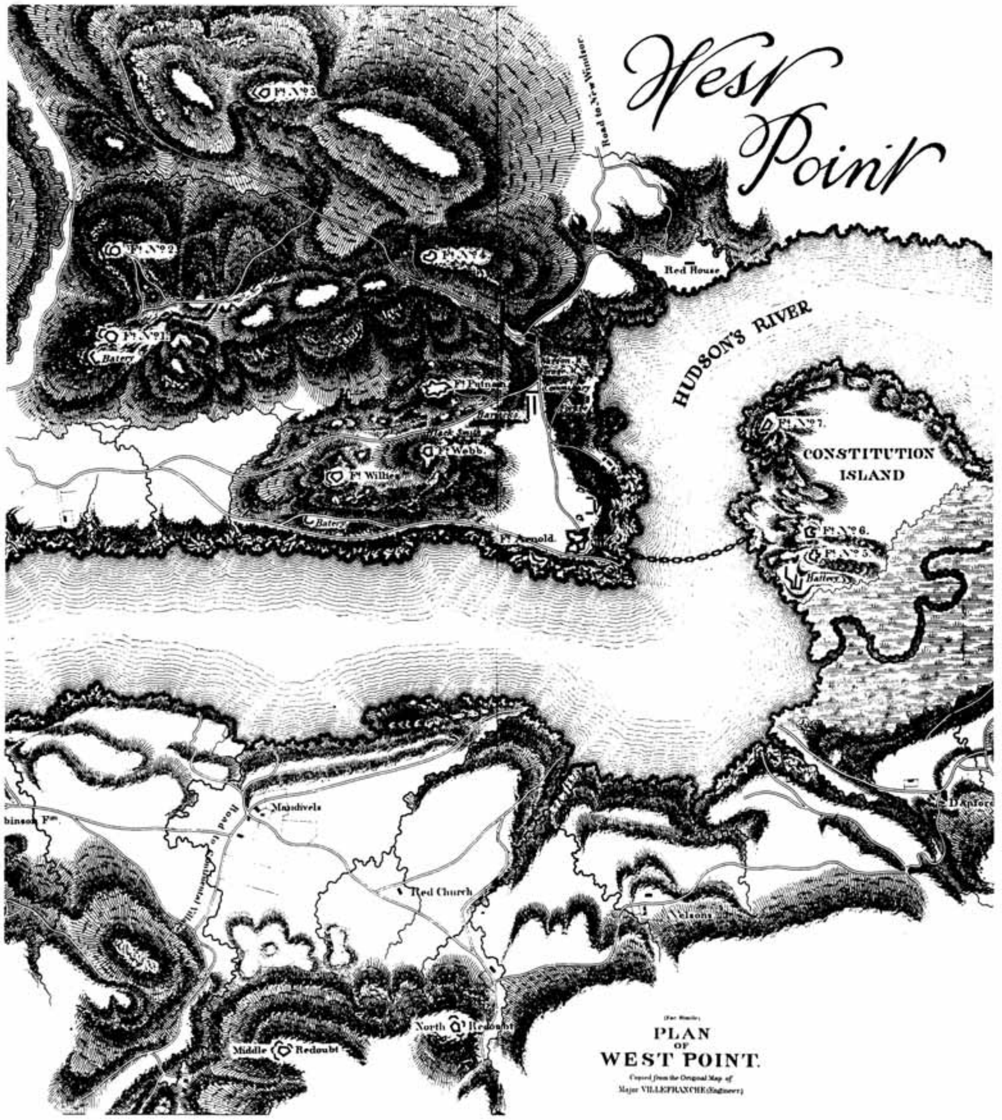


Figure 5. Revolutionary War map of the fortification plans for West Point as drawn by Major Villefranche, engineer.

On August 27, 1776, the Americans lost the Battle of Long Island and withdrew to Manhattan Island. On September 16, the Battle of Harlem was fought and thereafter the British slowly but surely crowded the Americans northward, and New York City became the headquarters of His Majesty's forces under Sir William Howe.

The summer of 1777 was a time of crisis in New York because of a 3-pronged plan of invasion:

- St. Leger moved eastward through the Mohawk Valley towards Albany;
- Burgoyne moved southward through the Hudson Valley toward Albany;
- Howe was to move northward through the Hudson Valley toward Albany. General Howe sailed to Philadelphia, however, leaving Sir Henry Clinton in command in New York.

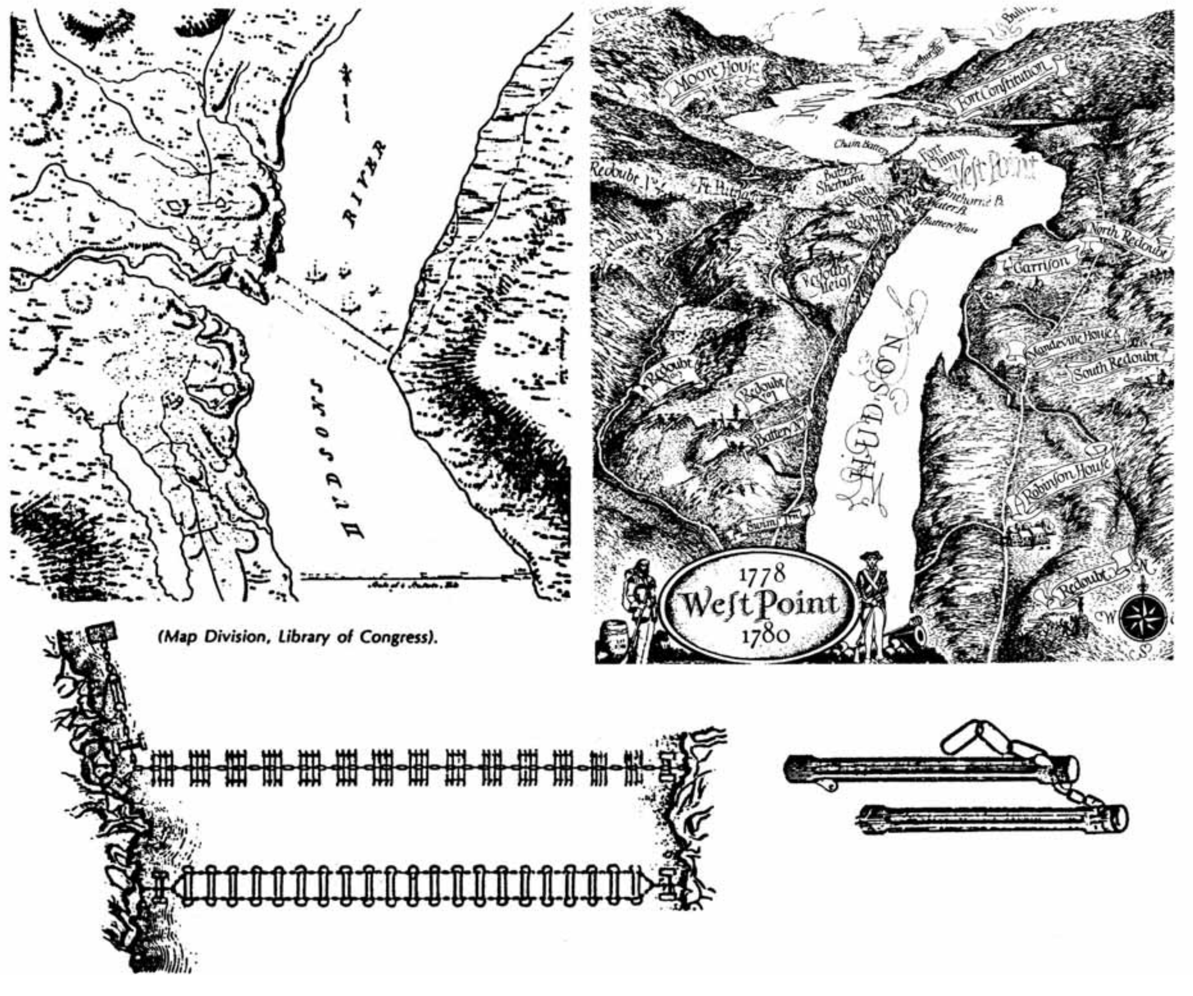
Sir Henry Clinton made plans for a thrust up the Hudson. On the night of October 3 and the morning of the 4th, he proceeded as far as Tarrytown where a landing was made. On October 5, he landed at Verplanck Point as a menacing gesture toward Putnam at Peekskill.

Early on the morning of October 6, Sir Henry Clinton landed a large number of troops at Stony Point for a march through the mountains to attack Forts Montgomery and Clinton from the rear. Early in the afternoon, The British forces under Generals Campbell and Vaughn and Sir Henry Clinton himself "invested Forts Montgomery and Clinton on all sides." For three hours the 500 to 600 defenders remained at their posts behind the protecting works of Forts Montgomery and Clinton. At five o'clock, the British called a truce and asked for surrender. The Americans replied that Forts Montgomery and Clinton would be defended and called, instead, for the surrender of the British. Ten minutes later the British launched a powerful attack. The attackers pushed their men up the fortifications where they were shot or bayoneted as the garrison beat them back. Despite their valiant efforts and the raucous cries of "Dee-fence, Dee-fence!" from the surrounding hills, however, the defenders were finally overwhelmed by the British forces several times their number. Under cover of darkness, less than half of the American defenders escaped.

The Americans had placed great confidence on chains and booms which were placed across the river (Figure 6). One of these was the great iron chain which was strung across the river at Fort Montgomery. Such devices, known by the French term chevaux-de-frise, were built of iron mined and refined in the Ramapo Range, NJ-NY (Ransom, 1966). The chains proved ineffectual, however, and a few days after the battle of the Twin Forts the British fleet sailed northward to Kingston and set fire to the whole town. Although the British won the batttle of the Hudson Highlands, they were too late to aid Burgoyne who surrended his entire army on October 16, the same day as the burning of Kingston. Sir Henry Clinton was ordered back down the river to New York City.

"Sir Henry Clinton's raid up the Hudson had been brilliantly executed; nevertheless, it had failed in its primary objective of relieving Burgoyne. It had resulted in the destruction of Forts Clinton, Montgomery, Constitution, and Independence. The great chain across the Hudson had been severed, and considerable amounts of American stores in the Continental Village, north of Peekskill, had been destroyed. The American fleet had been totally destroyed. Sixty-seven pieces of ordinance had been siezed with immense quantities of cannon shot, ammunition and powder in the two Popolopen forts. North of the Highlands the country along the river banks lay in shambles. Vessels on stocks had been burnt or captured. Kingston was in ruins; of over three hundred houses in the Town only one was left standing. The cheveaux-de-frise had proved a failure; the enemy fleet had sailed straight through it. In twenty days Sir Henry Clinton had undone everything the Americans had been laboring upon for more than two years. Destruction marked the location of every patriot post upon which the powerful blow fell. The dramatic history of the first set of fortifications in the Hudson Highlands drew to a close with the departure of the last British vessel in 1777."

In December 1777, on General Washington's initiative, work was resumed by the officers of the Continental Army and the State Legislature to plan new defenses in the Hudson River Highlands. West Point had become a citadel of such importance (Figure 6) that Benedict Arnold who was in command of the post, tried unsuccessfully to betray it to the British. The outer redoubt of Fort Clinton is in good condition and only traces remain at the other fortifications. The location of most of the Fort Montgomery fortifications can still be identified.



(Map Division, Library of Congress).

Figure 6. Sketch maps showing the positions of the heavy chains stretched across the Hudson in the late 1700s and a plan map of the Forts and Redoubts of the Hudson Highlands.

A BRIEF HISTORY OF EUROPEAN/AMERICAN INVOLVEMENTS WITH THE HUDSON RIVER

1524 April 17 - Giovanni di Verrazano sails the French vessel "Dauphine" into New York harbor at the mouth of the Hudson River.
1609 April 04-October 04 - Henry Hudson sails the "Half Moon," owned by the Dutch East India Company, up the Hudson River to Albany and back.
1624 May - First Dutch settlers arrive.
1700s - English settlers.
1756-1763 - Seven Years War ends when British kick the French out of India, thus cutting the French off from the best supply of saltpeter (a vital ingredient of gunpowder). French have to stop this war because they literally ran out of gunpowder.
1773 - Passage of Tea Act and Boston Tea Party.
1774 September - Continental Congress convenes in Philadelphia.
1775 April - British clash with colonists.
1775 May - Ethan Allen and Benedict Arnold capture Fort Ticonderoga near Lake Champlain.
1775 June - Continental Congress learns that the British intend to invade New England from Canada. On June 2, Colonel James Clinton and Mr. Christopher Tappan sent to consider fortifications of Hudson Highlands (e.g. - Stony Point, Verplanck's Point, Popolopen Creek).
1775 June 24 - French king signs decree revoking the scandal-ridden private arrangement on French domestic saltpeter and establishing a government operation under the direction of four regisseurs (administrators): Lafacheux, Clouet, Barabault de Glattigny, and Antoine Lavoisier, the renowned chemist. Chief Minister Turgot asks help from the Royal Academy to unravel the secret of saltpeter; vows a French "Project Independence" on saltpeter. (Saltpeter is a nitrate, and the two varieties involved in gunpowder are potassium nitrate, the kind formed naturally in India, and calcium nitrate, the kind the French could obtain from scraping their stable walls, places where animal urine had reacted with the calcium of the plaster to form calcium nitrate.)
1775 - Construction begins of Fort Constitution (Constitution Island) across from West Point.
1775 - George Washington (appointed by Continental Congress) attacks British in Boston. The British regroup in Nova Scotia under General Sir William Howe.
1775 November - Representatives of Congress inspect Fort Constitution and find it unsatisfactory for stopping British forays into the Hudson River.
1776 May - Forts Clinton and Montgomery under construction. Chain established across Hudson between Fort Montgomery and Anthony's Nose but it does not hold up.
1776 June-July - General Howe and army begins to arrive in New York City and push Washington and army (intact, however) northward. British anchor at Tappan Zee out of range of colonists.
1776 September - Battle of Harlem Heights won by Washington.
1776 September 2 - Fire devastates New York City; more than 400 buildings burned. On September 22, the British hang Nathan Hale, an arson suspect.
1776 October - British ships slip past Forts Lee and Washington. On 28 October, Howe attacks Washington in White Plains but is repelled. Washington slips away November 1st.
1776 November 16 - Fort Washington in New York City is attacked. Last Patriot bastion in New York City. Year ends with British in control of the city but Patriots hold Fort Ticonderoga and most of the Hudson Highlands.

1777 March - British attack Peekskill supply area and retreat to New York City. Civil War erupts in Westchester between Patriots ("skinners") and Tories ("cowboys").
1777 April - New York Constitution proclaimed in Kingston, NY.
1777 - Lavoisier issues instruction on the establishment of nitrate works for refining saltpeter. By July 1777, he reported satisfactory progress in improving the harvest.
1777 - London plans three-pronged attack from Canada (General John Burgoyne southward from Fort St. John and a second army under Barry St. Leger southeastward along the Mohawk River from Ft. Oswego) and a northward attack form New York City by Howe. The armies plan to converge near Albany but Howe decides to attack Philadelphia first (a colossal blunder from the British standpoint!).
1777 August 23 - St. Leger is defeated and retreats from Fort Stanwix.
1777 October 6 - Sir Henry Clinton takes over Stony Point and then splits forces to the west and east of Bear Mountain. He captures Forts Montgomery and Clinton.
1777 October 8 - Clinton forces rebels to flee Fort Constitution without a fight.
1777 October 17 - Burgoyne surrenders at Saratoga and Howe sends for reinforcements for Philadelphia campaign which he is losing.
1777 November - Clinton orders destruction of Forts Constitution, Clinton, Montgomery and Independence.
1777 December - Europe impressed by Washington's activities. French declare war on British.
1778 January 20 - Construction begins at West Point. Engineer Thomas Machlin builds new chain between West Point and Constitution Island (April 1778). The iron was mined locally from the Ramapo Range in the Hudson Highlands, New York.
1778 - French domestic production of saltpeter rises to 1,800,000 kilograms, creating a surplus of high-quality gunpowder of the new Lavoisier "recipe" based on his new chemistry.
1778 July - Washington's army regroups in White Plains and French join rebels forcing Howe to abandon plans for Philadelphia.
1779 - British campaign to draw rebels into final decisive battle of Hudson River valley. Full fortification is in place at West Point.
1779 June 1 - General Clinton captures Stony Point and Verplanck's Point thus cutting main new England supply line for patriots.
1779 July 15\16 - Successful and stealthful night attack by General "Mad Anthony" Wayne catches British by surprise at Stony Point. Fierce but brief bayonet attack by American Light Infantry. Victory marks end of British activity in the Hudson Highlands, reopened commerce between New England and southern states, impressed foreign observers and rekindled faltering support of rebels.
1780 - Commander Benedict Arnold conspires to turn over West Point garrison to British in exchange for 20,000 Pounds (10,000 Pounds if plan failed).
1780 Sept 21 - Arnold gives fortification documents to Major John Andre at Dobbs Ferry but Andre, who sheds British uniform in stealth, is captured by three rebel militiamen near Tarrytown.
1780 September 25 - Arnold, while awaiting Washington and dining with Washington's advance officers, learns of Andre's capture and escapes. He later becomes Brigadeer General in British Navy and led attacks on Virginia and Connecticut. Died in England, an expatriot.
1780 October 2 - Andre hanged in Tappan but colonists mostly felt hatred for Arnold.

1781 Summer - Invalid Corps (formed in 1777) brought to West Point to help train new soldiers. General Clinton feared attack of New York City by Washington and French but they attack General Cornwallis in Yorktown, Virginia.
1781 Late - Washington retreats to Newburgh, New York to await negotiations.
1783 April - Almost two years later end of war announced.
1783 November 25 - Final evacuation of New York City by British and triumphant arrival of Washington.
1783 December 4 - Washington bids farewell to Patriots in Fraunces Tavern.
1789 - Lavoisier writes: "One can truly say that North America owes its liberty to French powder" (Multhauf, 1971, p. 173).

PART 2 - GEOLOGIC BACKGROUND

The scientific goal of this trip is to examine five (and possibly six) sites illustrating the varieties of bedrock on both sides of the Hudson River gorge in the vicinity of Bear Mountain, New York. For reference, the field-trip route is shown on Figure 7 and a geologic time scale, specific to the Hudson Valley, is shown in Table 1. Table 2 (also near the end of guidebook) is a detailed description of the stratigraphic units of southeastern New York. An article by Vaux (1983) summarizes the relationships between geologists of Columbia University and the Hudson River.

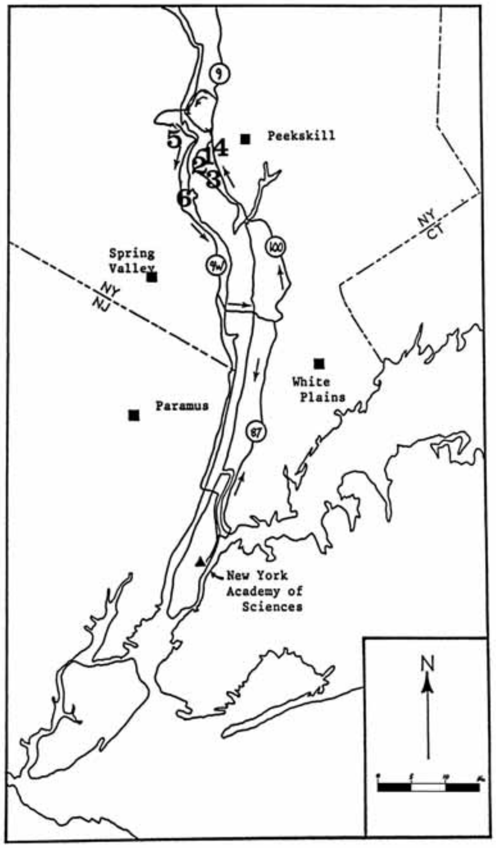


Figure 7. Road map sketch showing the locations of Stops 1 through 6.

The Manhattan Prong consists of highly deformed Paleozoic- and Proterozoic metamorphic- and igneous rocks. The Hudson River north of the Lincoln Tunnel bounds the Manhattan Prong on the west. Rocks of the Manhattan Prong are unconformably overlain by gently west-dipping Mesozoic reddish sandstone, siltstone, shale, and intercalated mafic volcanic- and shallow-level intrusive rocks that constitute the filling of the Newark Basin (Figure 8).

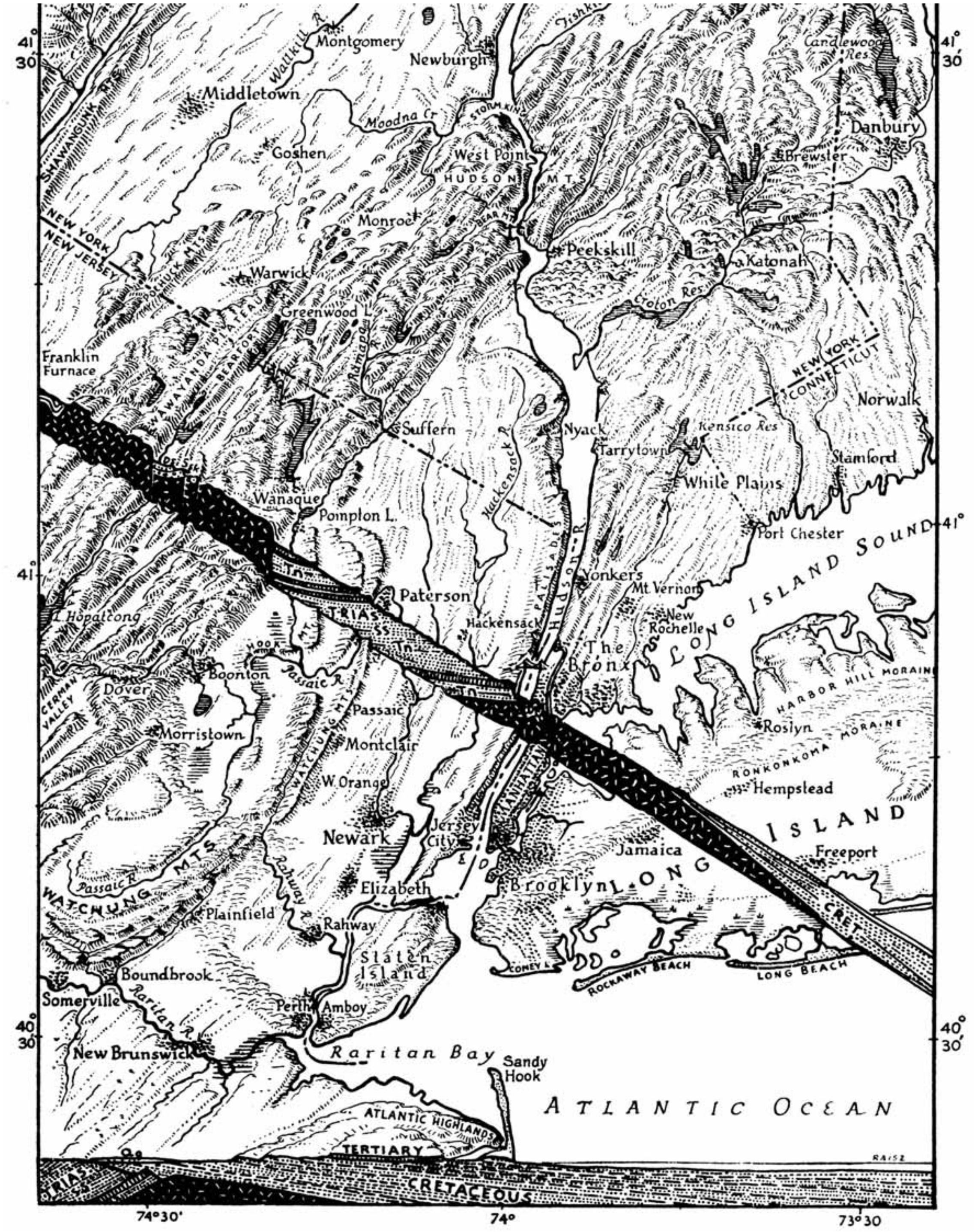


Figure 8. Physiographic block diagram of the lower Hudson River region (drawn by E. Raisz).

The prong forms a continuous belt northward to the Ramapo fault zone north of which Proterozoic rocks of the Hudson Highlands form an imposing terrain of rugged, glaciated mountains. Stretching from Reading, Pennsylvania northeastward into western Connecticut, this belt of deeply eroded Proterozoic rocks underlies the Reading Prong of the New England Uplands. From the Hudson Highlands southward to Manhattan Island, the Hudson River flows in an essentially straight course along the tilted and eroded unconformity between the Newark Basin and the Manhattan Prong. The ancestral Hudson undoubtedly flowed farther westward from its current path eroding the Millburn, Paterson, and Sparkill gaps in the Watchung mountains and in the Palisades cliffs (Figure 9).

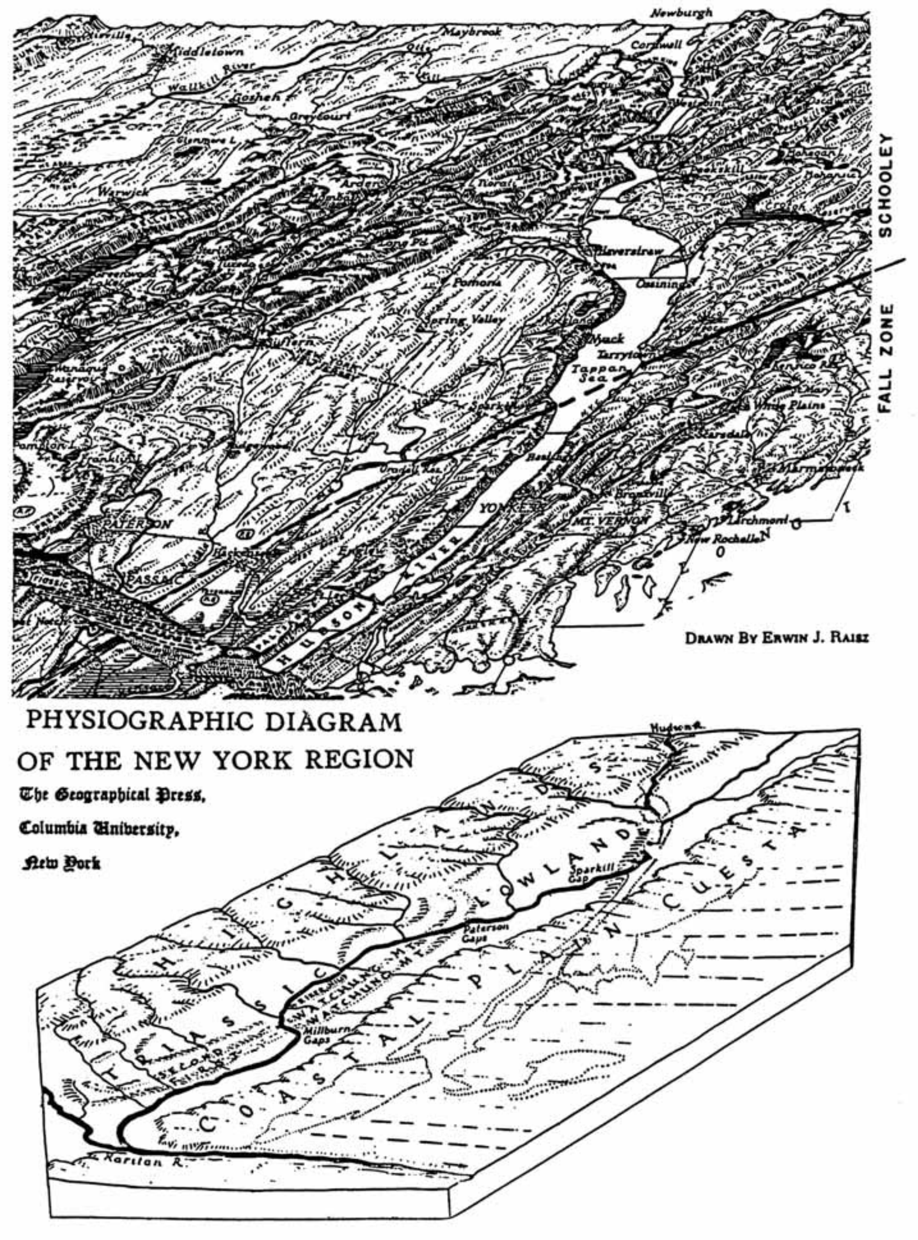


Figure 9. Physiographic diagrams of the New York region and the Hudson Highlands and hypothetical course of the Hudson River in Schooley time (Drawn by E. Raisz).

Channelization of the Hudson into its present valley took the modification of Pleistocene glaciers that helped carve the relatively straight southern part of the Hudson valley. As discussed later (Stop 5) the Hudson's zig-zag course through the highlands may be largely controlled by erosion of intersecting brittle fracture zones in the Proterozoic crust. Post-glacial flooding of the lower course of the Hudson has produced an estuary (drowned river valley) and has transformed the narrow Hudson Highland section of the river valley into a steep fiord (drowned U-shaped glaciated valley).

Today's field trip to the Hudson valley (Figure 1, on cover) is intended to introduce the participants to the wide range of bedrock- and glacial geologic features to be found north- and northwest of Manhattan Island. Table 1 presents a version of a geologic time chart for comparing the names of the geologic time subdivisions, such as Ordovician, Triassic, Jurassic, and Cretaceous, shown on the bedrock map, with estimates of numbers of years for their boundaries and a list of some important local geologic events. Table 2 summarizes the major local geologic units in terms of layers designated by Roman numerals. Table 3 summarizes our current thoughts on Pleistocene glaciations.

The method of analyzing the bedrock underlying a region in terms of "layers" was much emphasized by A. I. Levorsen (1931, 1933, 1934, 1943, 1960). L. L. Sloss (1963) extended Levorsen's approach (but without mentioning Levorsen) and formalized the "layers" by proposing the term "Sequence." The Sloss Sequences refer only to Phanerozoic bedrock underlying the North American craton; the scheme does not include Phanerozoic bedrock outside the limits of the craton nor Proterozoic "basement" or "shield" nor the Quaternary deposits, which are important geologic components of the New York metropolitan area. Our Layer IIA(W) is synonymous with Sloss's Sauk Sequence and our Layer IIB largely matches Sloss's Tippecanoe Sequence. But, our other layers do not closely match the Sloss arrangement. This is not surprising; the Sloss scheme applies to the interior parts of the craton, and many of the layers shown on our tables (Tables 1, 2) designate strata that were deposited on the fringes of the craton.

We continue our discussion of the geologic background with the bedrock units (Layers I, II, and V); Layer VI - the Coastal Plain sediments, Layer VII - the Quaternary sediments; and the drainage history of the region.

BEDROCK UNITS

The bedrock in the vicinity of the Hudson Highlands includes only Layers I and II, the pre-Newark complex of Paleozoic and older metamorphic rocks that underlies the Manhattan Prong of the New England Uplands.

Layers I and II: Pre-Newark Complex of Paleozoic and Older Rocks

The rocks of the pre-Newark complex, which are exposed in many parts of Manhattan and the Bronx, in a few places in Queens, and in one place in Brooklyn ("A Rock Grows in Brooklyn!"), but are present beneath a cover of younger deposits in Queens and Brooklyn where they are not exposed. They have been examined in drill core and on-site visits to the shafts- and tunnels of the New York City Aqueduct System and are found to consist of highly deformed and metamorphosed Lower Paleozoic- and older formations. These rocks compose the Manhattan Prong of the New England Upland physiographic province (Figure 10). The metamorphic rocks of New York City plunge southward beneath younger rocks to the south of Staten Island and reappear again in the Piedmont of eastern Pennsylvania. Together, they mark the deeply eroded, highly deformed and metamorphosed internal zone of the Appalachian mountain belt that stretches sinuously from Maine southward to Georgia, where they have been beveled by Cretaceous and younger rocks and sediments of the Atlantic Coastal Plain.

In New York City, a basal unit (Layer I) of Proterozoic gneiss (the Fordham Gneiss, 1.1 billion years old) is overlain by Layer II, metasedimentary- and metavolcanic rocks that are inferred to have been deposited along the margin of the ancient North American continent in a long-disappeared ocean, the precursor of the modern Atlantic Ocean (it has been called Iapetus). This layer can be divided into two sub-layers, IIA and IIB. The older of these, IIA, is inferred to represent an ancient passive-margin sequence with its various facies spanning the sedimentary realms from near shore (shallow-water deposits) to off shore (deep-water deposits). Thus, Layer IIA can be split into two parts that differ according to their original geographic positions across the inferred ancient passive continental margin.

One part of the older sublayer, part of the Sauk Sequence, was deposited on eroded- and submerged Proterozoic crust in shallow water [Layer IIA(W)]. The oldest unit of IIA(W) is the Lowerre Quartzite, of Early Cambrian age. The Lowerre is thin and very discontinuous and represents mature clastics eroding from the Archean to Proterozoic Canadian shield area. Occurring above the Lowerre is the Inwood Marble (largely a dolostone with lesser interbedded limestone) whose lower part is of Cambrian age and upper part, of Ordovician age. The Inwood Marble resulted from the metamorphism of a extensive sheet of dolomitic carbonates which were formerly deposited in the shallow, Sauk tropical sea that submerged large parts of the North American craton during the early part of the Paleozoic Era.

At the same time that Layer IIA(W) was being deposited in shallow water, fine-textured terrigenous- and volcaniclastic sediments and interlayered volcanics of Layer IIA(E) were being deposited farther east, in deeper water (inferred to have been the ancient continental rise and adjacent deep-water "abyssal" deposits). These deep-water deposits form the bulk of the Taconic Sequence (Table 2) and the protoliths of what is now the middle unit of the Manhattan Schist (Ꞓ-Om) and the Hartland Formation (Ꞓ-Oh) (Figure 10).

The sediments of the Sauk Sequence were lithified and then experienced uplift and erosion that resulted in local karst topography within the Inwood and correlatives to the north and resulted in a regional disconformity. Submergence of the shallow-water carbonate platform heralded a major bathymetric reversal that we think was caused by loading of the edge of the continental margin by the encroaching Taconic arc and subduction complex. Whatever the causal mechanism of the reversal from shallow- to deep-water environments, it resulted in the deep-water infilling of a vast, thick sequence (Tippecanoe Sequence) of terrigenous sediment into a foreland basin (Figure 11) above Layer IIA(W). Immediately above the disconformity surface occurs a thin limestone ("Balmville-type") that is demonstrably interstratified within the typical carbonaceous shales and sandstones of Layer IIB. These interstratified carbonaceous shales and lithic sandstones (graywackes or turbidites) are currently mapped throughout the region as the Normanskill, Martinsburg, Walloomsac, and as the lower part of the Manhattan formations.

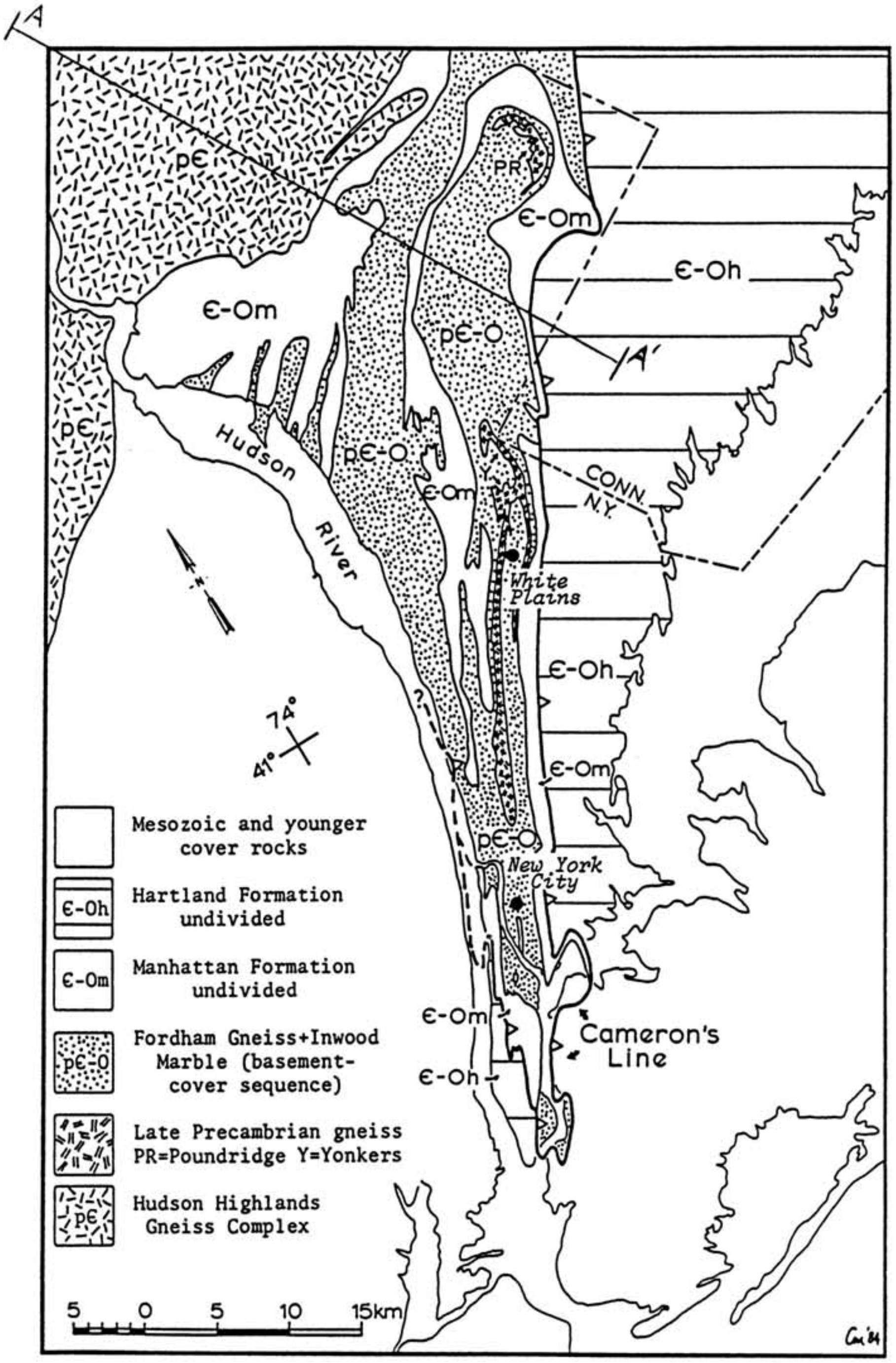


Figure 10. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985). See figure 39 for section A-A'.

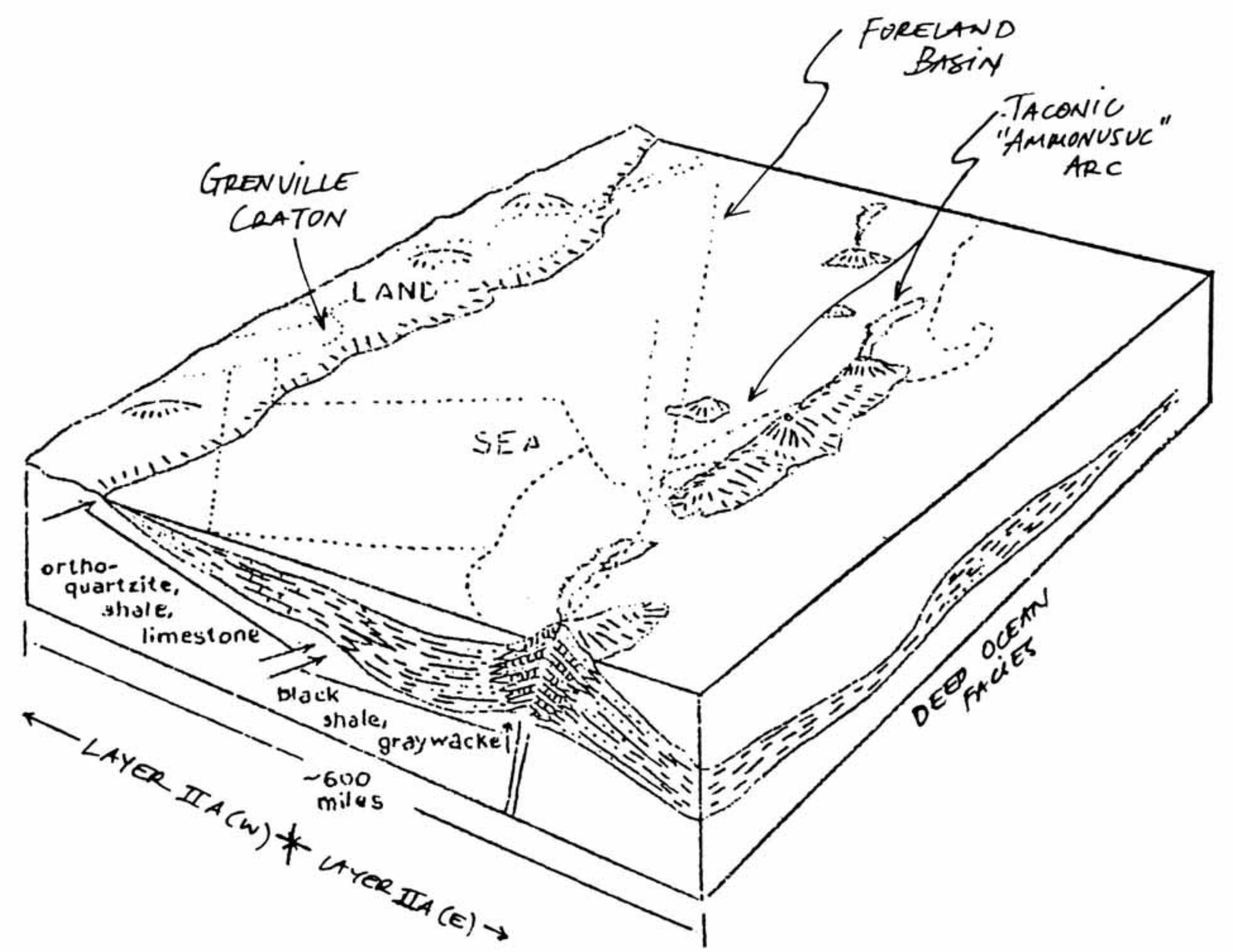


Figure 11. Block diagram showing the Early Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

Thus, above the Inwood Marble are various schistose rock formations that CM and others have mapped as the Manhattan Schist and the Hartland Formation (Figure 10). Very little remains of the "Tippecanoe"-type Manhattan Schist in New York City. CM's mapping identifies only a few places where his lower unit, the "Good Old Manhattan Schist" can be found. As such, much of what was originally mapped as the Manhattan Schist and thought to be entirely younger than the Inwood Marble are now recognized as rock units that are the same age as or older than this schist and the underlying Inwood Marble. During medial Ordovician time, roughly 450 million years ago, and prior to the main events of the Taconic orogeny, these older eastern, deep-water formations and intervening sediments of the continental slope and rise, were juxtaposed at considerable depth into a position above the Inwood Marble and the younger overlying schist (the Manhattan "Tippecanoe" Schist as originally conceived). As will be discussed at Stop 3, the events during the Taconic orogeny probably included the initial displacement of a piece of the former mantle that later became the Staten Island serpentinite body.

The New York City rocks have been complexly folded together and metamorphosed under amphibolite-facies conditions. This can be inferred from the presence of such "indicator" minerals as kyanite, sillimanite, and garnet. The presence of these minerals suggests that rocks now exposed at the present land surface of New York City formerly were at depths of 20 to 25 km. If this is correct, it indicates that enormous uplift and vast erosion took place between the middle of the Paleozoic Era, the time of the last great metamorphism, and late in the Triassic Period, when these metamorphic rocks began to be covered by the sedimentary strata filling the Newark basin. Therefore, as you observe outcrops in New York City, you are vicariously walking backward in time and figuratively descending deep within a former mountain building zone or subduction complex.

The low area followed by the Harlem River is underlain by the easily eroded Inwood Marble. This is because in a moist climate, carbonate rocks, such as marbles and limestones, are easily dissolved by rainwater. (Just the opposite is true in dry climates, where carbonate rocks are resistant and hold up the highest mountain peaks.) The Fordham Gneiss (Proterozoic) is a ridge former and crops out in western Bronx in the road cuts along the Major Deegan Expressway.

Geology of the Cortlandt Complex

The Cortlandt Complex, a world-class mafic-ultramafic igneous intrusive, is one of a number of similar plutons that were emplaced across the Taconic suture zone (Cameron's Line) in Medial Ordovician time. These composite intrusives, including the Hodges Complex, Mount Prospect Complex, and Bedford Augen Gneiss in western Connecticut as well as the Peach Lake, Croton Falls, Torment Hill, Rosetown, Cortlandt, and Stony Point Complexes in New York, are similar in structural setting, mineralogic composition, and age as noted by many workers.

Since the late part of the nineteenth century, geologists interested in igneous rocks have studied the various phases of the Cortlandt complex of plutons near Peekskill, New York. Work by Dana (1881, 1884) and Williams (1884, 1885, 1886, 1888a,b,c) helped set the stage for early twentieth-century studies by Rogers (1911a,b) (Figure 12), Balk (1927) and later studies by Shand (1942) and Bucher (1948). A geologic map of the complex at this time identified a central basin with western- and eastern "funnels" (Figure 13). By the 1950's geophysical- and geologic data of Steenland and Wollard (1952), and work by Friedman (1956) allowed new models of the crustal structure of the Cortlandt Complex. A summary diagram (Figure 14) shows the various structural models proposed for the complex by this time. Figure 15 shows a regional gravity map with a +20 milligal gravity bullseye centered on the Cortlandt Complex.

Modern studies since the 1950's have built upon the geological data base of earlier workers and using geochemical- and geochronologic data to supplement detailed field work, Ratcliffe (1968, 1971, 1981) and Ratcliffe and others (1982, 1983) have better defined the age of intrusion, contact-metamorphic relationships, and internal configuration of the Cortlandt pluton(s).

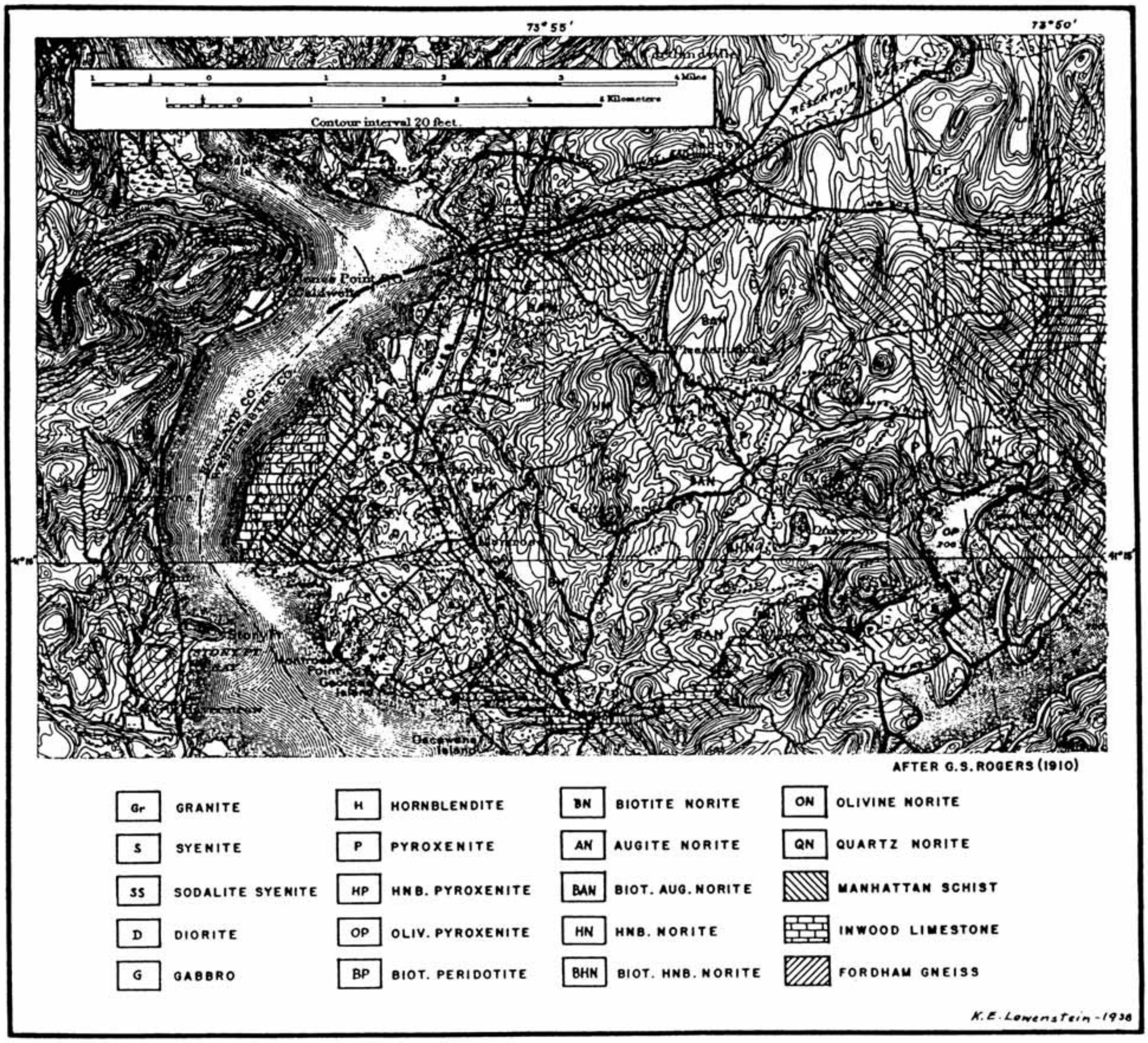


Figure 12. Geologic map of the Cortlandt Series according to Rogers (1911) as redrafted by K. E. Lowe in 1938.

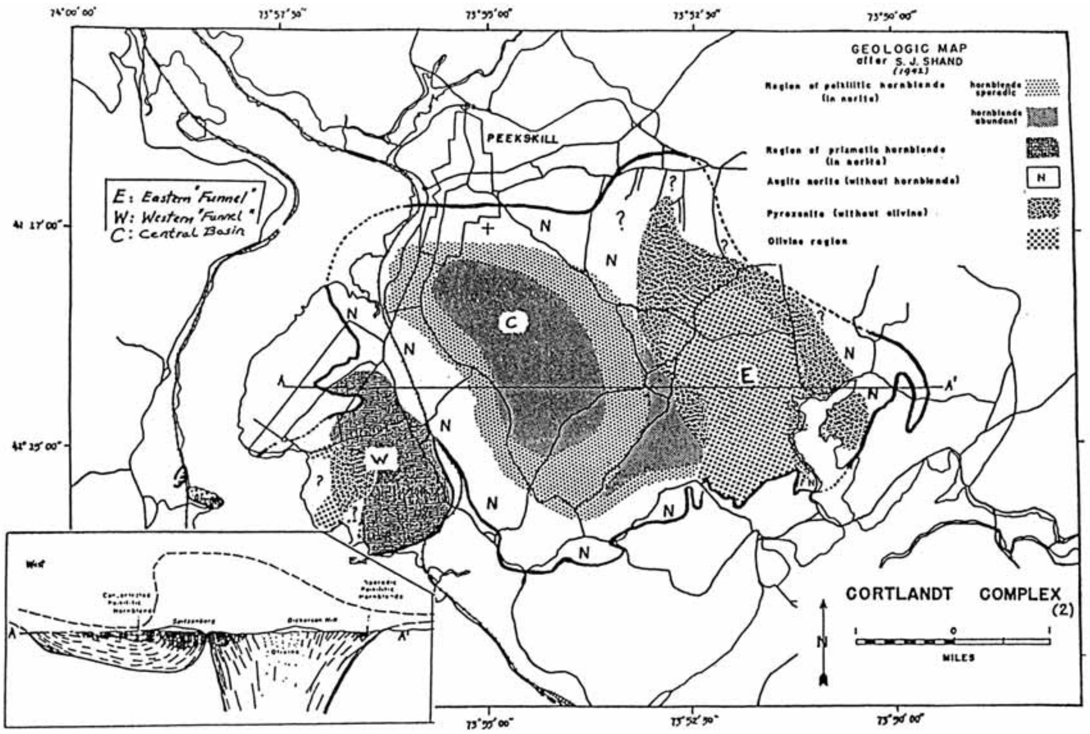
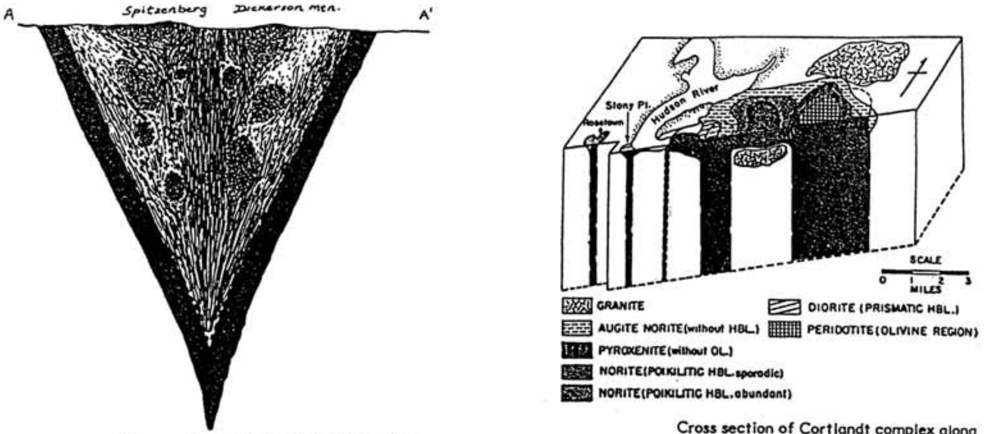
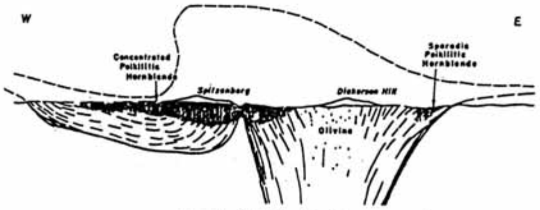


Figure 13. Geologic map of the Cortlandt Complex after Shand (1942) showing "critical phases" reproduced from Bucher (1948).



Cross section of Cortlandt complex along line A-A' according to Balk, 1927.

Cross section of Cortlandt complex along A-A' according to Bucher, 1948.



Model of Cortlandt plutons according to Steenland and Woollard (1952) as modified by Friedman (1956). Reproduced from Friedman (1956).

Figure 14. Summary diagram showing various cross-sectional interpretations of the Cortlandt Complex.

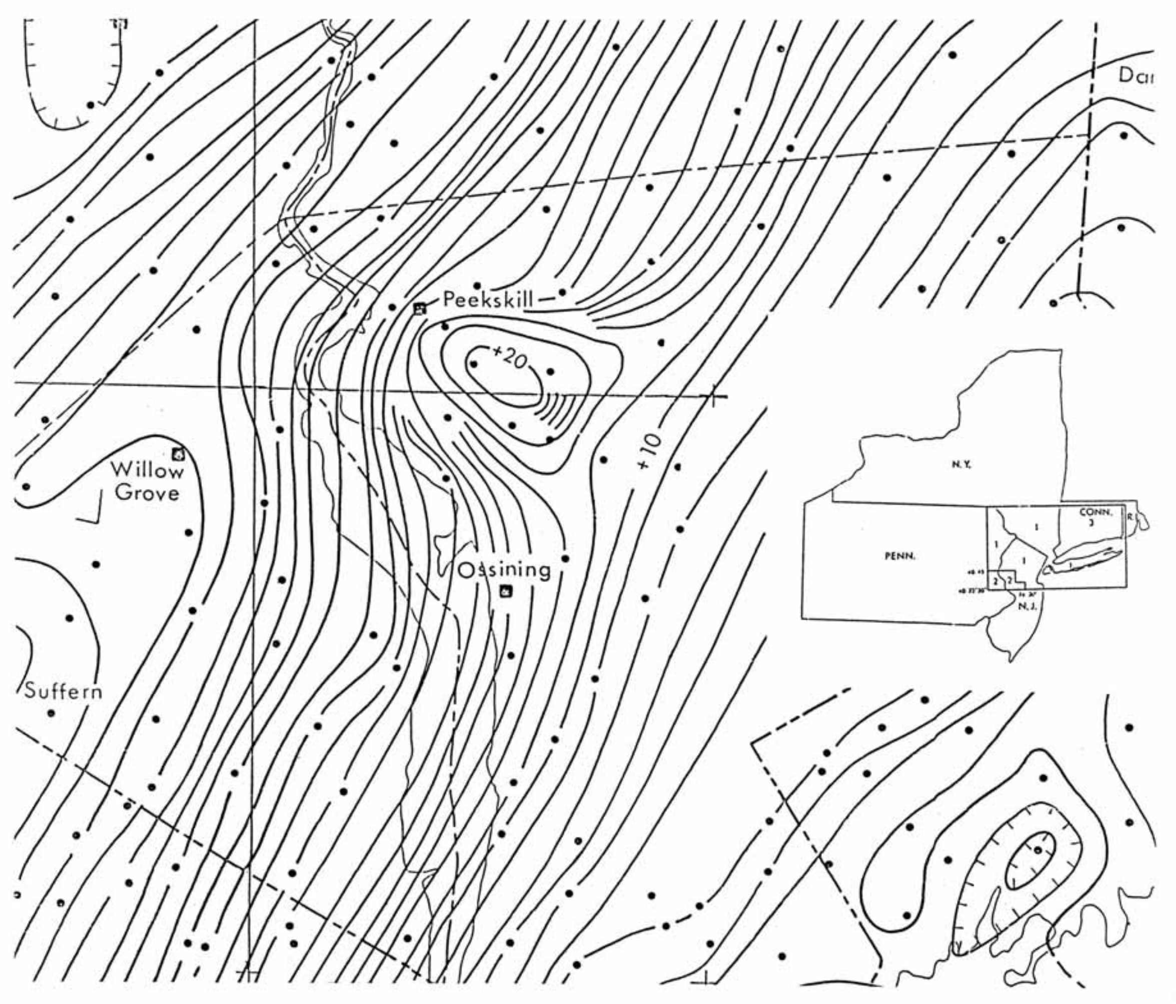


Figure 15. Simple bouguer gravity anomaly map of the Peekskill area with contour interval of 2 milligals. From Urban and others, 1973.

Nick Ratcliffe's work indicates that the Cortlandt Complex is a lopolithic (inverted mushroom shaped) mass consisting of six temporally related plutons of varying compositions (Figures 16-18). The oldest pluton (Pluton I), intrudes the metamorphic rocks of the Manhattan Prong. Pluton I consists of kaersutite (an alkalic amphibole) hornblendite, gabbro, and pyroxenite that grade internally into norite (gabbro containing orthopyroxene). The primary amphiboles of the rocks of Pluton I are aligned; this alignment defines the well-developed internal flow layering. Pluton II consists of a green hornblende gabbro, diorite, and biotite quartz diorite that are correlative with identical rocks at Stony Point on the west side of the Hudson (Figure 19). Pluton III cuts across the core of Pluton I, sends apophyses (offshoots) into Pluton II, and consists of clinopyroxenite and hornblende pyroxenite (websterite). Pluton IV consists of hornblende pyroxenite, peridotite, and cortlandtite that display cumulate-type layering formed by crystals settling through the magma. These four plutons form the western "funnel" of Balk; they are now interpreted (Figure 20) as separate intrusives along the western edge of the Cortlandt lopolithic mass.

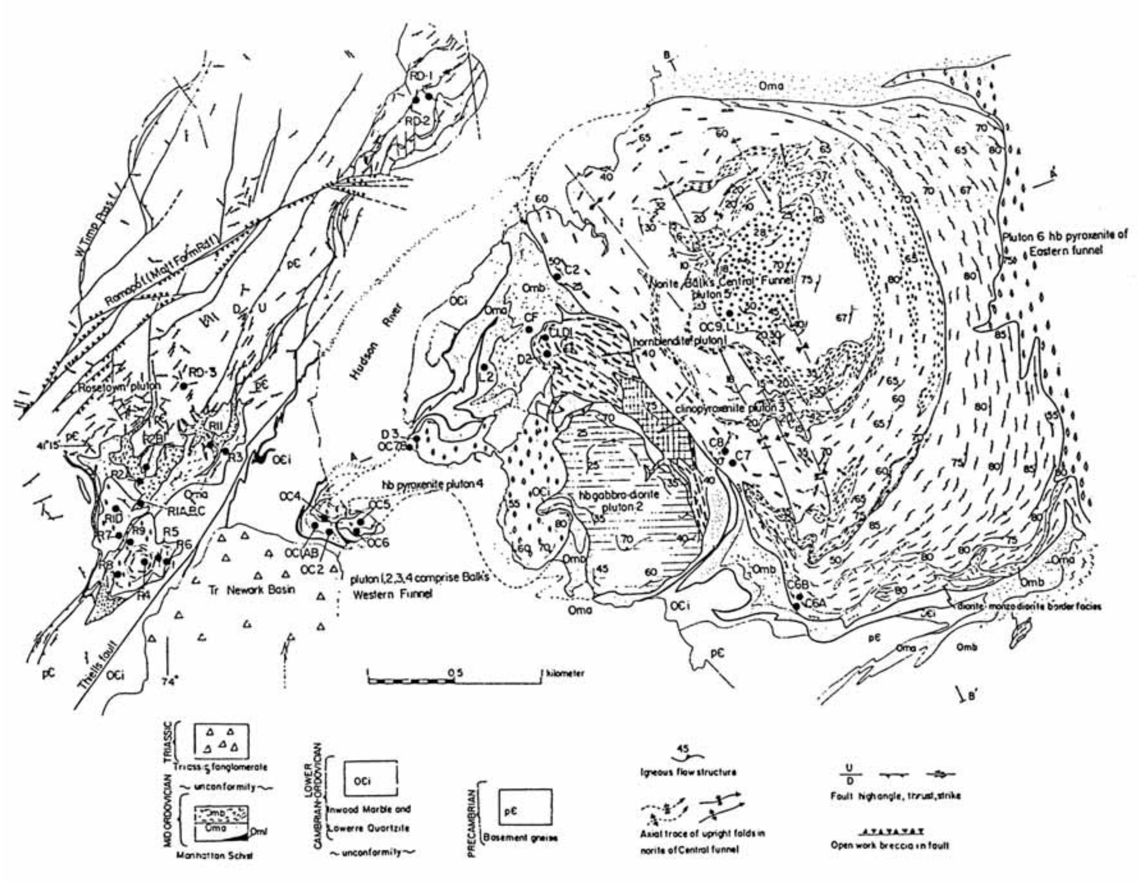
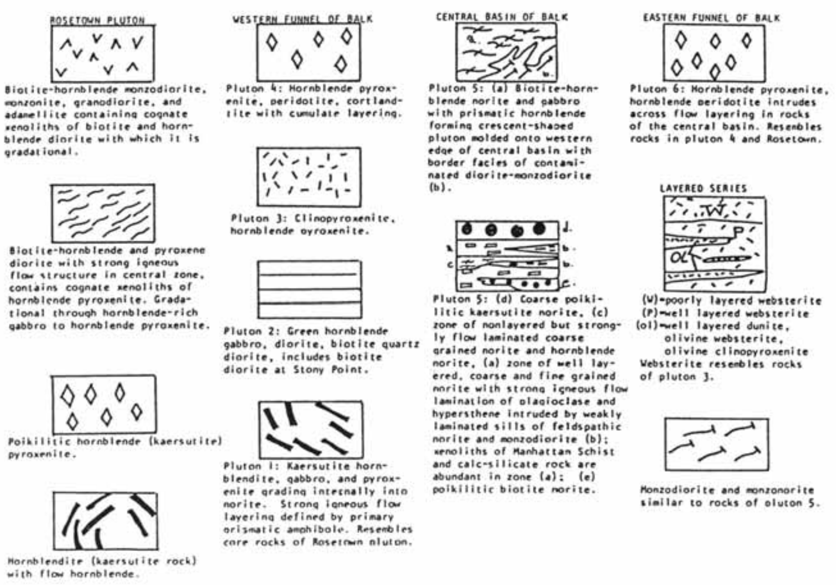


Figure 16. Geologic map of the western and central funnels of the Cortlandt Complex and the Stony Point and Rosetown extensions of the Cortlandt (Ratcliffe and others, 1982, 1983).



Biotite-hornblende monzodiorite, monzonite, granodiorite, and adamellite containing cognate xenoliths of biotite and hornblende diorite with which it is gradational.

Biotite-hornblende and pyroxene diorite with strong igneous flow structure in central zone, contains cognate xenoliths of hornblende pyroxenite. Gradational through hornblende-rich gabbro to hornblende pyroxenite.

Poikilitic hornblende (kaersutite) pyroxenite.

Hornblendite (kaersutite rock) with flow hornblende.

Pluton 4: Hornblende pyroxenite, peridotite, cortlandtite with cumulate layering.

Pluton 3: Clinopyroxenite, hornblende oyroxenite.

Pluton 2: Green hornblende gabbro, diorite, biotite quartz diorite, includes biotite diorite at Stony Point.

Pluton 1: Kaersutite hornblendite, gabbro, and pyroxenite grading internally into norite. Strong igneous flow layering defined by primary orismatic amphibole. Resembles core rocks of Rosetown nluton.

Pluton 5: (a) Biotite-hornblende norite and gabbro with prismatic hornblende forming crescent-shaped pluton molded onto western edge of central basin with border facies of contaminated diorite-monzodiorite (b).

Pluton 5: (d) Coarse poikilitic kaersutite norite, (c) zone of nonlayered but strongly flow laminated coarse grained norite and hornblende norite, (a) zone of well layered, coarse and fine grained norite with strong igneous flow lamination of plagioclase and hypersthene intruded by weakly laminated sills of feldspathic norite and monzodiorite (b); xenoliths of Manhattan Schist and calc-silicate rock are abundant in zone (a); (e) poikilitic biotite norite.

Pluton 6: Hornblende pyroxenite, hornblende peridotite intrudes across flow layering in rocks of the central basin. Resembles rocks in pluton 4 and Rosetown.

(W)=poorly layered websterite
(P)=well layered websterite
(ol)=well layered dunite, olivine websterite, olivine clinopyroxenite
Websterite resembles rocks of pluton 3.

Monzodiorite and monzonorite similar to rocks of oluton 5.

Figure 17. Explanation and lithologic descriptions of rocks of the Cortlandt Complex to accompany figure 16 (Ratcliffe and others, 1983).

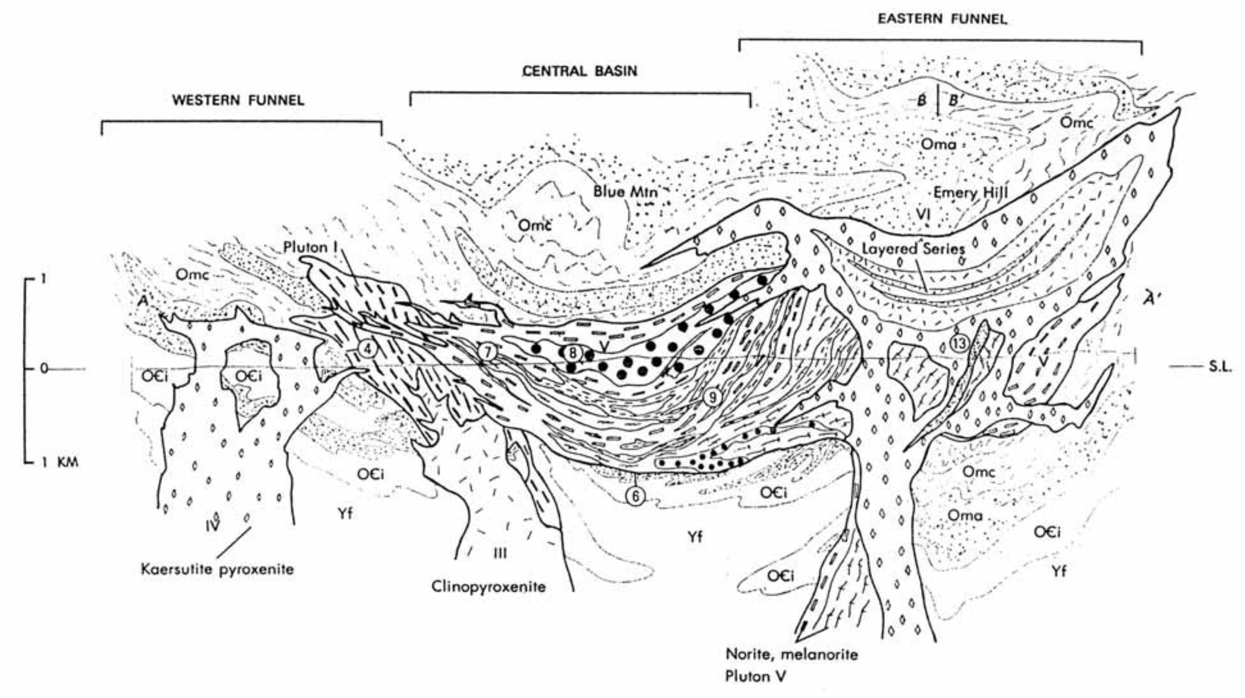


Figure 18. Geologic section oriented SW to NE of the Cortlandt Complex (Section A-A' on Figure 16) showing internal flow structure, cross cutting relationships, and general lopolithic form of the intrusion (Ratcliffe and others, 1983).

The central basin is underlain by Pluton V which consists of biotite-hornblende norite and -gabbro, and coarse poikilitic kaersutite norite. This pluton, that contains abundant xenoliths of Manhattan Schist and calc-silicate rock (Inwood Marble?) shows evidence of intrusion under compression in the form of bent crystals of plagioclase and biotite and delicate folds in igneous flow layers of the norite. The eastern "funnel" is composed of hornblende pyroxenite and hornblende peridotite of Pluton VI which engulfs abundant cognate xenoliths of Pluton V.

The results of geochronologic dating of various phases of the Cortlandt Complex indicate that the plutons were intruded roughly 430 to 470 Ma (million years ago). Because the intrusives are surrounded by contact aureoles, 25 to 50 meters thick, in which rocks of the Manhattan Prong, which already possessed a regional metamorphic fabric related to the Taconic orogeny, have been subjected to contact metamorphism, these radiometric dates on the intrusive rocks set a medial Ordovician minimum age for the Taconic event. Such a date corroborates estimates from structural- and paleontologic studies farther to the north along the sole thrusts of the Taconic Mountains.

The fact that the Cortlandt rocks have not been metamorphosed indicates that they were intruded during the waning stages of the Taconic orogeny and lay outside the domain of Devonian metamorphism. In addition, studies of the contact-metamorphic minerals within the contact aureole of the Cortlandt Complex are the basis for the interpretation that the complex was intruded at depths of 25 kilometers into the Manhattan Prong.

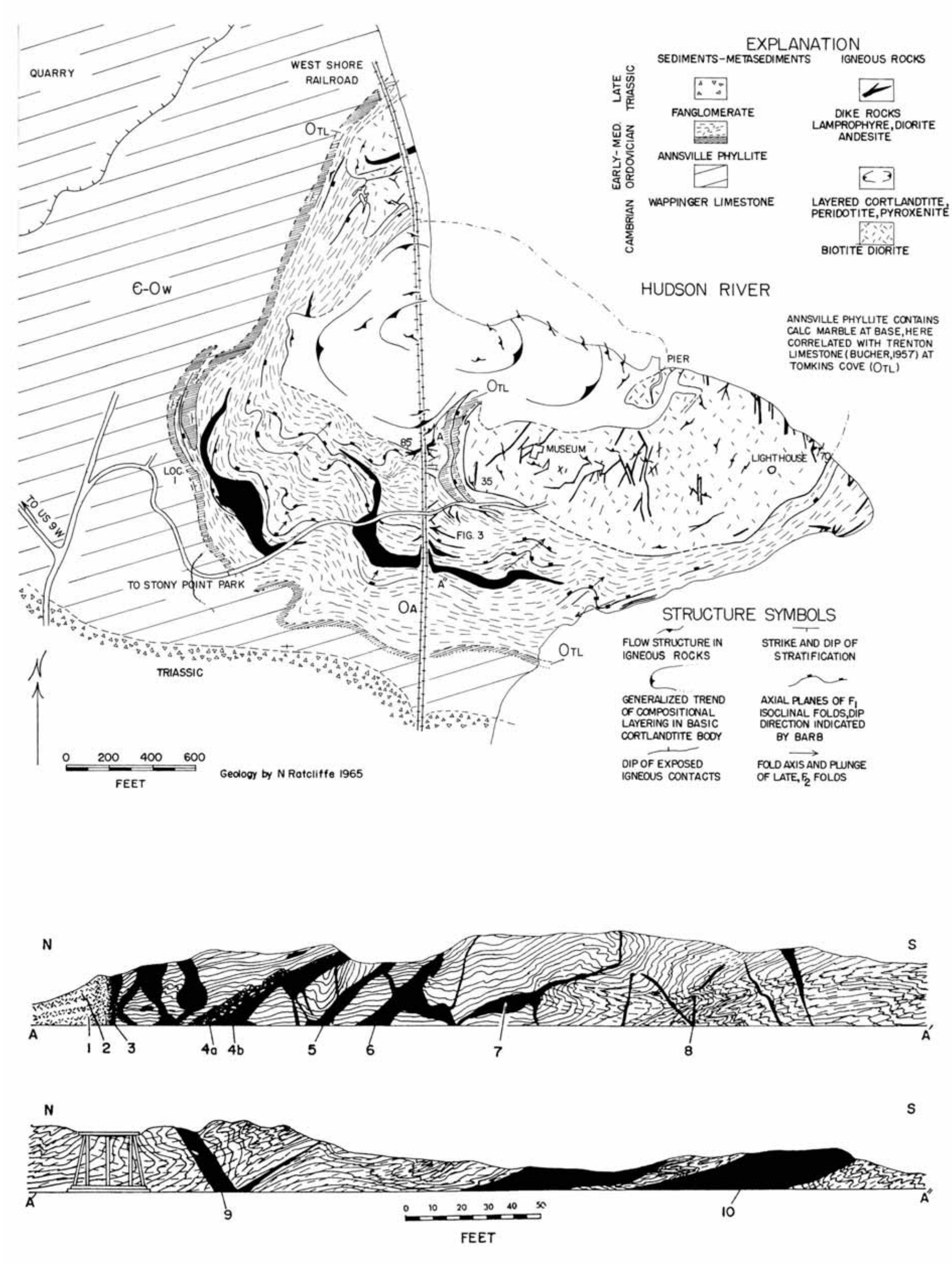


Figure 19. Geologic map and sections from Stony Point showing plutonic rocks and their contact with metamorphosed bedrock. From Ratcliffe (1968).

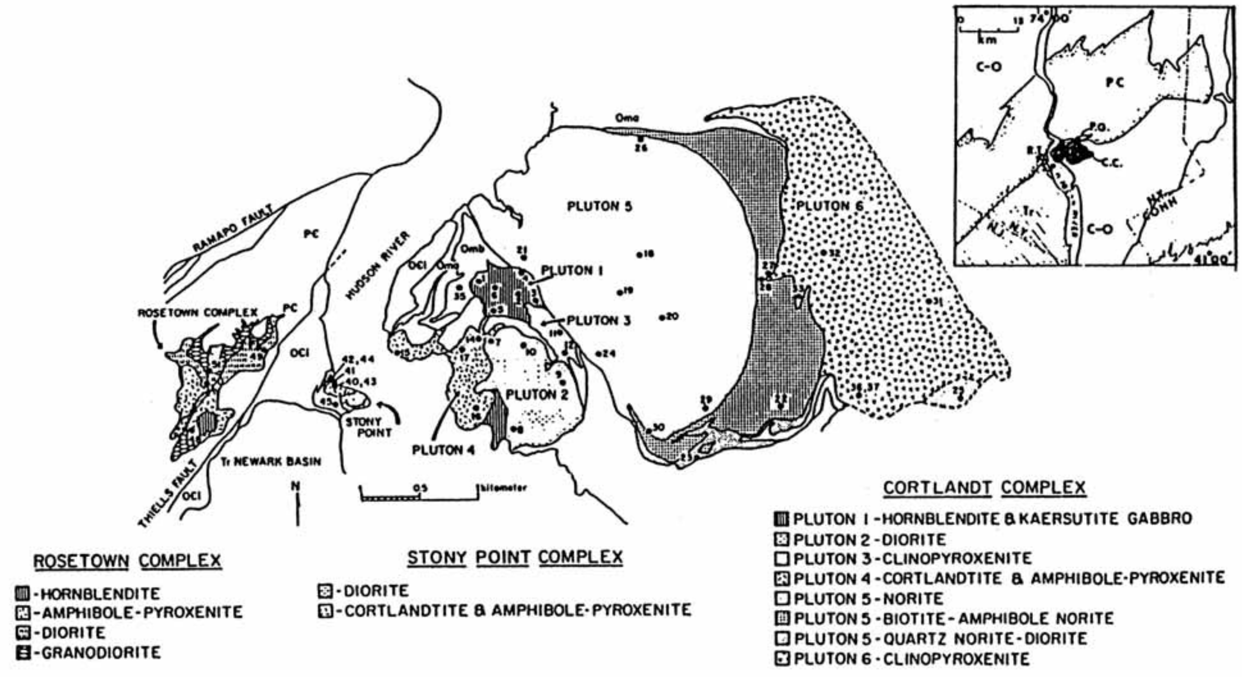


Figure 20. Generalized geologic map of the Cortlandt, Stony Point, and Rosetown Complexes. From Ratcliffe, 1980.

Contrasting Ways For Upper-mantle Material To Get Into The Continental Crust

All mafic igneous rocks are thought to have been derived from the Earth's upper mantle. But, the final appearances of a particular body of mafic rock will differ drastically depending on where crystallization took place (in the mantle or in the pluton within the Earth's crust) and on the mode of emplacement in the continental crust (as magma or as a thrust slice).

The two contrasting loci of origin are: (a) beneath the sea floor as part of an ophiolite sequence in which new oceanic lithosphere formed at a mid-oceanic spreading ridge, and (b) as magma which rose upward through deep-seated fractures that extend through the continental lithosphere and into the upper mantle.

In (a), the mafic magma from the mantle chilled against cold ocean water under considerable pressure. Pillows formed where the lava contacted the sea water; rapid chilling produced basalt (Ophiolite Sequence [OS] Layer 1). Deeper down, gabbro crystallized. It was much fractured; magma invaded these fractures to feed further sea-floor lava flows. The result was the sheeted complex of OS Layer 2. At greater depth, cumulate-type ultramafic rocks formed (OS Layer 3). Ophiolite sequences from the oceanic lithosphere can become part of the continental crust only as a result of great overthrusting (or underthrusting depending upon whether you see things as half-empty or half-full), in which the interface of displacement begins say 10 km beneath the ocean floor and eventually steps its way upward to the Earth's surface, involving subducted sediments of the continental shelf in the process.

In (b), the mafic magma from the mantle worked its way upward into the continental lithosphere through deep-seated fractures and crystallized as intrusive igneous rocks forming tabular plutons (dikes or sills) or even reached the Earth's subaerial surface to form lava flows (and thus to solidify as extrusive igneous rocks).

In both (a) and (b), cumulate-type rocks may be formed, but the probability is much greater that such rocks will be more extensive from oceanic-lithosphere ophiolite sequences than from plutons that crystallized within the continental crust.

Layer V: Newark Strata and the Palisades Intrusive Sheet

The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figures 8, and 9, the Newark strata generally dip about 15° to the northwest.

The formal stratigraphic name for the Newark strata is the Newark Supergroup. Included are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the Palisades Sill has been intruded. Higher up are other sedimentary units and three interbedded sheets of mafic extrusive igneous rock (ancient lava flows), whose tilted edges are resistant and underlie prominent ridges known as the Watchungs (now called the Orange Mountain, Preakness, and Hook Mountain basalts). (These were the subjects of our On-The-Rocks Trip to the Newark Basin and Palisades.) The age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of latest Early Jurassic age (P. E. Olsen, 1980).

The Newark sedimentary strata were deposited in a fault-bounded basin (Figure 21) to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate.

Despite all these environments of deposition, a general pattern prevails in the distribtion of particle sizes. Close to the basin-marginal fault the sedimentary debris is coarse: cobbles and boulders are typical. In the past, most of these coarse rocks have been called "fanglomerates" (literally, conglomerates deposited on fans, usually meaning subaerial fans). Because the evidence about an origin on subaerial fans is not always definitive, we shall refer to these coarse materials by the more-general non-environmental term of basin-marginal rudites.

Another point of general interest about these basin-marginal rudites is their composition. The kinds of clasts indicate what kind of bedrock was being eroded in the elevated basin-marginal blocks. The history that the clasts in these basin-marginal rudites reveals is one of unroofing of the Proterozoic basement complex. In nearly all of the studied examples, the predominant rock types are Paleozoic carbonates (not metamorphosed), and various terrigenous rocks such as the Silurian sandstones and conglomerates, and Ordovician graywackes. Only rarely (and high in the stratigraphic succession) does one find a clast from the Proterozoic basement. This distribution of clasts implies that during the episode of sediment accumulation, the rivers in the elevated Ramapo Mountains block had not yet cut down through the cover of

Paleozoic rocks. The clasts of non-metamorphosed carbonates prove that the elevated Ramapo Mountains block lay northwest of the zones of Paleozoic metamorphism and that prevailing climates were hot and dry to preserve the carbonate clasts.

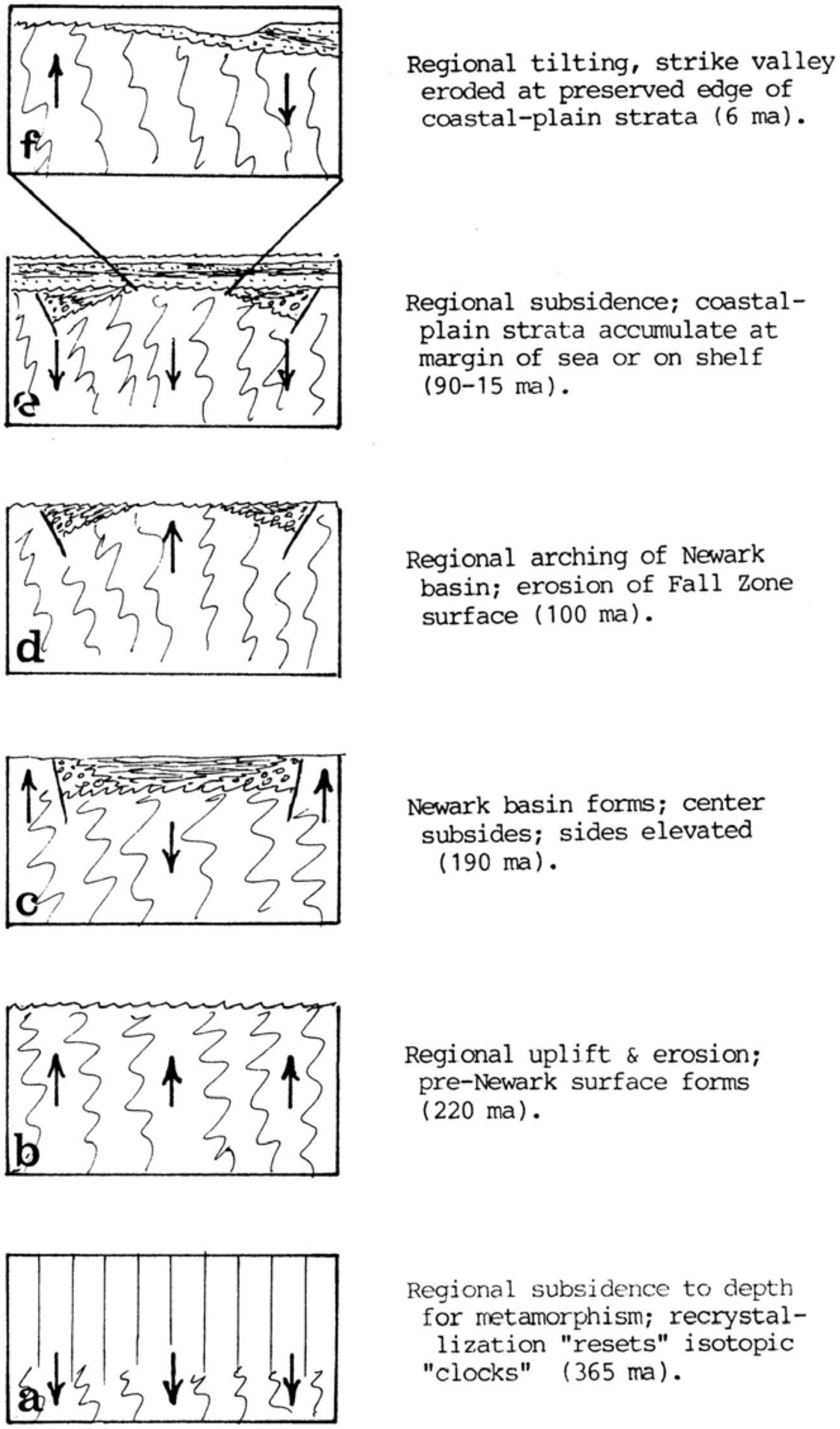


Figure 21. Simplified profile sections showing the development of the New York City region from 365 Ma to 6 Ma. (JES sketches).

In contrast to the basin-marginal rudites are the finer sediments that predominate at distances of only 1 or 2 kilometers away from the basin-marginal faults. Outside the basin-marginal zone, sand is typical, silt and clay are abundant, and coarser grain sizes are scarce. Interbedded conglomerate layers consist of well-rounded boulders which, similar to the vertical, internal stratigraphy of the basin-marginal rudites, show increasing clast age higher up in the section (which, because of the westward dip of the strata translates into the proposition that as one goes farther west, one finds older clasts in the Newark conglomerates).

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. (See On-The-Rocks Trip to the north end of the Newark Basin and Merguerian and Sanders 1994a, 1994b). They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited (Figure 21, F).

Layer VI: Coastal-plain Sands and Clays of Late Cretaceous age

The strata underlying the coastal plain began to accumulate after the Atlantic Ocean began to open and eastern North America had become a passive continental margin. The regime thus established mirrors the kind of setting that prevailed during the deposition of the Lowerre Quartzite and Inwood Marble.

The coastal-plain strata consist of sands that have been cemented only locally (the hematite-cemented sandstones and -conglomerates, or "ironstones"), and the interbedded clays have not become fissile. Hereabouts, the exposures show only the Upper Cretaceous part of the sequence. Elsewhere, however, younger units are present. The youngest widespread marine unit in the coastal-plain succession is of Miocene age.

A characteristic of the coastal-plain sands is their great mineralogic maturity. They generally lack feldspar and contain only quartz and resistant varieties of heavy minerals, such as zircons. Notably absent are any particles derived from the Newark Supergroup. The absence of Newark debris supports the conclusion that the coastal-plain strata formerly extended far enough inland to bury the Newark outcrop areas. Some of the distinctive heavy minerals show that the crystalline central core of the Appalachians was not covered, but was providing debris. Similarly, sand composed of serpentinite particles indicates that the Staten Island Serpentinite was exposed.

Late in the Miocene Epoch, the coastal-plain sands and clays were elevated and truncated by erosion to form a surface upon which the Quaternary glaciers acted.

LAYER VII - QUATERNARY SEDIMENTS

The Quaternary sediments include: (1) the Pleistocene deposits made by continental glaciers that formerly flowed across the region and various bodies of outwash that were deposited when the glaciers melted; and (2) Holocene sediments that were deposited during the Flandrian submergence, which took place as the continental glaciers disappeared.

Pleistocene Deposits

The Pleistocene deposits consist of several contrasting varieties of sediments deposited either directly by now-vanished continental glaciers or as a consequence of the melting of these glaciers. We will be especially interested in the characteristics of till and asymmetric features created by glaciers, and outwash.

Till And Asymmetric Features Created By Glaciers

Till is a general name for any sediment deposited directly by the flowing ice of a glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay. Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water. We discuss these two kinds of deposits at greater length in the following paragraphs.

An important point to be determined in studying a glacial deposit is which way the glacier flowed. Because glaciers create scratches and even large grooves on solid bedrock, it is usually a straightforward matter to infer ice-flow direction. It is along the trend of the linear grooves, striae, and other elongate features.

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable. Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 22).

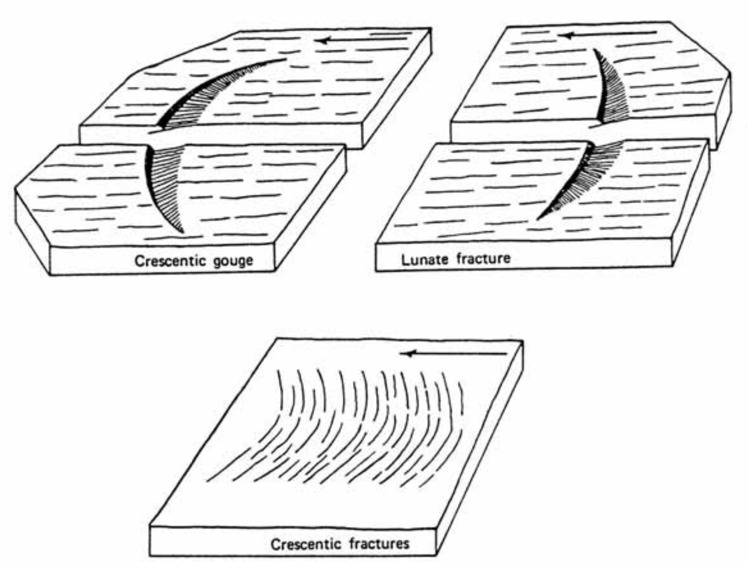


Figure 22. Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Glaciers also sculpt larger-scale asymmetric relief features in the bedrock known as roche moutonnée (Figure 23). These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow), but jagged, irregular, and steep on the side toward which the ice flowed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction (Figure 23)].

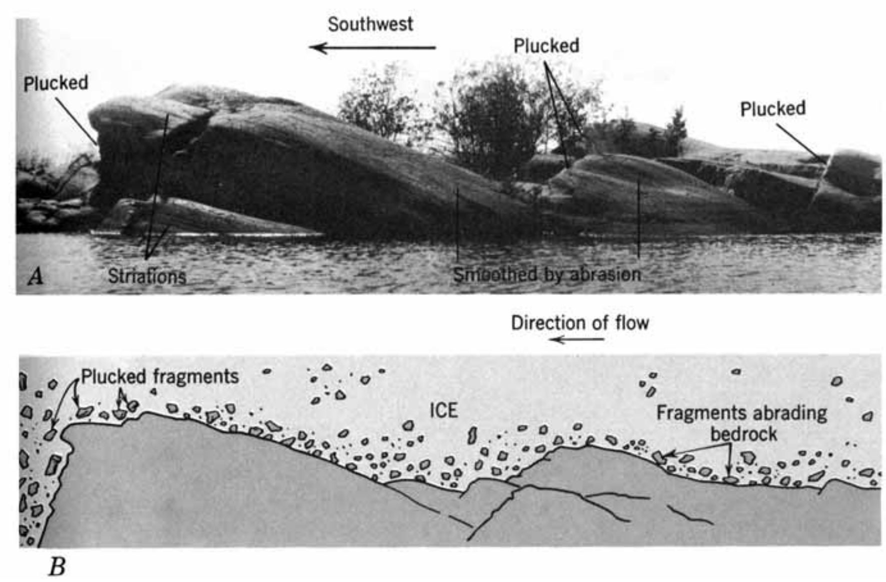


Figure 23. Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnée beneath a glacier.

Another kind of asymmetric feature fashioned by a glacier is an elongate streamlined hill known as a drumlin. The long axis of a drumlin is parallel to the flow direction of the ice; the steeper side is toward the direction from which the ice came (Figure 24). Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consisting of both till and of bedrock. A rock drumlin consists only of bedrock. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.)

Direction of flow may also be inferred by studying provenance; that is, the source of the particles in the deposits. Because glaciers can transport stones long distances, one commonly finds a collection of glacial particles unlike the bedrock on which the glacial deposits rest. Such stones are known as erratics. If an erratic can be traced to a distinctive source, it becomes an indicator stone. For example, at Croton Point, the ultramafic rocks from the Cortlandt Complex are excellent indicator stones as discussed on our On-The-Rocks trip to Peekskill Hollow.

Striae, crescentic marks, directions of asymmetry of roche moutonnée, long axes of drumlins, and indicator stones all show that more than one glacier flowed across the New York region; flow indicators prove that the ice came from not one but rather from several directions.

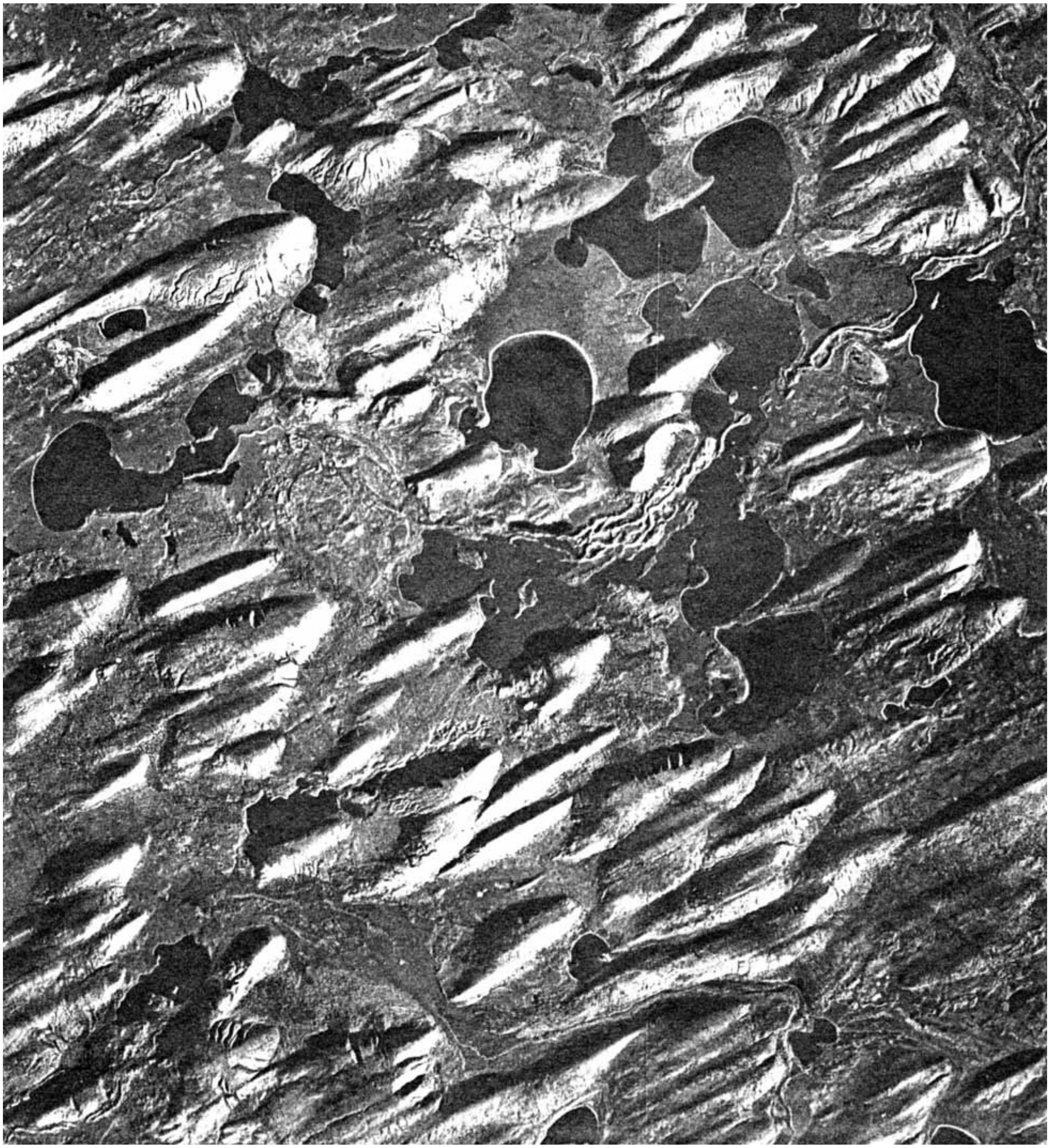


Figure 24. Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

Figure 25 shows a map of North America with what was for a long time the standard view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Figure 25. Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier (Figure 26).

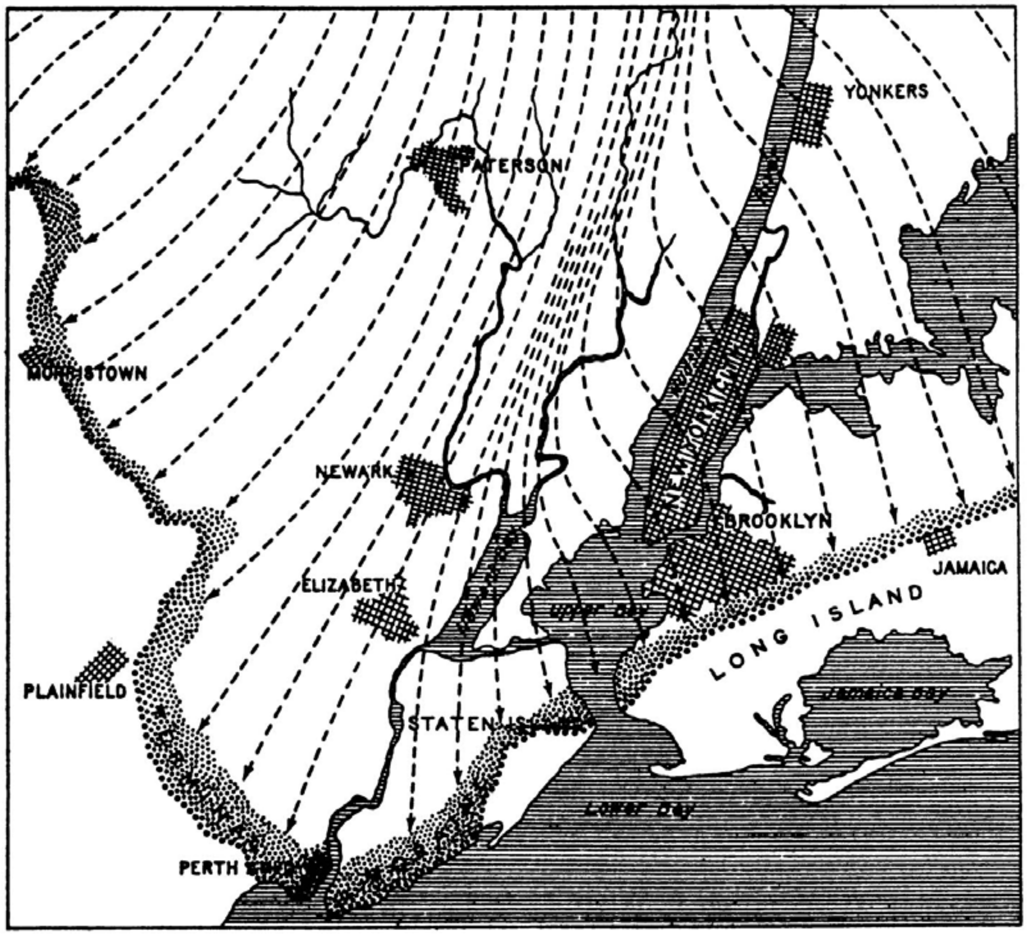


Figure 26. Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW-to-SE course. This concept of a single glacier flowing in a direction that is parallel to the Hudson Valley was reinforced by the results of thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other valleys that trend NE-SW. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and -silts) overlain, in turn, by estuarine deposits. By contrast, the borings from valleys that trend NW-SW display a more-complicated succession of sediments. JES infers that these complex sediments in the fillings of valleys that trend NW-SE are products of glaciers that flowed from NW to SE that that would tend to deepen valleys having orientations parallel to their direction of flow. Any sediments that were deposited in valleys trending NW-SE would tend to be preserved from destruction by ice flowing from NE to SW. By contrast, any such complex deposits that may have been deposited in valleys trending NE-SW would have been especially vulnerable to total removal by a glacier flowing from NE to SW. The JES views on multiple glaciations have been summarized in an article published in 1989 by Robert Sullivan.

From studying the stratigraphic relationships, provenance, grooves and crescentic gouges on bedrock surfaces, directions of asymmetry of roche moutonnée and of drumlins, we propose an alternative view. In our scheme of things, the flow indicated in Figure 26 is not the product of one glacier, but of more than one (two, possibly more). Figures 27 and 28 show how we interpret the glaciers in the same area of Figure 26. In Figure 27, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier and not abberations in topography. Figure 28 shows the flow from NNE to SSE as resulting from a later glacier. According to our studies, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 27. The latest glacier, shown in Figure 28, did not reach much of Long Island. It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known.

The distribution of erratics derived from as far away as the anthracite district in eastern Pennsylvania (Figure 29) in the red-brown tills and -outwashes in localities east of the Hudson River (as in New York City and Westchester County, New York) lends strong support to the interpretation shown in Figures 27 and 28, as contrasted to Figure 26.

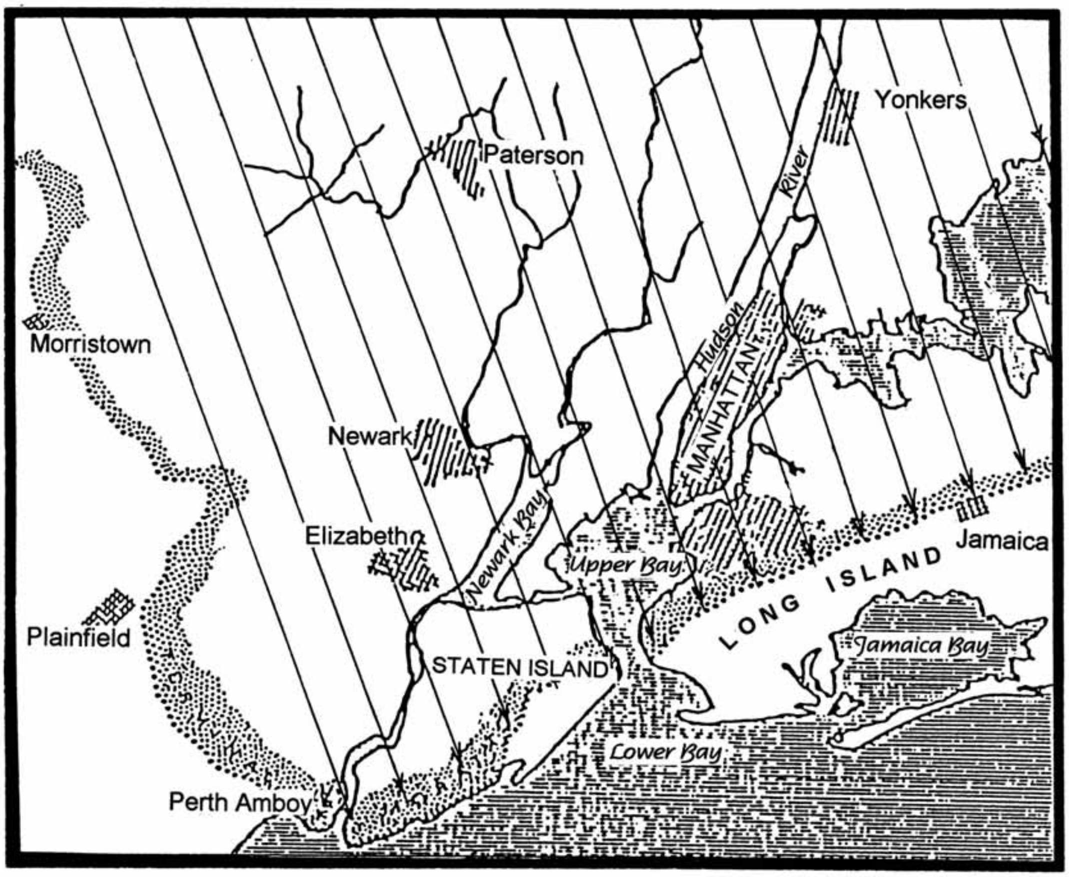


Figure 27. Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

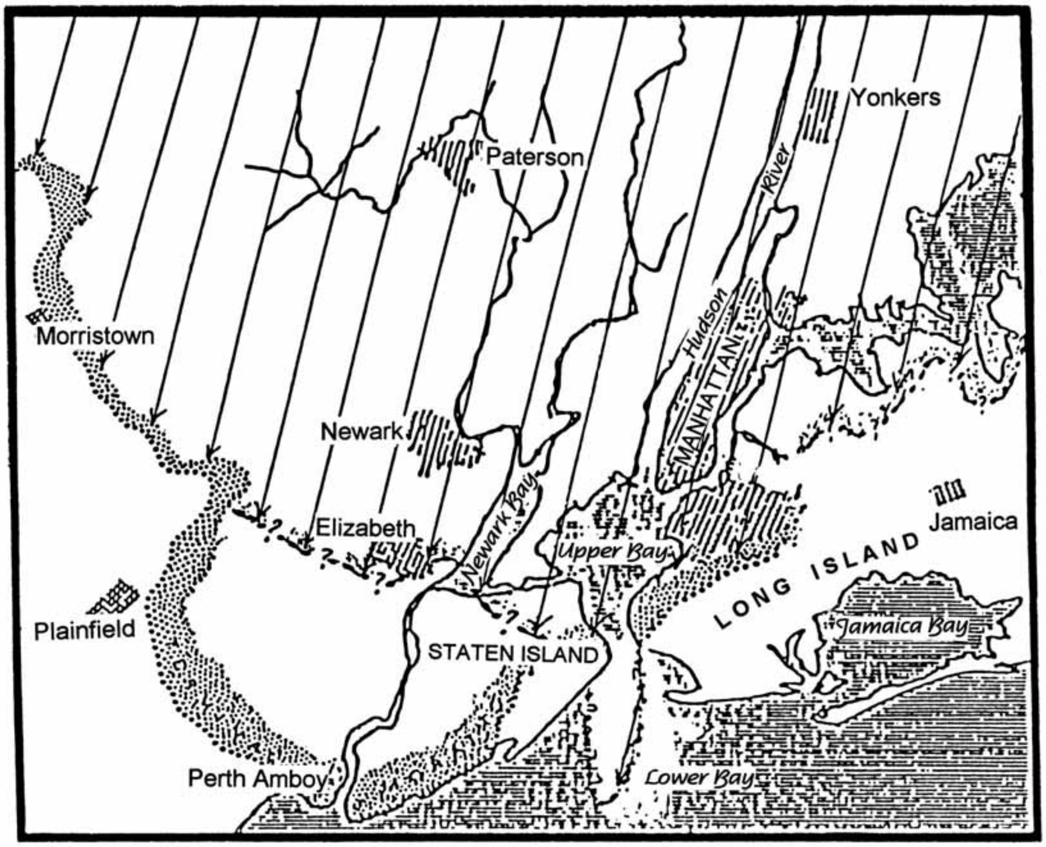


Figure 28. Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

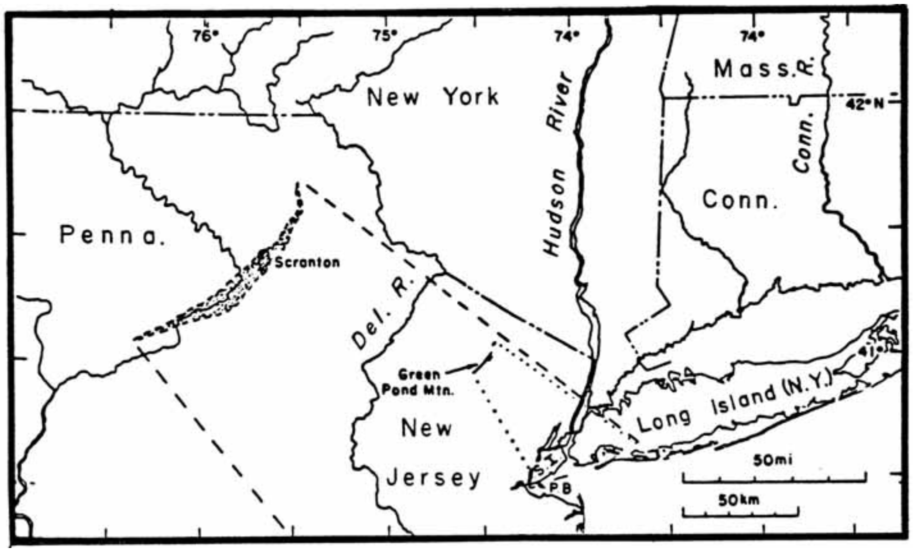


Figure 29. Distinctive erratics found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (Friedman and Sanders, 1978, Figure 2-1, p. 27.)

The stratigraphy of glacial deposits is worked out by noting the relationships among till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York, glacial deposits are interstratified with marginal-marine deposits. This has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted. Although the exact climate settings involved in these changes are not as well known as one might suppose, it is well established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City. Figure 30 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.

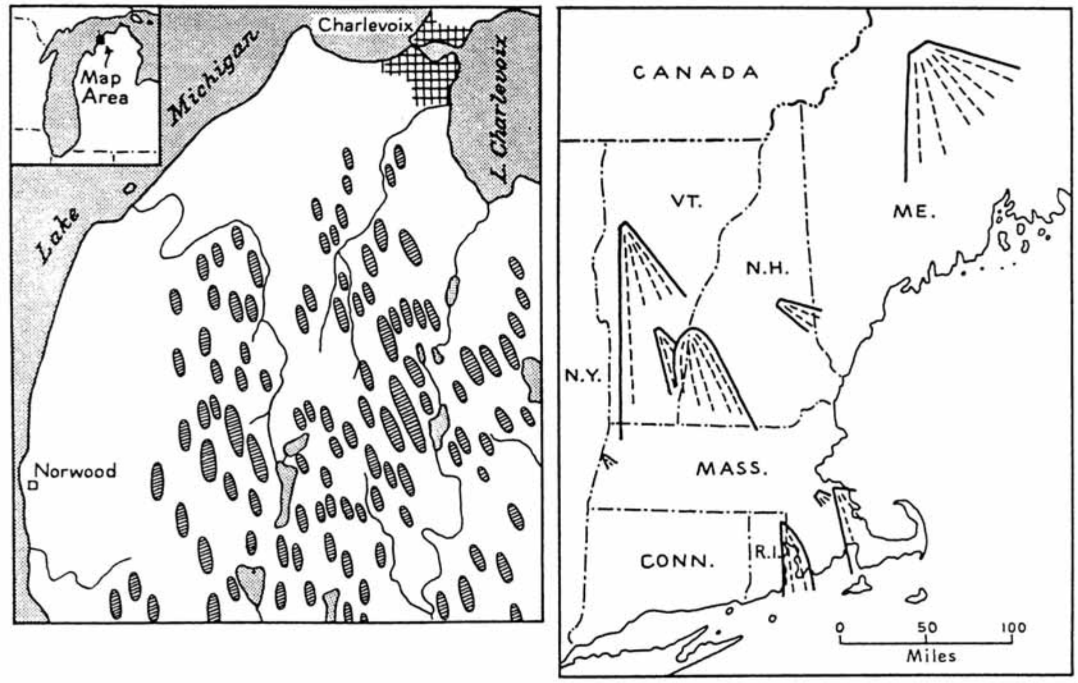


Figure 30. Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, Michigan. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, all products of regional glacier flow from NW to SE. (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p. 190.)

In addition to ripping up individual fragments from the material over which it passes, a glacier may also deform the strata it overrides. One of the Pleistocene glaciers profoundly affected some of the Upper Cretaceous strata: it stripped several large thin slabs (up to 0.5 km in one dimension and a few tens of meters thick) away from their pre-glacial positions and incorporated them as great thrust slices in the till.

Comparison of Pleistocene sediments of the New York City region with those of Boston, Massachusetts

In the foregoing discussion of the stratigraphy of the Pleistocene formations and of the previous interpretations of the Pleistocene sediments of the New York City region, mention was made that the one-glacier view for the Wisconsinan was given strong support by the engineering borings from the major valleys in the New York City region, which trend NE-SW (such as the Hudson and Hackensack valleys). Borings from such valleys show one till overlain by outwash overlain by Holocene estuarine sediments. (Peek ahead to Figures 32 and 33.) As a result, the "standard" interpretation has been that of a single Wisconsinan glacier that is inferred to have deposited both of the moraine ridges on Long Island. Also summarized are the provenance data and how they fit with the directions of striae and grooves cut into the bedrock. Our conclusions, summarized in Table 3, are similar to those reached by Clifford Kaye (1982) from his study of the Quaternary sediments in the Boston area. Kaye found evidence of several Wisconsinan glaciers. The flow directions of these Boston glaciers inferred by Kaye are virtually identical to those we infer for the ancient glaciers in the New York City region. To quote from Kaye's paper:

> "The direction of ice flow in the Boston Basin and adjoining uplands was studied by means of the orientation of striations (sic) and grooves on the bedrock surface, the orientation (sic) of the long axes of drumlins, the direction of transport of erratics in till, and the direction of thrusting and overturning of bedding in glacially deformed drift. These data range through 360 degrees in azimuth. Analysis of this confusing message shows the existence not of an ever-shifting ice current but of at least four separate and distinct ice currents of different ages. Three of these flowed fairly rectilinearly, but one (the last) was multicomponent and marked by strong lobation" (1982, p. 31).

Kaye numbered these tills from I (oldest) to IV (youngest). Tills I, II, and III flowed from the NW to the SE, with means as follows:

Till	Mean flow direction
III	S31°E, +/- 02°
II	S64°E, +/- 18°
I	S23°E, +/- 01°

Outwash

As mentioned previously, outwash consists of stratified sediments deposited by the meltwater from a glacier. In the region of today's trip, most of the outwash has been submerged; it lies beneath the estuarine sediments deposited by the rising sea. But, no account of the geologic history of the New York City region would be complete without a discussion of the freshwater lakes that occupied the Hudson valley from the time when the last glacier disappeared (about 13,000 years ago) until the sea invaded the area (about 11,000 years ago).

When the most-recent of the Wisconsinan glaciers (the Woodfordian, reaching a maximum about 14,000 yr ago, and beginning its rapid disappearance starting about 13,000 yr ago), had attained its southernmost limit, it completely covered the basins now occupied by the Great Lakes (Figure 31, a). By 13,000 yr ago, the retreating ice had uncovered the south end of today's Lake Michigan basin and much of the basin of modern Lake Erie. The only outlet available was situated at Chicago, via the Illinois River into the Mississippi and Gulf of Mexico (Figure 31, b). By about 10,500 yr ago, the ice had melted out of the basins of Lake Michigan, Lake Erie, and Lake Ontario, but still covered the eastern part of the basin of Lake Superior and the northern part of the basin of Lake Huron. The St. Lawrence outlet was plugged; hence, the water drained out of Lake Ontario into the Mohawk, then eastward to a large lake that occupied the Hudson Valley and adjacent lowlands (Figure 31, c). Counts of varves (sediments deposited in a year) in the proglacial-lake clays at Little Ferry, New Jersey (Reeds, 1926, 1927, 1933) showed that this arrangement lasted for at least 2,550 years. The south end of this narrow lake was formed by the natural dam of the Harbor Hill moraine. Two factors, dates not well known, contributed to the demise of this Hudson Valley lake: (1) the dam burst at The Narrows, and the surge of water is thought to have eroded the Hudson Shelf Valley; (2) the ice melted out of the St. Lawrence lowland, making possible the modern-day discharge route into the Gulf of St. Lawrence, Canada (Figure 31, d).

Holocene Sediments Deposited By The Flandrian Submergence

The rapid melting of the Late Wisconsinan ice sheet returned vast quantities of water from the ice back to the oceans. As a result, the sea rose rapidly. This rapid rise of sea level has been named the Flandrian submergence. In the New York City region, the oldest deposit of the rising sea is the so-called gray "organic silt" found in the major river valleys, such as the Hudson.

The thickness of the Holocene organic silt ranges up to 150 feet or so, as indicated in borings made for engineering structures (Figure 32).

Once this silt began to be deposited in an area, the pattern has not changed. We note a few points about this Holocene silt. First of all, it is full of gas bubbles. As a result, it is very reflective to sound waves. This means that the silt serves as a blanket which effective precludes the use of ordinary small-boat continuous seismic-reflection profiling, as with sparkers, boomers, and air guns. Many a hopeful investigator has supposed that it would be possible to obtain seismic profiles of the sediments in the Hudson Estuary. An equal number has been defeated; all they ever got was multiples (remember the chorus in the song about Mary Ann McCarthy who went out to dig some clams? "All she ever got was mussels, etc.")

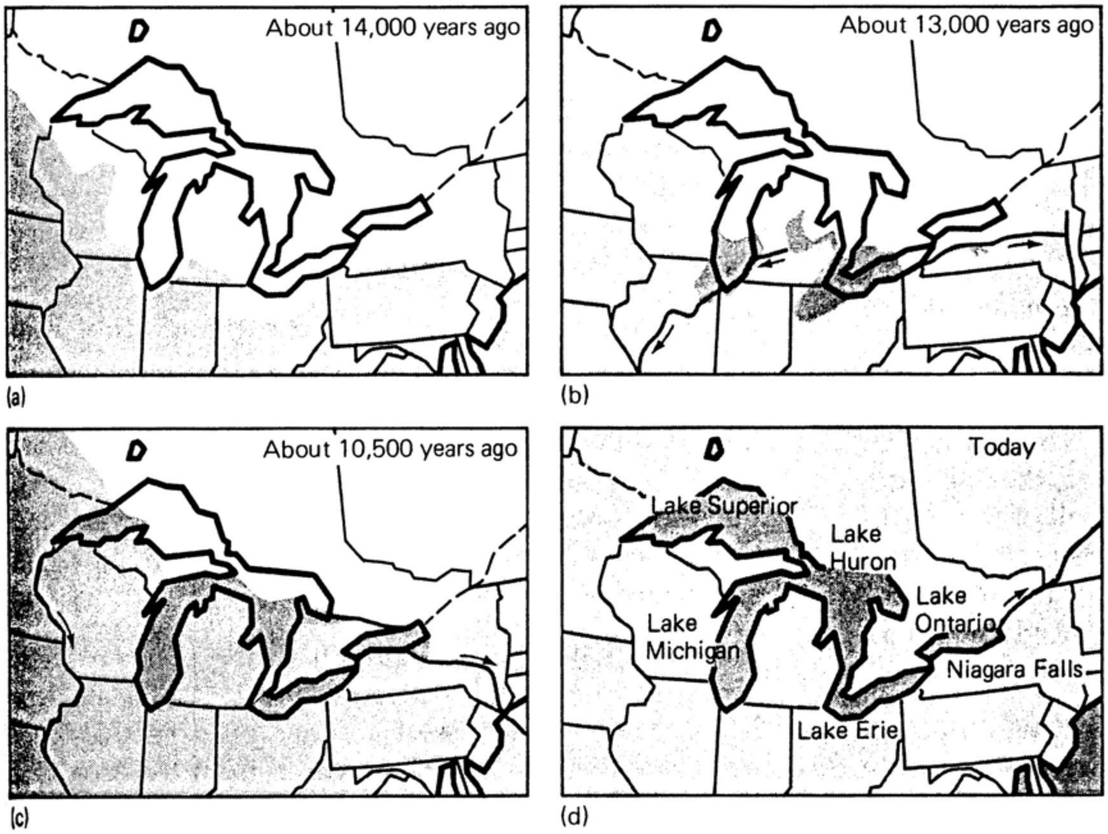


Figure 31. Sketch maps showing Great Lakes at Wisconsinan glacial maximum, at two stages during deglaciation, and at present. (From F. B. Taylor, in Frank Leverett and F. B. Taylor, 1915, (b), pl. 17 facing p. 392; (c), pl. 19 facing p. 400; redrawn by J. E. Sanders, 1981, fig. 13.34, p. 333.)
(a) Maximum of Wisconsin glacier (in white).
(b) Early stage of deglaciation; outlet to Gulf of Mexico via Illinois River at Chicago, Illinois, and Mississippi River.
(c) Later stage of deglaciation; St. Lawrence lowland still blocked by remnant of glacier; outlet from Lake Erie via Niagara Falls into Lake Ontario, thence eastward via Mohawk Valley into Lake Hudson/Albany, which was dammed at south end by terminal-moraine ridge.
(d) Conditions today; outlet from Lake Ontario into St. Lawrence lowland, within which the water flows northeastward into the Atlantic Ocean via the Gulf of St. Lawrence, northeastern Canada (not shown).

Attempts have been made to date the basal silt from samples obtained at Iona Island and at the Newburgh-Beacon bridge on I-84. Based on samples dated by the radiocarbon method, Newman, Thurber, Zeiss, Rokach, and Musich (1969) concluded that the age of the oldest estuarine silt is 12,000 radiocarbon years. D. Weiss (1974) placed the date at 11,000 years B. P. (before present). Owens, Stefansson, and Sirkin (1974) compared the clay minerals from the lake sediments with those of the estuarine silt and also performed chemical analyses on the silt. Other papers devoted to the Holocene sediments are by Agron (1980) in the Hackensack meadowlands, New Jersey; and by Averill, Pardi, Newman, and Dineen (1980) for both the Hackensack and Hudson valleys.

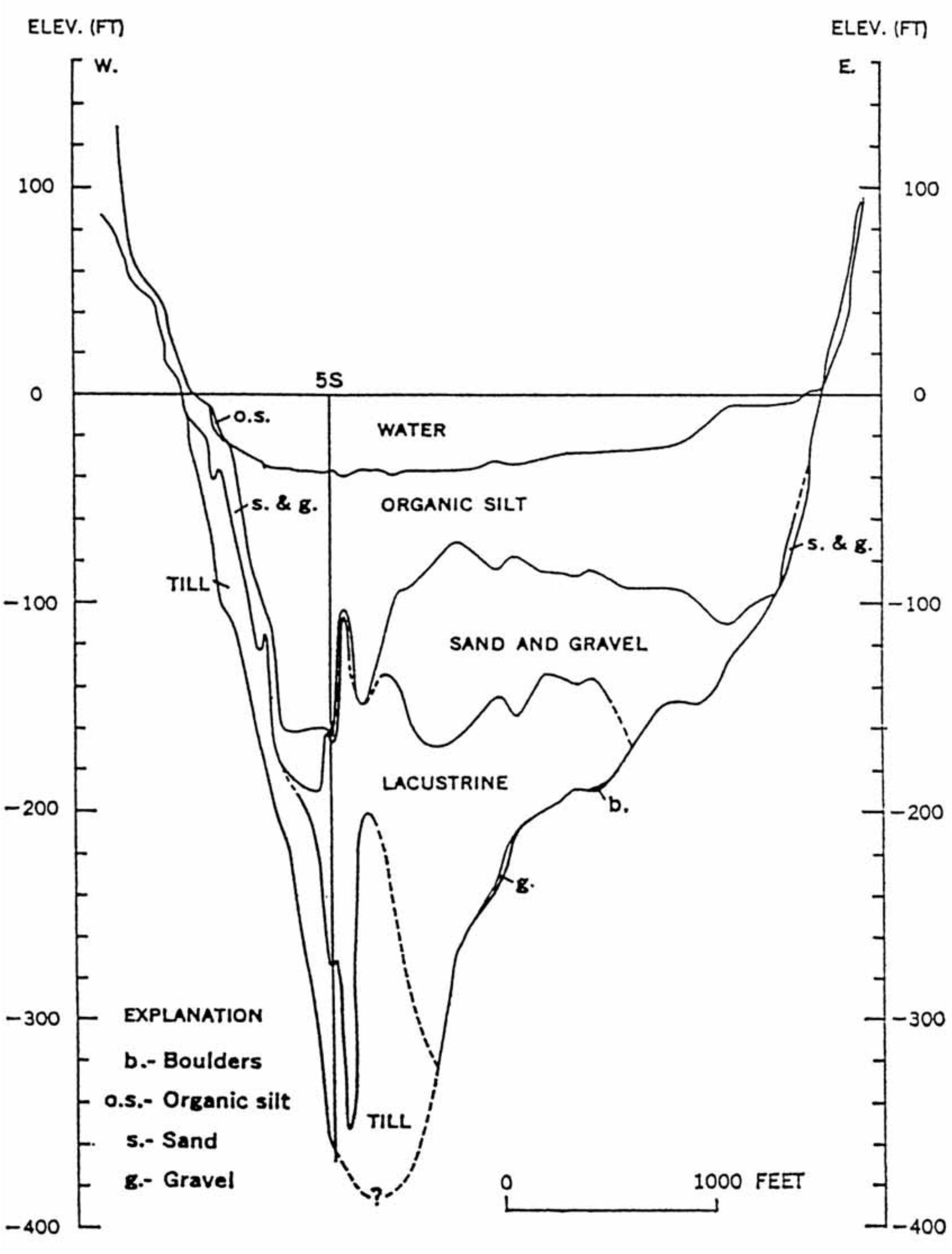


Figure 32. Profile-section across Hudson River at Newburgh-Beacon bridge on I-84, based on samples from engineering borings. Geologic interpretation by Newman, Thurber, Zeiss, Rokach, and Musich, 1969; samples from boring 5S studied by Owens, Stefannson, and Sirkin (1974). (J. P. Owens, K. Stefannson, and L. A. Sirkin, 1974, fig. 10, p. 403.)

New insights into the behavior of the fine sediments in the Hudson Estuary have come from the use of geochemical tracers, from the atmosphere, from discharges of radionuclides from the Indian Point reactors, and from the General Electric capacitor-manufacturing plants at Hudson Falls and Fort Edward (results from the geochemical laboratory at Lamont-Doherty Geological Observatory of Columbia University, by the team headed by H. J. Simpson, and including Richard Bopp, Curt Olsen, and others).

Using the vertical distribution in sediment cores of the radioactive isotope of cesium (137; derived from nuclear-weapons tests carried out in the late 1950's and distributed worldwide via the atmosphere), these investigators have found two contrasting depositional settings: (1) marginal flats, where the post-fallout sediment is only a few millimeters thick (equals the modern rate of submergence); and (2) dredged channels, where the thickness of post-fallout sediment ranges up to several tens of centimeters. In the marginal flats, sediment has evidently built up to the profile of equilibrium and new sediment can be added only as this profile is lowered (as it is during submergence). In newly dredged channels, sediment fills in very rapidly, at rates in the tens of centimeters per year (C. R. Olsen, Simpson, Bopp, S. C. Williams, Peng, and Deck, 1978; Simpson, C. R. Olsen, Trier, and S. C. Williams, 1976).

In the spring of 1974, and again in 1976, two mighty surges of sediments highly contaminated with PCBs from the General Electric plants at Hudson Falls and Fort Edward spread throughout the Hudson Estuary and beyond. Prior to 1973, these sediments were kept upriver behind the ancient Fort Edward Dam. For reasons of safety, and to prevent a disastrous downriver surge of sediments that would accompany a damburst flood, the Niagara-Mohawk Power Company, owner of the dam, obtained permission from the Federal Power Commission and New York State Department of Environmental Conservation to remove the Fort Edward Dam. Granted this permission, Niagara-Mohawk dismantled the dam, starting in July 1973 and ending in October 1973. Two subsequent floods and a general time of high flows brought about the very result that removal of the dam was supposed to forestall!

The effects of industrial pollution have obliterated the once-flourishing oysters of the Hudson estuary. In 1966, JES participated in a small experiment of lowering a TV camera and light to the bottom of the Tappan Zee off Irvington. The bottom is paved with dead oyster shells.

DRAINAGE HISTORY

In attempting to work out the drainage history of an area, one can make use of one or more of the following "tools of the drainage-history trade:" (a) "prospect" the geologic record for times when the lands stood high and were being eroded; (b) actually find valleys that have become "fossilized" (i. e., filled with sediment) and then use geologic evidence to infer their ages; (c) use provenance data and relate such data to regional geologic history (with reference to times when particular rock types may or may not have been available to circulate as sediment at the Earth's surface); (d) use cross strata and other features within sediments to infer which way the currents flowed when these sediments were being deposited. The following paragraphs elaborate on these "tools."

Times Of Erosion

Reference to the geologic time chart (Table 1), shows that after the Newark basin-filling strata ceased to accumulate and before the Pleistocene glacial ages, two times of significant erosion are: (i) post-Newark and pre-coastal-plain strata (from about 180 million years ago to about 100 million years ago); and (ii) after the spreading of fans away from the Appalachians late in the Miocene Epoch until the first Pleistocene glacier arrived (from about 6 million years ago to about 1.5 million years ago). The Pleistocene Epoch included several times of erosion and the start of new drainage networks. Each arriving glacier covered and possibly obliterated previous river systems. As each glacier melted, a possibility existed for establishing new drainage networks. Although these Pleistocene times of erosion were short (possibly not longer than a hundred thousand years), they included powerful agents of erosion: glacial ice and torrents of meltwater.

Buried Valleys

Buried valleys are "fossil" evidence for ancient drainage. The significance of a buried valley in drainage history depends on how closely one is able to determine its age. The age of a buried valley can be bracketed by finding the youngest strata the valley cuts and the oldest sediments in the valley fill. Complications exist because an old valley may have been filled and later uncovered in part or in whole and re-occupied by a river that was not responsible for the original erosion of the valley.

Provenance Data

Provenance data can become parts of drainage history by suggesting directions of travel of distinctive debris and by their implications for what areas may have been eroded to contribute sediment and, by contrast, what areas may have been covered and thus could not have contributed sediment. Both of these aspects of provenance data affect reconstructions of ancient drainage networks.

Features In Sediments Made By Currents

Many kinds of features are made in sediments by currents and some are particularly useful for inferring the directions of flow of the ancient currents. Cross strata furnish a useful example. Cross strata, defined as layers that are oblique to their enclosing strata, result from the migration of bed forms (Figure 33a, d) or from the building of "embankments" (Figure 33c,e). The direction of dip of the cross strata formed by downcurrent migration of a bed form or from the forward growth of an "embankment" is downcurrent. Trough cross strata form by the migration of cuspate megaripples (Figure 34).

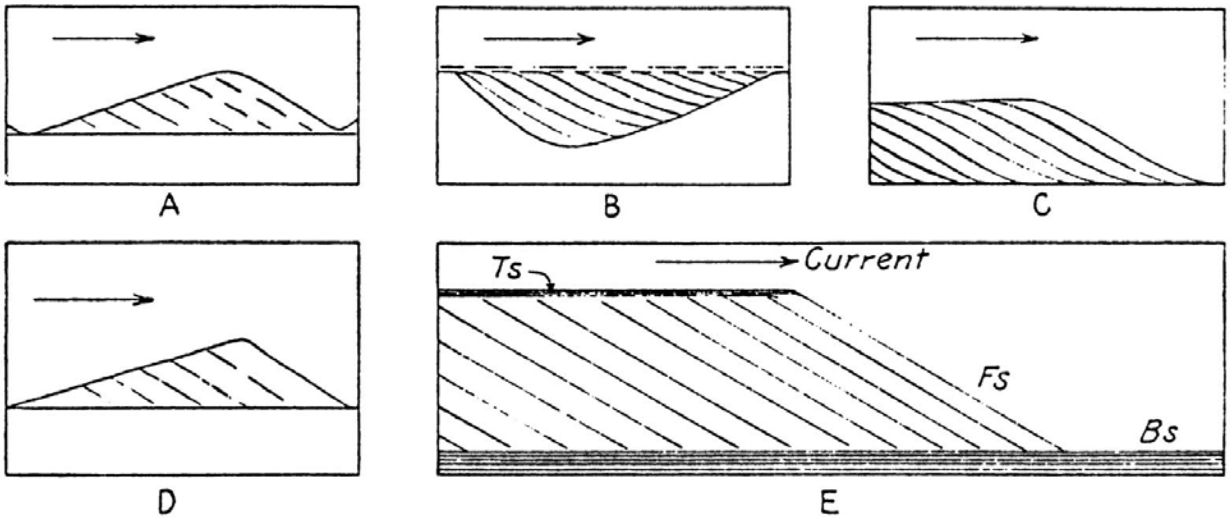


Figure 33. Sketches of cross strata dipping to the right and formed by current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one wavelength, thus preserving as internal cross strata many former downcurrent faces.
B, Longitudinal profiles through cross strata that have filled in an asymmetric depression.
C and E, Longitudinal profiles through cross strata deposited by downcurrent growth of an embankment (such as a delta lobe), built where the flow enters slightly deeper water. (R. R. Shrock, 1948, fig. 207, p. 245.)

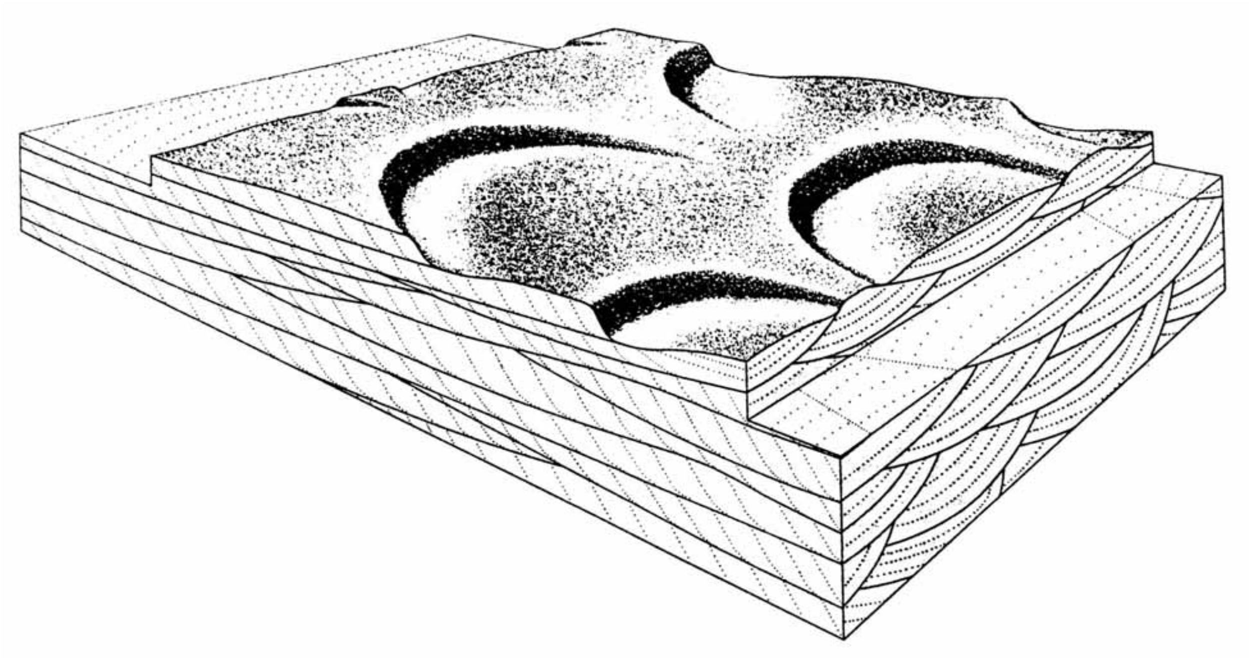


Figure 34. Block diagram showing trough-type cross strata formed by downcurrent migration of lunate megaripples. Current from upper left to lower right. (H. E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

Drainage Anomalies

Anomalous drainage is a term applied to any drainage network in which the predominant flow is not down the regional slope. Obviously, water does not flow uphill, but it can flow along the contours of the slope rather than straight down the slope. Another category of drainage anomalies includes rivers that cut across high-standing areas of resistant rocks, collectively designated as cross-axial drainage. A water gap is the name given to a river valley that cuts across a resistant layer (Figure 35a). Cross-axial drainage can result from several combinations of geologic circumstances. For example, after a stream has become well established in a valley, an anticline or fault may grow along a line trending across the stream. If upward growth is slow and stream power sufficient, the stream may maintain its course and eventually, can cut a water gap (Figure 35b). Such a stream is known as an antecedent stream; it is older than the axis it has cut across. Another possibility is superposition (Figure 35c). Superposition results from a multi-stage geologic history. First the belt of resistant rock is established. Then it is buried. The stream becomes established on the covering strata and commences downcutting. After the stream has cut through the cover, it "discovers" the buried transverse axis. But, because its course has been locked in, so to speak, on the covering strata, it is able to cut a water gap through the resistant transverse axis and may do so in more than one place as has been inferred for the ancestral Hudson across the Watchung Mountains, New Jersey (Figure 9, bottom).

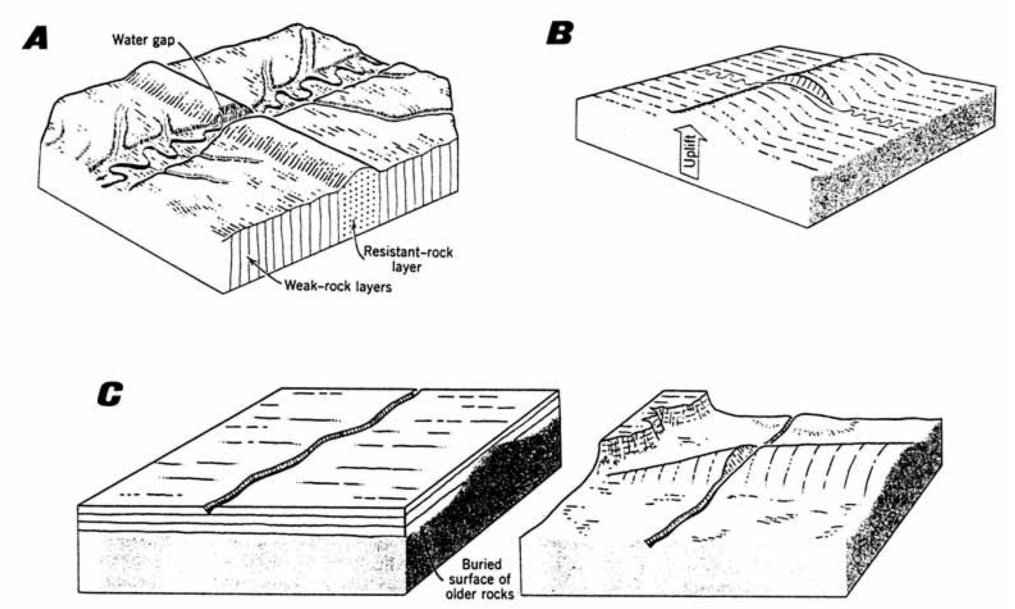


Figure 35. Drainage anomalies associated with cross-axial stream flow, schematic block diagrams. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969: A, fig. 10-12, p. 225; B, fig. 10-15, p. 227; C, fig. 10-16, p. 227.)
A. Stream cuts a water gap through a ridge formed by resistant rock.
B. Stream continues to flow as anticline is uplifted across its path; downcutting equals or exceeds rate of uplift, thus enabling the stream to maintain its course. The stream, which is older than the uplift of the anticline, is named an antecedent stream.
C. Two stages in the history of a superposed stream. In block at left, a prominent ridge has been buried by horizontal strata, on which the stream establishes its course. In block at right, all covering strata except for a small remnant at upper left have been removed and the stream has cut a cross-axial path through the ridge of resistant rock.

A final category of drainage anomaly is what is known as a barbed tributary, defined as a tributary that enters the master stream in such a way as to make an acute angle in what is the downstream direction of the master stream (Figure 36). The usual arrangement is that the tributary joins the main stream and makes an acute angle in the upstream direction. This follows from the fact that the slope of the master valley is downstream. Therefore, any tributary from the side tends to flow down the master valley before it joins the master stream. In so doing, it makes an acute angle on the upstream side.

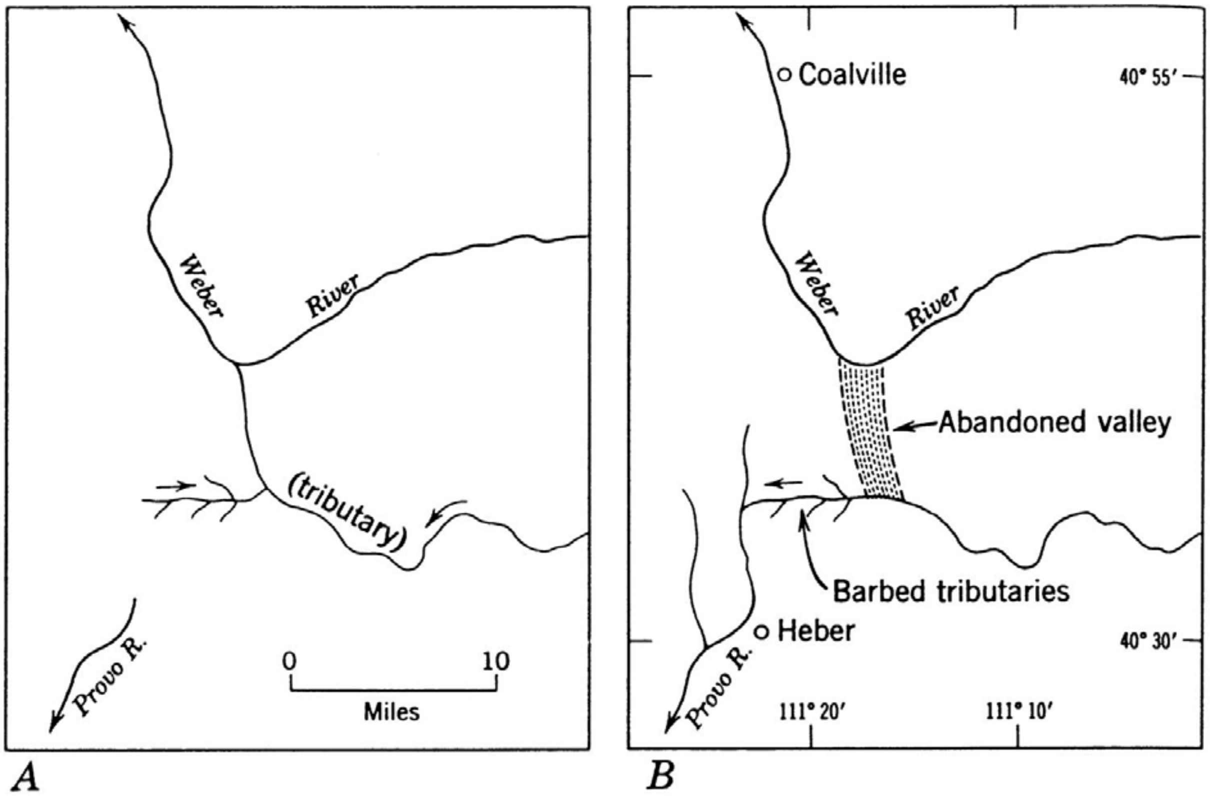


Figure 36. Two stages in formation of barbed tributaries, sketch maps of Weber River and Provo River south of Coalville, Utah. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 10-17, p. 228.)
A. Inferred earlier drainage network in which Provo River is confined to extreme southwestern part of area shown and tributary drainage flows north to the Weber River. Short tributary below center of map flows eastward (to right); its even-shorter tributaries make acute angles on the upstream sides of the larger stream.
B. Headward growth by Provo River has captured former tributaries to the Weber River, reversing the direction of flow of the short tributary below center of map and establishing the barbed relationship with the even-shorter tributaries.

Local Examples

In the drainage history of the New York City region, the oldest clear-cut evidence dates from the Late Triassic-Early Jurassic, when the Newark basin was being filled. Reference to the physiographic diagrams of Figures 8 and 9 shows the morphologic expression in today's landscape of what is left after elevation and erosion of the Newark basin-filling strata. The longer of the two profile-sections (the one that extends diagonally across the middle of the page) displays the existing arrangement of the basin-filling strata (eroded base in contact with the metamorphic complex of the Manhattan prong, northwest dip along the line of this profile-section, and abrupt ending on the northwest against the Ramapo fault).

The northwest-dipping Newark strata end abruptly along a line at the base of the Ramapo Mountains. Geologic analysis indicates that this line marks a fault, the Ramapo fault, which has been active for more than a billion years (Ratcliffe, 1971). During Late Triassic and Early Jurassic time, this fault separated an actively elevated block on the northwest from an actively subsiding block on the southeast. From the elevated block came sediment composed almost entirely of Paleozoic formations. The sediments were transported to the southeast and accumulated to form the Newark Supergroup. Near the Ramapo fault, these sediments are coarse; but, with distance from this fault, they become finer. Cross strata also indicate that ancient streams flowed from the northwest to the southeast. By contrast, both provenance data and the cross strata prove that some of the sediments composing the basal strata of the Newark Supergroup, namely the gray arkoses within the Stockton Formation, were derived from the southeast and were deposited by rivers that flowed westward, a direction that is down the present-day dip of the strata (Glaeser, 1966; Klein, 1969). This general pattern of sediment supply and transport directions has been further supported by geochemical provenance studies based on determining radiometric ages of the feldspars (Abdel-Monem and Kulp, 1968).

One of the major mysteries associated with the Newark basin-filling strata is what happened (and when) to disrupt the drainage and to end the episode of sediment accumulation in the Newark basin. The drainage pattern that began with the initial elevation of the marginal blocks and initial subsidence of the basin block fed sediments into the basin. This drainage pattern persisted for perhaps 30 million years. Then, something happened to disrupt it. Sanders (1963) argues that the elevation of the central part of the formerly subsided basin block, as indicated by the modern-day dip of the strata, was the event which changed the drainage pattern and caused the basin-filling strata to be eroded. As a result of this change, the Newark basin changed from being an importer of sediment into a condition of being an exporter of sediment.

As the Newark strata were elevated and eroded, a strike valley is inferred to have formed along their base. A strike valley is a linear- or curvilinear valley whose axis is parallel to the strike of non-horizontal strata. An example of a strike valley is the Hudson Valley between Stony Point, New York, and a point opposite Hoboken, New Jersey. (See Figure 37; no label appears on Figure 37 for Hoboken, but the short sector of the river under discussion is the north-south segment just east of the "y" in the label for Jersey City.) At Hoboken, the Hudson makes about a 15-degree bend to its left (facing downriver). In so doing, it flows out of the strike valley at the base of the Newark Supergroup. However, the strike valley continues to the SSW. It goes under Jersey City, western Staten Island, and into New Jersey. (See Figure 37 and also Figure 8, a profile-section along the bottom margin of the map, just above the "30'" of the label for 74° 30'). The fact that this basal-Newark strike valley passes beneath the coastal-plain strata proves that the initial age of this valley is pre-Late Cretaceous. How long the Hudson has flowed in it is not securely known. Presumably, this whole strike valley is the same age throughout. It has been reoccupied by the Hudson from Haverstraw to Hoboken. Another valley, not a strike valley and now completely full of sediment and thus hidden from view and that may pass beneath the cover of the coastal-plain strata, extends on a WSW trend out of New Haven harbor and into Long Island Sound (Haeni and Sanders, 1974; Sanders, 1989 ms.; 1994).

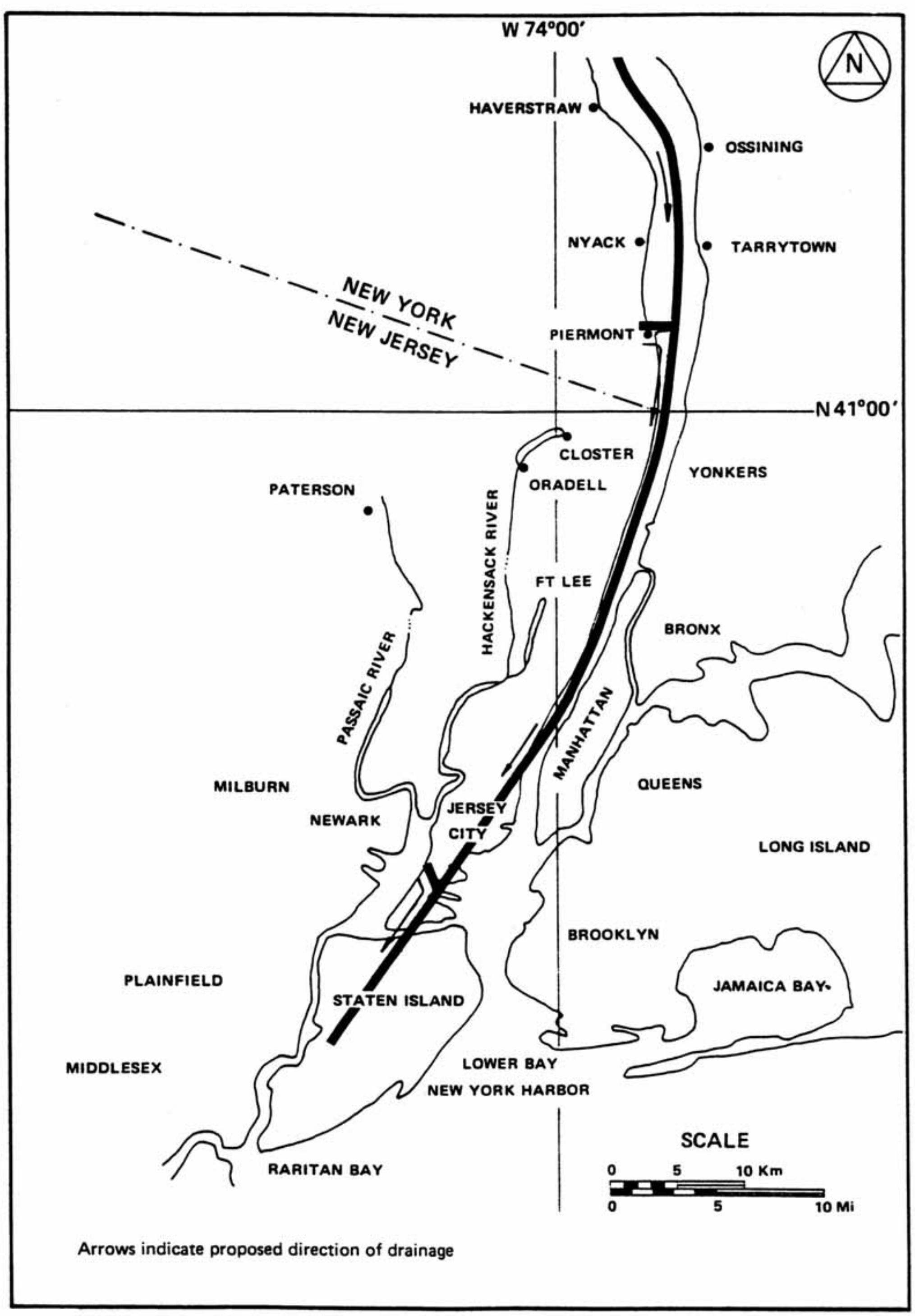


Figure 37. Strike valley at base of Newark Supergroup as inferred during the late Cretaceous, after tilting and erosion of Newark strata (Layer V) but prior to submergence and deposition of coastal-plain strata (Layer VI). (J. Lovegreen, 1974 ms., Figure 19, p. 148).

A second strike valley exists at the base of the tilted- and eroded coastal-plain strata. Locally, ocean water fills this basal-Cretaceous strike valley and we call it Long Island Sound. This valley and many others (Figure 38) resulted from erosion associated with the post-Miocene elevation of the Appalachians and of New England and the accompanying drop of sea level.

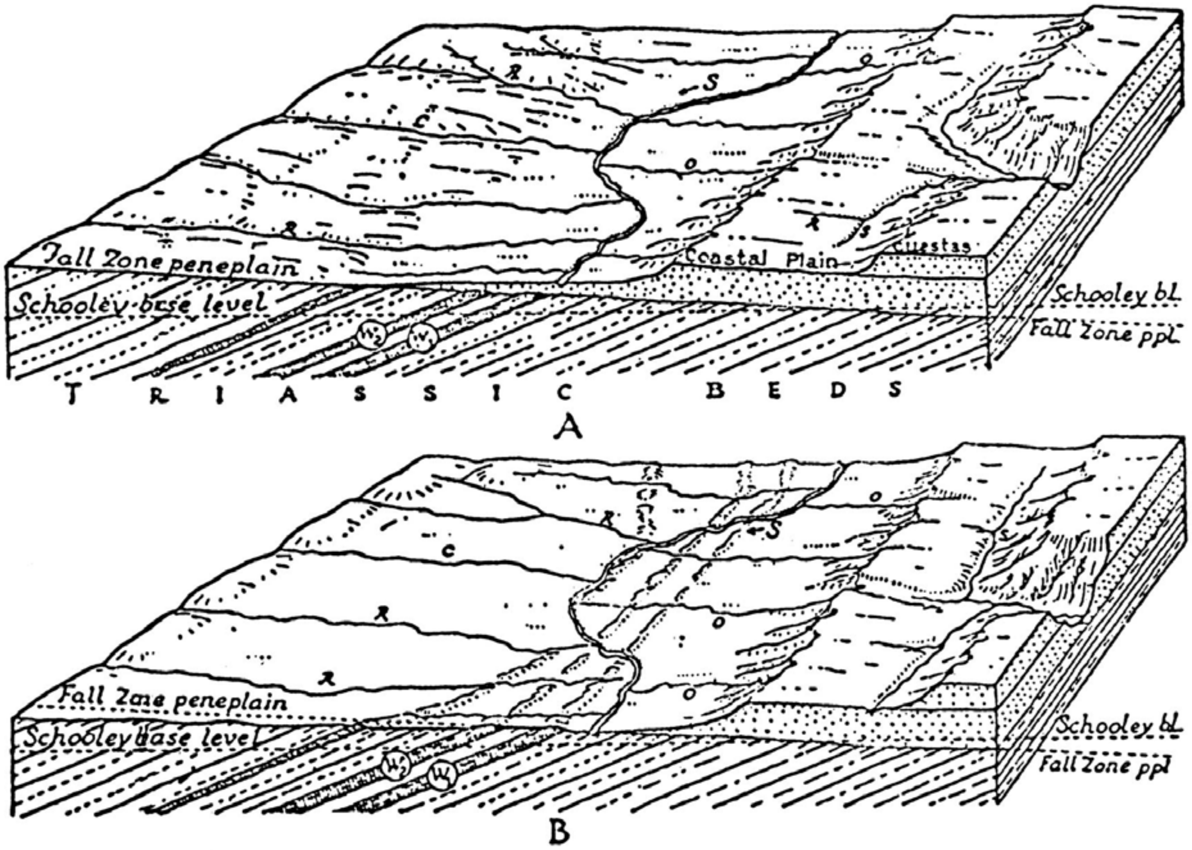


Figure 38. Inferred cuesta and lowland topography above the Watchung trap sheets in Schooley time. A, earlier stage of erosion; B, later stage of erosion; C, possible consequent stream flowing southeast; R resequent streams flowing southeast; O, obsequent streams flowing northwest; S, subsequent streams draining broad lowlands; W1, W2, First and Second Watchung Mountain trap sheets. From Johnson, 1933.

Modern rivers are flowing in lowlands some of which have been in existence for hundreds of millions of years, and others of which are only a few tens of thousands of years old. The oldest probable lowland is the strike valley at the base of the Newark Supergroup, just described.

Locally, three rivers cross parts or all of the Hudson Highlands and thus might qualify as being cross-axial drainage anomalies. The Ramapo River begins at Central Valley, where NY 17 (the Quickway) branches off from the NY State Thruway, and flows southward to across the Ramapo Mountains to Suffern. The Thruway was built in the valley of the Ramapo River, part of which follows along the axis of a structural feature that has been named the Thruway graben (Jaffe and Jaffe, 1973). The Hudson River cuts a zig-zag course across the Highlands from Storm King to Peekskill. And, the Croton River, whose lower reach lies within the Manhattan

Prong, cuts across the Highlands from Carmel into the Harlem Valley. Of these, only the course of the Hudson through the Highlands has been much discussed by geomorphologists. H. D. Thompson (1936) showed how the Hudson's course through the Highlands follows zones of weakness in the bedrock. To this JES would add the point about the parallelism of the zigs to one of the glacial-flow directions and of the zags to the other direction.

So much for geologic background. We now turn to the specifics of the trip, starting with the objectives.

OBJECTIVES

1. To get to our third "new" van rental garage before they go out of business.

2. To enjoy the spectacular scenery of the southern Hudson Valley, New York, during its finest viewing season.

3. To examine the geologic evidence which proves that the mafic- and ultramafic rocks, including cumulates, of the Cortlandt Complex, are parts of a pluton intruded into the continental crust as magma and later cooled in place, and were not thrust upon it (as are ophiolitic sequences from the deep-sea floor).

4. To study the contact between the Inwood Marble and the stratigraphically overlying pelitic unit (lower schist of CM's revisions of the geology of the Manhattan schist, and/or Annsville Phyllite) and the contact metamorphic effects on both within the contact metamorphic aureole of the Cortlandt plutons and in xenoliths within the pluton.

5. To examine the effects on the bedrock surface of glaciers that flowed across the region at different times and from different directions, with particular emphasis on the crescentic marks made on the Proterozoic granitoid rocks of Bear Mountain.

6. To compare the composition of the clasts from near the base of the Newark Supergroup with the composition of bedrock now exposed nearby.

LIST OF LOCALITIES TO BE VISITED

Stop 1: Bleakley Avenue, Buchanan.
Stop 2: Eleventh Street, Verplanck.
Stop 3: F. D. Roosevelt Veterans Hospital, Montrose.
Stop 4: US Route 9, southern Peekskill.
Stop 5: Perkins Observatory, Bear Mountain.
Stop 6: Stony Point State Park (Optional).

ROAD LOG AND DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

Geology from NYC to the Cortlandt Complex, Buchanan, New York

The crystalline bedrock beneath our feet at the start of today's trip in Manhattan forms a sequence of highly folded- and metamorphosed Lower Paleozoic rocks which trend northeasterly into western Connecticut (Figure 10). We stand today on a surface underlain by bedrock that acquired its present-day characteristics at depths of more than 10 km. Thus, in order that rocks formed at such great depth can now been seen at the Earth's surface, an enormous amount of uplift and erosion must have taken place. But, back down into the rock-making "trenches."

Multiple periods of folding and metamorphism have created a series of plunging antiforms and synforms that, as a result of differential erosion, form ridges that parallel the dominant northeasterly strike of the Appalachian mountain belt in New England. Rocks known as the Lowerre Quartzite, Inwood Marble, and Manhattan Schist crop out in the vicinity of Manhattan. Now metamorphosed into quartzite, schist, and marble, respectively, the Paleozoic rocks of the Manhattan Prong were originally deposited as shallow-water marine sediments. By correlation with less-metamorphosed equivalents farther northward (Stops 3, 6), geologists are confident that the Lowerre-Inwood-Manhattan sequence is of Cambrian and Ordovician age. Recent mapping in Manhattan by Merguerian indicates that the stratigraphy and structure of the Manhattan Schist is much more complex than previously imagined (Topics of On-The-Rocks Trips to Manhattan and the Bronx Parks). For the purposes of today's trip, a simplified cross-sectional view of the Manhattan Prong in the vicinity of the Manhattan Prong is shown in Figure 39. The line of section, A-A', is shown in Figure 10.

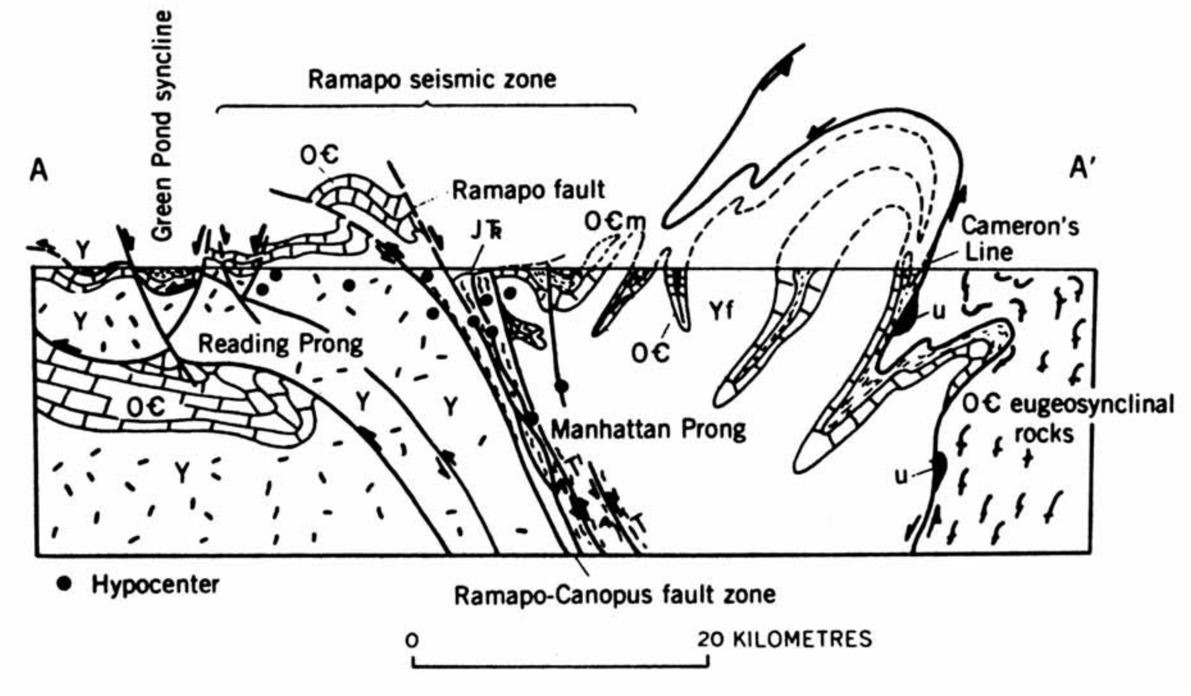


Figure 39. Cross section across the Reading and Manhattan Prongs. From Ratcliffe, 1980.

The Lowerre-Inwood-Manhattan sequence rests unconformably above a much-older sequence of deformed granitic gneiss, schist, and amphibolite gneiss composing the Fordham Gneiss. The Fordham preserves stratigraphic- and structural evidence for deformation that antedates deposition of the Lowerre-Inwood-Manhattan sequence as sedimentary strata. In Westchester, a sample of the Fordham has yielded a uranium-lead date of 1.1 Ga (billion years ago). Together the ancient Fordham substrate and younger Paleozoic rocks represent the deformed, deeply eroded remains of a broad continental shelf facing outward into the lower Paleozoic proto-Atlantic Ocean (Figure 11). In New York City, this ancient continental substrate is the Fordham Gneiss. As such, the Manhattan Prong forms the "Continental Terrane" of eastern North America composed of Proterozoic basement rocks (Fordham and correlatives) and autochthonous (in place) Lower Paleozoic cover rocks (Lowerre-Inwood-Manhattan).

To the east, the Manhattan Prong is in ductile-fault contact (Cameron's Line) with the Hartland Terrane, a vast eugeosynclinal (deep-water) sequence of metamorphosed sedimentary- and volcanic rocks. Detailed mapping and -stratigraphic analysis in western Connecticut indicates that the Hartland Terrane originated, not on a continental shelf, but in the proto-Atlantic (Iapetus) ocean. On either side of Cameron's Line, the unique rock sequences can be traced continuously northward into less- metamorphosed correlatives that contain fossils or datable cross-cutting igneous rocks. As such, the overlapping age of the sequences mandates a major fault between these products of adjacent coeval continental- and oceanic realms.

This boundary, a zone of highly sheared rock known as mylonite, has now been recognized and mapped by many geologists from New York City northward beyond western Connecticut. This important regional contact is within a plate boundary (suture) which marks the easternmost exposures of the basement cover sequence and the westernmost occurrences of thick metavolcanic rock units (Merguerian 1983, 1994). It marks a collisional scar that formed when a volcanic arc and its associated fringing oceanic deposits (Hartland Terrane) were accreted to the Early Paleozoic continental shelf edge (Continental Terrane) during the Medial Ordovician Taconic orogeny (Figure 40).

As we drive northward through the rolling hills of Westchester, views out the van windows will show numerous road cuts (recently enlarged and rendered less prone to shedding rocks onto passing motorists) which expose various units of the Continental Terrane. A diagrammatic cross section of the Manhattan Prong from the Hudson Highlands southeastward to western Connecticut is shown in Figure 39. As a result of their contrasting relative resistances to weathering and glaciation, the valleys of the Manhattan Prong are underlain either by faults or by the Inwood Marble. Less obvious are a series of mafic- to ultramafic plutons (Cortlandt, Rosetown, Stony Point complexes) and cross-cutting dike rocks of Paleozoic- (Beemerville Series) and Mesozoic (Newark Rift Basin Series) ages that have intruded the rocks underlying the Manhattan Prong in southeastern New York.

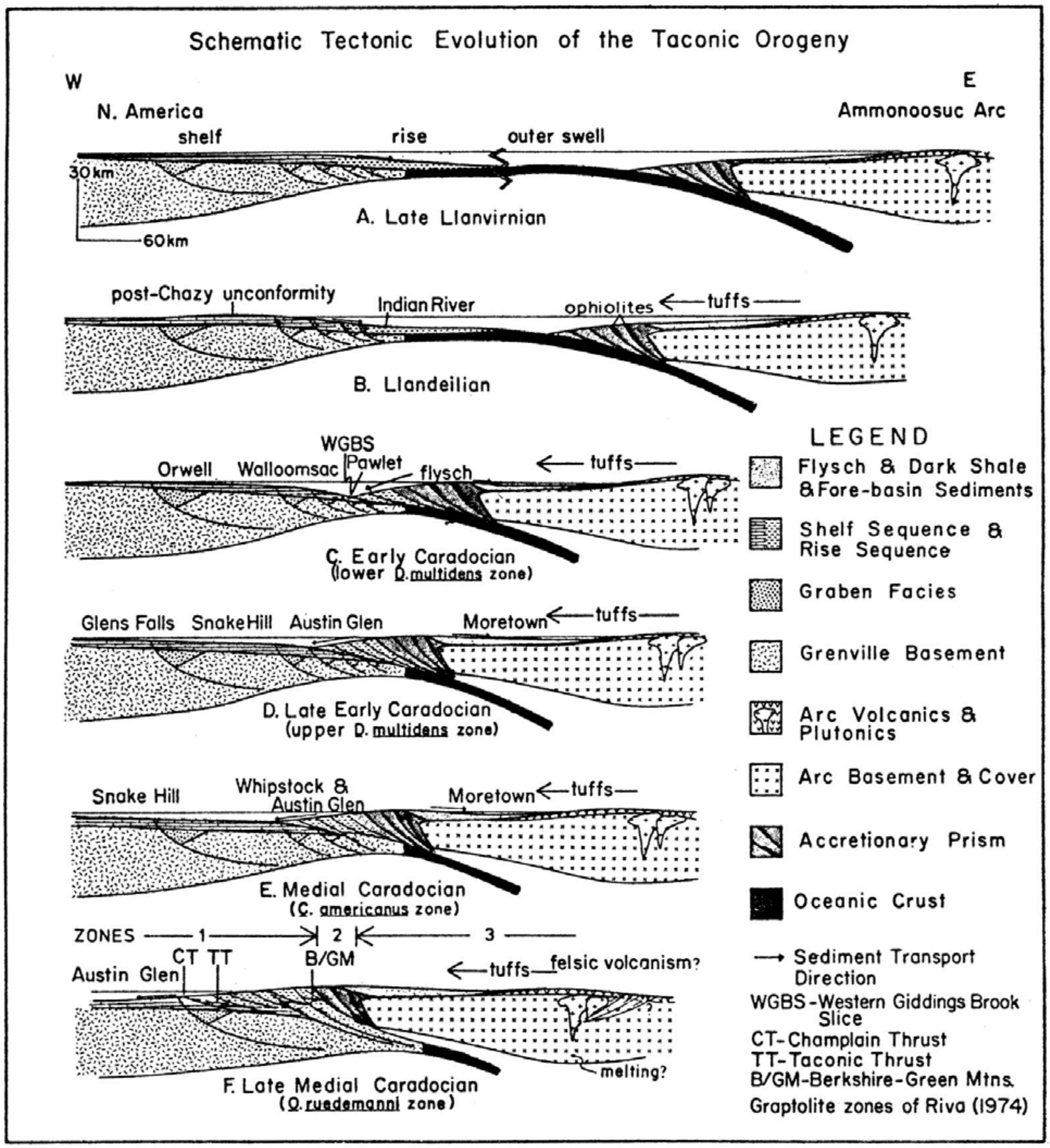


Figure 40. Sequential tectonic cross sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

The following detailed road log for today's trip (On-The-Rocks Trip #30) begins at traffic signal at the junction of NY 117, NY 9A and NY 100 Northbound (near the start of our On-The-Rocks Taconic Trip Log).

0.0 Junction NY Routes 117, 100, and 9A.
0.2 On 9A North. Leave White Plains quadrangle, enter Ossining quadrangle.
0.7 Powerline crossing. Beware of 60-cycle alternating magnetic fields.
1.7 Under bridge where Pleasantville Road crosses (start of Road Log for Taconic trip). Outcrop of Manhattan Schist.
2.0 NY 100 splits off to R. Continue N on NY 9A.
2.3 Traffic signal for North State Road.
3.1 Traffic light. Chappaqua Road intersection.
3.6 Turnoff on R for NY 133 (Croton Avenue).
4.4 New York State Armory on L. Start big curve to L.
5.0 Traffic light at intersection of NY 134 (Croton Dam Road).
5.4-.6 Exposures of Manhattan Schist in cuts.
5.7 View ahead to Hudson Highlands.
5.8 Start long stretch downhill.
6.5 New cuts, Proterozoic rocks on R.
6.55 Join US Route 9. More cuts on R just before bridge.
6.8 Bridge across Croton River. Leave Ossining quadrangle, enter Haverstraw quadrangle.
7.2 Ramp on R for Croton Point Avenue and Croton-Harmon Railroad Station (Metro North).
7.9 Ramp on R for NY 9A, NY 129.
8.6 Ramp on R for Senasqua Road.
9.7 Exposure of bedrock on R. What is it?
10.6 Entering Town of Cortlandt (est. 1788).
10.7 Passing ramp on R for Exit 5 to NY 9A, Montrose.
11.5 Cuts on E side of US 9, igneous rocks of Cortlandt Complex.
11.8 End of cuts on R.
12.2 More cuts exposing Corltlandt igneous rocks on E side of US 9.
12.7 Powerline crossing; end of cuts on R.
12.8 Start of more cuts on R; Cortlandt igneous rocks.
13.0 End of these cuts.
13.3 Cuts on both sides of US 9; more Cortlandt igneous rocks.
Keep R for upcoming exit to R.
13.8 Take ramp on R for exit to US 9A.
13.9 After stop, turn L at bottom of ramp, US 9 southbound.
13.95 Traffic light.
14.1 Turn R into Westchester Diner (formerly known as the New By-pass Diner. After his first meal there, CM said the name ought to be "Triple Bypass Diner." Despite its new name, old-time On-The-Rockers know of it the CM handle). [REST STOP I].

14.1 Leave diner, turn R (south on NY 9A).
14.3 RR underpass. Go uphill to traffic light.
14.4 Turn R onto Bleakley Avenue.
14.5 Pull over to R for STOP 1.

STOP 1 - Igneous flow layering in norite, Pluton V of Cortlandt Complex. [UTM Coordinates: 588.94E / 4568.78N, Peekskill quadrangle.]

The purpose of our initial stop is to examine flow layering in mafic igneous rocks of Pluton V (Norite) of the Cortlandt Complex. We are situated at the western edge of the Central Funnel of Balk (1927) (See Figure 16). Here notice the well-developed, northeast-dipping coarse- to medium-grained norite with an igneous flow lamination composed of plagioclase laths (reddish tint) and hypersthene (an orthopyroxene). Note the northeast-dipping lithologic contact between texturally and mineralogically different phases within the igneous rock, the presence of schlieren (mafic clots), and the compact, dense nature of the mafic rock here.

During intrusion, the refractory nature of these dense, iron+magnesium enriched mafic rocks resulted in great contrasts in temperature across their boundary with the adjacent country rocks. The chilling, progressive effects of contact metamorphism will be examined in detail and discussed at Stop 3.

14.5 Reboard vans, continue ahead on Bleakley Avenue.
14.55 Outcrop on R.
14.6 Outcrops on L.
14.7 Outcrops on R.
14.8 Traffic signal at Indian Point. Turn L onto Broadway.
14.9 Exposure on L; Inwood Marble?
15.6 Outcrop of Manhattan A on R opposite cemetery.
16.0 Turn R on Eleventh Street for exposure at 18.0. but continue ahead for U-turn first.
16.2 Park on R. Exposures on both sides of road.

STOP 2 - Glaciated Inwood Marble and Manhattan Schist? [UTM Coordinates: 587.29E / 4567.44N, Peekskill quadrangle.]

Note the low outcrop on the north side of 11th Street of Cambro-Ordovician marble. Here, both dolomitic- and calcitic marbles are present. They are fine textured and foliated and show some recrystallization to calc-silicate minerals typical of contact metamorphism. The vertical foliation in the marble strikes N15°E. Glacial grooves and scratches on the marble here are oriented N20°E to S20°W.

On the south side of the street occurs marble plus schist(?) phyllite showing glacial striae and grooves trending N7°W. The Manhattan Schist member A (of Hall, 1968) is weakly metamorphosed here according to Ratcliffe and others (1983) and in our opinion is technically a compact, carbonaceous- and pyritiferous phyllite or -slate (We call it the Annsville Phyllite.) showing none of the coarse mica textures typical of schist. Oxidation of the abundant fine pyrite in the rock creates a deep iron-stained weathering color. The phyllitic foliation is oriented N30°E, 60°SE. This stop is included to examine the Manhattan A and to take a sample and to compare it to the Manhattan Schist at Stop 3. Of geologic significance, Stops 2 and 3 are two of the few places where the low regional metamorphic grade allows one to examine the contact between the Cambro-Ordovician carbonates and their Medial Ordovician pelitic cover rocks. As such, the stratigraphic contact here is overturned and dips toward the southeast. We suspect that the calcite marble exposed here should be assigned to the Balmville. If so, then within the marble at this exposure, is the sequence boundary between the Sauk Sequence (dolomitic marbles) and the basal limestone of the Tippecanoe Sequence.

16.2 Continue E on Eleventh Street.
16.25 Turn R onto Broadway (southbound toward Verplanck).
16.4 Traffic light, Eighth Street.
16.5 Turn L in front of Verplanck Post Office at Sixth Street.
16.7 Traffic light at Westchester Avenue.
16.9 Crossing Lake Meahagh.
17.1 Outcrop on R by curve before going uphill.
17.3 Sunset Road on R.
17.4 Blinker light Tate Avenue. Sixth Street is now Kings Ferry Road.
17.5 Outcrop of mafic rocks on R.
17.55 Bannon Road on L.
17.6 Traffic light on curve to R.
17.9 Montrose Point Road to R. Outcrop of mafic rock on curve to L (recently brushed back for our viewing pleasure).
18.1 Crest of hill. Mafic rock exposed on R.
18.3 Traffic light at intersection of NY 9A (New York-Albany Post Road). Turn R onto NY 9A southbound.
18.4 Travis Avenue on R.
18.55 Mafic rocks on L.
18.9 Dutch Street on R for Georges Island Park.
19.0 Entrance on R for Franklin Delano Roosevelt Veterans hospital for Stop 3.
19.05 Guard house on R.
19.1 Bear L at double blinker light.
19.5 Parking Lot F, after D, and E, on L. Continue on main road.
19.7 Turn L following sign to Picnic Area and River Front Area.
19.75 Where road starts downhill, exposure on R of Cortlandt diorite.
19.8 Small knoll on R by gate is Manhattan Schist (Lower Member). We have just crossed the contact between the diorite and the schist.
19.9 Park in parking lot at bottom, by river for Stop 3.

STOP 3 - Glaciated Manhattan-Inwood contact and the Cortlandt Complex, Franklin Delano Roosevelt Veterans Hospital. [UTM Coordinates: Traverse from 589.55E / 4565.1N to 589.1E / 4565.1N, Haverstraw quadrangle.]

Walk back uphill on the paved road to the glaciated knoll of bedrock. The rounded knoll has been sculpted by glacial ice coming from two directions. As a result, two roche moutonnées intersect so that the asymmetry of the first has been modified by the ice that formed the second. The obvious grooves, oriented N15°E to S15°W at north end of the outcrop that swing to S10°W at the south end, are products of the most-recent glaciation. These grooves all but mask an older general rounding to the surface of the bedrock knoll, which resulted from glacial flow N47°W to

S47°E. Thus, according to our scheme, we see the results of the last two (youngest) glaciations. In the somewhat comparable bi-directional bedrock knoll in Inwood Park that we discovered on our On-The-Rocks Manhattan trip, the inferred order of glacial sculpting is the reverse: the older feature sculpted by ice flowing NNE to SSW was modified by ice flowing from NW to SE.

The Manhattan Schist (Member A) bedrock is a fine-textured, highly laminated mica schist with cm-scale quartzose interlayers and thinner, discontinuous calcareous interlayers now metamorphosed to calc-silicate rock. The schist has been thoroughly recrystallized and peppered with small garnets in the micaceous layers. The pervasive enrichment in garnet is undoubtedly a result of post-regional-foliation contact metamorphism at the margins of one of the plutons of the Cortlandt Complex. Note that the Cortlandt kaersutite-biotite diorite crops out immediately up the road (we noted an exposure in the road log). Therefore, the contact between the "city rock" of the pluton and the "country rock" of which this knoll is a part, would be mapped through the bushes to our east. Note that no garnets are present in the quartzose- and calcareous interlayers. This distribution of garnets illustrates the phenomenon of compositional restriction (namely, no alumina, no garnets!).

The bedrock here has been disharmonically folded; within the foliation are numerous tight- to isoclinal folds (some with floating hinges and sheared-out limbs). Locally, elliptical quartzose pods up to 30 cm long are strung out within the foliation. As a result of refolding and the forceful intrusion of the adjacent Cortlandt Complex, the orientations of the early folds are variable. Nevertheless, they typically plunge N85°W. All of these early structures have been refolded by open folds with axial surfaces trending N75°E, 82°SE and plunging steeply into S45°W. Note how the quartzose layers behaved in a brittle fashion, forming boudins and how the adjacent schistose rocks illustrate ductile flow.

One interesting feature is a small vein of quartz oriented N72°W, 90° on the upper surface of the bedrock knoll. Because it cuts all of the previously mentioned structural features, the vein is obviously a late structure. Note the two tapered "wedges" of quartz that seem to have been displaced roughly 6 cm in a left-lateral sense, thus suggesting the presence of a small strike-slip fault. Careful examination shows that a strike-slip fault interpretation is all wet. The central vein can not be traced very far beyond these two quartz "wedges." The "apparent offset" is not real because the lenticular pods project, with smaller offshoots directly across the thin vein. A preferred interpretation is that the vein, lenticular pods, and their offshoots were all formed at the same time. The are fillings of pre-existing- or developing cracks or joints.

Walk toward the water's edge and up the trail to see an important stratigraphic contact exposed along the edge of the river. Rarely seen by mortals, the contact between the Cambro-Ordovician Inwood Marble and the overlying Manhattan Schist (Member A) crops out in this vicinity. Forming a ledge along the east side of the trail the Manhattan A is a highly laminated, muscovite-rich phyllite with mm-scale calcareous laminae. The contact-induced garnet, so numerous on the knoll, are virtually absent here. This absence demonstrates that contact metamorphism is a spatially limited phenomenon. The foliation and subparallel bedding (compositional layering) are oriented N67°E, 67°NW; a strong stretching-type lineation extends downdip. The Manhattan A is a direct lithostratigraphic correlative of the Annsville Phyllite. The top of the bedrock surface has been glacially polished and grooved. The orientation of the glacial grooves here implies ice flow from N10°E to S10°W, the same direction indicated by the youngest grooves observed at the previous glacially sculpted knoll.

The Inwood-Manhattan A contact is exposed at the water's edge a little farther up the trail and to the left. Here is a unique place where you can actually put a finger on the original medial Ordovician depositional contact between the carbonate-shale protoliths of the Inwood-Manhattan A sequence. We point to the calcareous interlayers in the Manhattan A as evidence of a gradational sedimentary contact between the marble and phyllite. Not far from here, a short distance north, at the Verplanck Point quarry (between Stops 2 and 3) is a famous fossil locality for the Inwood Marble. Pelmatazoan stem plates, of early Paleozoic age, were discovered in the Inwood Marble near the Inwood-Manhattan A contact (Paige, 1956).

The Inwood consists of interlayered dolomitic (buff-colored) and calcite (white- to gray-colored) marble with bedding and foliation parallel, oriented N70°E, 67°NW. An F_2 isoclinal fold, roughly 1 meter long and 15 cm wide, is visible on the top surface of the outcrop. The axial surface of the fold is oriented EW, 71°N with a fold axis plunging 64° into N70°W. Shearing along the limbs is spaced 12-15 centimeters and show 1-3 cm scale right-lateral offset. Joints, oriented N19°W, 87°SW, are prominent in the Inwood at this locality. Vestiges of post-Pleistocene Indian clam bakes can be found at this location! Note the oyster-shell middens decaying out of the soil above the Inwood on the slope leading down to the exposure.

Scramble along the outcrop to the Manhattan A and observe the parallelism of the metamorphic fabric with the foliation in the Inwood. Also note the total lack of garnet and relative low-grade of the micaceous phyllite compared to the garnetiferous Manhattan A exposed on the trail above, a function of relative distance from the edge of the Cortlandt intrusives. Looking south down the axis of the Hudson, Croton Point (On-The-Rocks Trip to Croton Point and Peekskill Hollow) is in the distance to the left (east) and the eroded tilted edges of the strata filling the Newark Basin dip to the right (on the west side of the river).

From here, scramble back up to the trail and walk uphill to the next exposure of Manhattan A in the distance. Here, the Manhattan has been thoroughly recrystallized, and in micaceous layers, garnet is once again abundant. We have re-entered the contact aureole. Briefly, note the abundance of isoclinal folds and the lithologic differences between these rocks and their previously examined counterparts. Follow the trail uphill and to the north. Turn right past the small pond and follow the dirt trail uphill to see the contact between the Manhattan Schist and kaersutite (an alkalic amphibole) diorite (Pluton II) of the Cortlandt Complex. Here, the texture of the diorite is very coarse to pegmatitic. Such textures are inferred to be the result of the availability of abundant water that during contact metamorphism, was flushed from the country rock inward toward the city rock of the pluton. A beautiful example of Bowen's reaction relationship is found here: large, euhedral amphiboles reacted with the magma to form coarse rims of platy biotite.

At the contact, the Manhattan has been thoroughly altered. The contact product is a kyanite-sillimanite-garnet-biotite-plagioclase hornfels. In the cores of the kyanites can be found relict staurolite. The contact-induced development of kyanite is noteworthy in that it marks the westernmost regional presence of this important aluminosilicate index mineral. Studies in geobarometry, comparing contact-induced metamorphic assemblages to those in Manhattan Schist outside the contact aureole, led Ratcliffe and others (1983) to propose that the Cortlandt Complex was intruded at depths of roughly 25 km. Thus, as we traverse across the bedrock surface east of the Hudson River this morning, we are examining a deeply eroded horizontal cross section of the Earth's crust that during the waning stages of the Taconic orogeny, experienced intense folding, and major mafic-ultramafic intrusive activity.

Time to walk back to the vans, have our lunch at the river's edge and move onward to our next few stops. Bathroom facilities are available at Building #1 (First Floor), across from the flagpole.

19.9 Drive back up hill from Stop 3. At yield sign, bear R to retrace route toward toward exit and Route 9A.
20.6 Guard shack.
20.7 Junction with 9A north, turn L.
20.75 Road on L to Georges Island Park.
21.1 Cortlandt plutonic rocks exposed on R.
21.3 Traffic light, Kings Ferry Road on L (to Verplanck).
21.6 Lake Street, Village of Buchanan, New York.
22.0 Bottom of hill.
22.1 Traffic signal for Tate Avenue. New roadcut of norites on R.
22.35 Bleakley Avenue on L.
22.5 Bridge under AMTRAK RR.
22.6 Turn L into Westchester (Triple Bypass) Diner on L. [REST STOP II].

22.8 Turn L out of parking lot and continue ahead for entrance to US 9 North.
22.95 At traffic light, turn R then get set for immediate L under bridge.
23.0 As promised, turn L onto ramp.
23.4 Light pole by blocked off ramp, new cuts on R for mafic rock. Keep R by new entrance ramp.
23.8 Stop on R just before new bridge for Stop 4.

STOP 4 - Poikilitic, flow-layered Cortlandt norite (Pluton V) with spectacular xenolith of contact-metamorphosed Inwood Marble. [UTM Coordinates: 589.65E / 4570.3N, Peekskill quadrangle.]

Just a quick stop here to examine more of the norites of the Central Funnel of Balk (1927). As a result of the extensive shrub clipping and dirt removal by JES and CM in May 1990 (Stop 7 of On-The-Rocks Trip #10), and abundant rain this spring and summer, previously hidden geologic details of this new roadcut have emerged for our view. The mafic rocks before you are orthopyroxene-bearing gabbro (norite) of Pluton V of the Cortlandt Complex. Here, the mafic rocks exhibit poikiloblasts of primary igneous kaersutitic amphibole ranging from 1-4 cm and averaging 2 cm in size. Often confused with metamorphic overgrowths (called porphyroblasts) illustrating sieve texture, true poikilitic textures result from late crystallization of residual magma which produces ghost-like crystals (in this case, amphiboles) that enclose early, preformed crystals of the host igneous rock. In this case, primary kaersutite encloses flow-oriented plagioclase and pyroxene(s). The roadcut before you offers a textbook example of this unique igneous texture.

Of particular interest here, the poikiloblasts enclose flow-layered norite with the layering (oriented N62°E, 32°SE) defined by alternating bands of plagioclase laths (the reddish mineral), and clino- and orthopyroxene. Note, later, that as we drive northward on Route 9, we can see that the igneous layers begin to dip more toward the east and southeast. This change in attitude of the layers is the basis for Balk's Central Funnel, in which he inferred that the attitudes of the flow layers define a conical structure (Figures 16-18).

Cameras ready for an additional "textbook" shot, note the elongate xenolith of folded, contact metamorphosed Inwood (Wappinger equivalent) Marble. The xenolith is roughly 3 m long by 1.5 m high and marks a tight fold of the foliation and parallel compositional layering in the marble. Note how the axial surface of the fold parallels the flow layering of the adjacent norite. The metamorphic + compositional layering is 2-3 cm in thickness and shows contact metamorphism to greenish diopsidic calc-silicate rock within the exposure. Cortlandt norite has intruded into the axial region of the fold producing a "micro-phaccolith" according to On-The-Rocker Bob Cassie and locally has squirted across the metamorphosed layering forming an apophyse extending roughly 15 cm deep into the xenolith. What is more, the norite is chilled against the xenolith with an obvious decrease in grain size within 3-4 cm of the xenolith contact. Note the pyrite crystallized along steep joints at the grass level. Such layers of pyrite are very common. As the paper-thin layer of pyrite decomposes, it forms a limonite coating on joint faces and this colors the rocks a yellowish brown. Although such color changes commonly are cited as evidence that the silicate minerals are being decomposed (changed by chemical weathering), in reality, the silicates can be fresh just behind the iron-stained joint faces on which limonite has formed be destruction of pyrite.

Based on crosscutting geologic relationships noted above (intrusion of norite into axial surface and apophyse), the chilled margin, and the general orientation of the elongate xenolith parallel to the mafic flow layering, the xenolith must have been folded before or possibly during the late stages of the intrusion. If so, then the regional foliation in the marble (as sampled in the xenolith) had been already folded at the time of intrusion of the Cortlandt Complex, as discussed earlier under Geologic Background. According to Ratcliffe and others (1983), the xenoliths may represent pieces of country rock, plucked during sill-like, concordant injections of magma. Many xenoliths of the Inwood are known in this area.

23.8 Back in vans and continue north on Route 9.
23.85 More flow-layered mafic rock of Cortlandt Complex.
23.9 Dip of flow layering becomes steeper toward the SE at about 75x. Fewer joints here but phenomenal layering in the mafic rocks. Near the second bridge, the dip of the layering decreases to about 30°.
24.0 South Street and Hudson Avenue exit. Surface of bedrock exposed in new cut by ramp displays glacial polish. Stay on US 9.
24.3 Bridge over deep valley leading westward into Peekskill Bay.
24.4 Pass ramp on R for US 202, US 6, and NY Route 35.

24.5-.7 Proterozoic rocks light-colored felsic gneisses, etc. in big cut on R. Exposed all around curve to junction at light for Bear Mountain Parkway. Bear L for L turn onto US 9 Northbound.
25.0 Left turn onto US 9 and follow signs. Because of construction on the approach road for the Bear Mountain Bridge in Fall '90, US 9 is also the detour route for US 6 and 202 R.
25.2 Bridge over Annsville Creek and embayment into Peekskill Hollow.
25.3 Turn R on US 9.
25.5 Behind bushes the Proterozoic is exposed where Pleistocene gravel has been removed.
25.6 More Proterozoic behind house.
25.8 Start divided highway with Proterozoic on L exposed by gravel removal.
25.9 On R, Roa Hook Road to Annsville, New York.
26.2 More Proterozoic on R.
26.7 Proterozoic gneiss on L.
26.9 Proterozoic gneiss on L.
27.3 On L, Manitou Road (not the "official detour," but is a shortcut to the Bear Mountain Bridge!)
27.5 Enter Putnam County (from Westchester County).
27.7 Exposed on R, Proterozoic light-colored granitic rock.
27.9 Massive gneisses with strike parallel to US 9 and dips of about 35°E.
28.2 Proterozoic gneisses, foliation dip steeper.
28.3 More gneisses.
28.4 Gneisses on L.
28.7 End of big cut on R inside curve to R. Monastery on R.
29.3 At traffic light, turn L onto NY 403 (also October 1990 detour for US Routes 6 and 202), the road to Garrison, New York.
29.7-.9 Exposure on L Proterozoic gneisses. More ahead.
30.0-.2 Exposures on R with road bending to L.
30.7 Old West Point Road on R.
31.5 Sign on R for Garrison.
31.7 At traffic light, turn L onto NY Route 9D (Bear Mountain - Beacon Highway) southbound.
32.2 Stone gate on L at entrance to Castle Rock, the Hudson River Foundation's Garrison field station.
33.4 Gneisses with steep foliation on both sides of road.
33.7 Gneisses on L, no fabric noticed at 45 MPH.
33.8 More gneisses on L.
33.9 Small exposure on R with glacial polish on top surface.
33.95 Gneisses on R.
34.1 Massive, felsic gneisses on L.
34.2 Gneisses on R.
34.4 Canada Hill (type locality for Canada Hill Gneiss) on L.
34.8 Gneisses on L.
34.9 More of, guess what?, the same, opposite Polhemus Construction Company.
35.0 Junction with Manitou Road (the shortcut mentioned prevously).
35.1 Gneisses both sides of road.
35.5-.7 Gneisses on L.
36.0 Gneisses on L.
36.1-36.3 Westchester County line. Exposure of gneiss on L.

36.4 Turn R for Bear Mountain Bridge over the Hudson River.
36.9 Toll booths at W end of bridge.
37.0 Enter traffic circle and drive 3/4 way around to US Route 9W Southbound.
37.15 Enter US Route 9W Southbound.
37.3 Hessian Lake on R.
37.6 Entrance on R for Bear Mountain Inn.
37.8 Big exposures on R and L of Proterozoic gneiss.
38.1 Gneisses on R.
38.2 Iona Island on L marking old course of the Hudson River.
38.3 Proterozoic gneiss exposing itself on R.
38.5 Hairpin turn to R onto Seven Lakes Drive (can get there from the Inn entrance = preferred way). Proterozoic gneisses are continuously exposed on the L along this road as it winds up the hill.
39.2 Bear Mountain Circle with access road to Inn on R. Continue on Seven Lakes Drive.
39.7 Steep exposure face on R.
40.0 More gneiss exposed on R. Start curve to R.
40.65 Leave Peekskill quadrangle, enter Popolopen Lake quadrangle.
41.1 Make R turn for Perkins Drive (No Buses Please!). Drive to top.
43.2 Start one-way loop near top.
43.3 Park along loop at top for STOP 5.

STOP 5 - Perkins Observatory, crest of Bear Mountain: Proterozoic granitic gneiss with crescentic glacial gouges. [UTM Coordinates: 583.15E / 4573.5N, Popolopen Lake quadrangle.]

During the drive across the Hudson River gorge and up Seven Lakes and Perkins Drives, we hope you have enjoyed the spectacular views both up- and down the river. We've put a lot of work into them! The zig-zag course of the Hudson River has resulted from the river's selecting zones of weakness parallel to joints and faults in the bedrock underlying the Hudson Highlands. Beneath us, the northeast-trending Timp Pass fault skirts along the west side of Anthony's Nose and controls the northward trend of the Hudson River beneath the Bear Mountain Bridge. South of the bridge, the southeasterly bend in the river is controlled by the northwest-southeast-trending Popolopen Creek fault which cuts across the river into the highlands north of Bear Mountain. The narrowness of the gorge served as a natural constriction point for British ships travelling the Hudson (Figure 41). As such, many battles were fought in the Hudson fiord between Constitution (near West Point) and Iona islands. (See diagrams and notes in Part 1.) Large chains and wooden booms were constructed across the Hudson Highlands at various points to stop the British ships and to allow attacks launched from the many coves and inlets along the steep walls of the Hudson gorge.

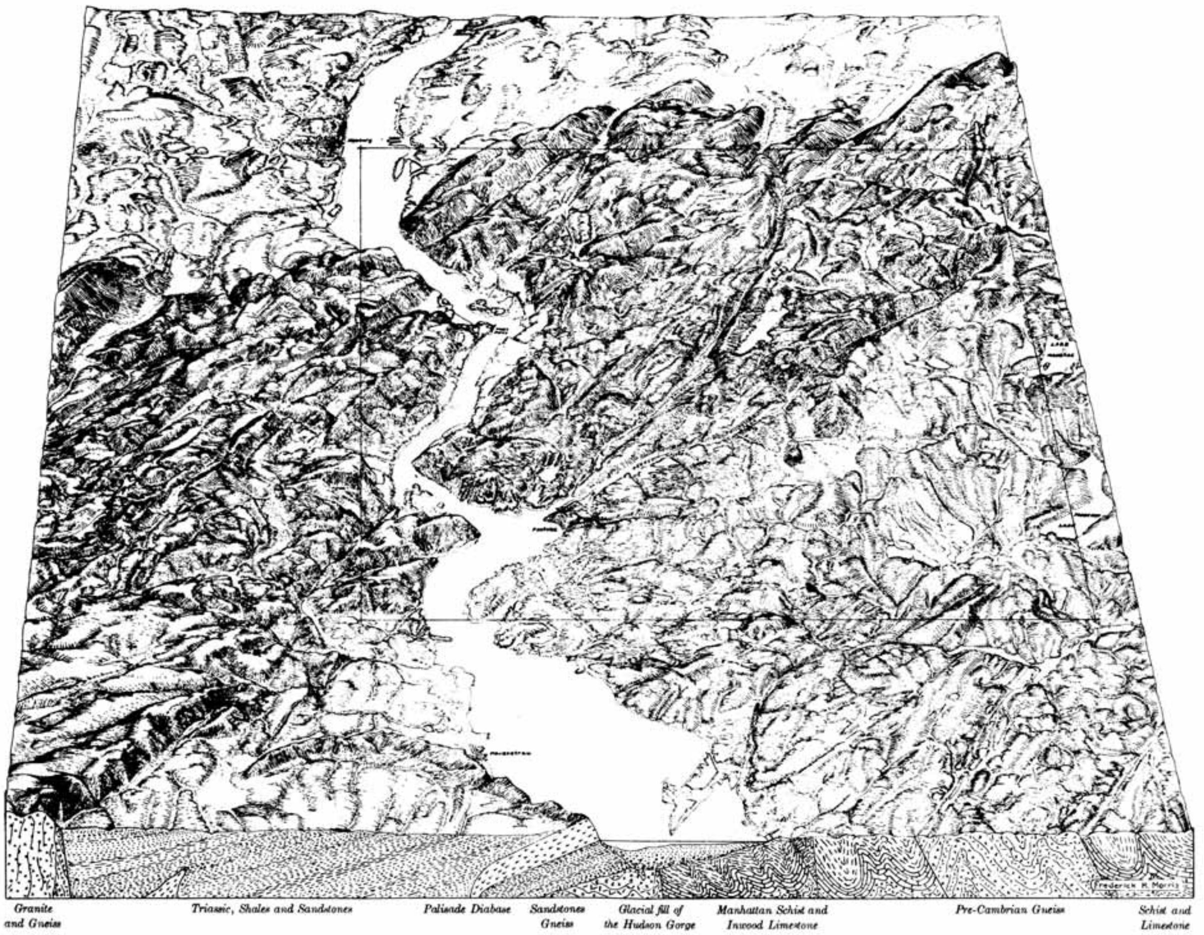


Figure 41. Block diagram of the Hudson Highlands showing the zig-zag course of the river valley. Drawn by F. K. Morris.

Pioneering work by Kurt E. Lowe (1949, 1950) indicates that Bear Mountain is composed of a northward-plunging synform of hornblende granite (Storm King Granite) that was intruded as a phacolith during deformation of the Grenvillian metasedimentary country rocks (Figure 42). The Storm King Granite and associated paragneiss yields 1147 + 43 Ma ages (Helenek and Mose, 1984) and crops out to the west of Hessian Lake forming the main synformal mass of Bear Mountain. Hessian Lake is situated along the contact between the Storm King Granite, the Grenville Series (beneath the lake), and the Canada Hill gneiss (Figure 43). Contact relationships indicate that both the Canada Hill phase (913 + 45 Ma according to Helenek and Mose, 1984) and the Storm King Granite crosscut the Grenville metasedimentary rocks.

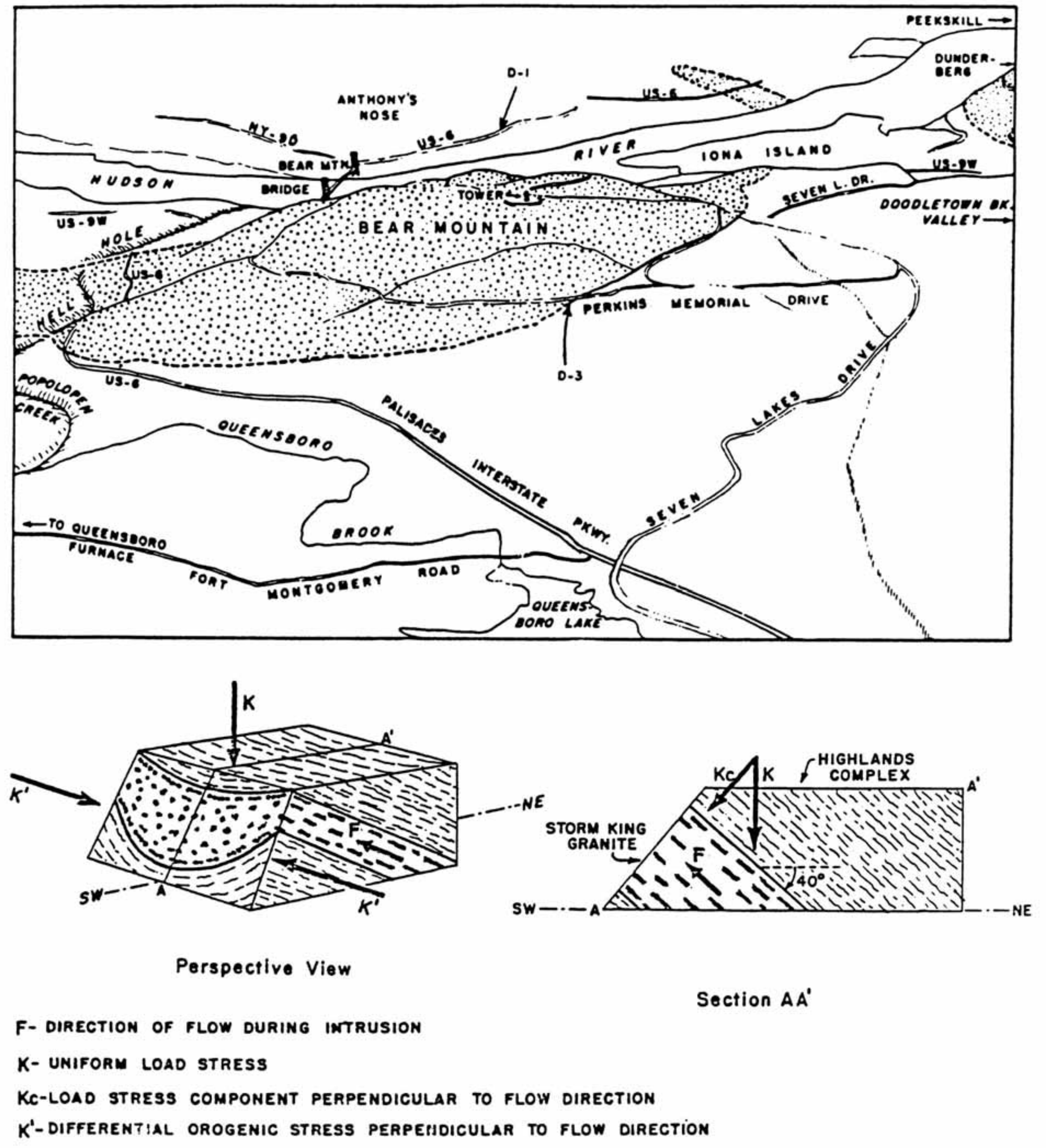


Figure 42. View of Bear Mountain showing K. E. Lowe's interpretation of the phaccoidal structure of the Storm King granite. (From Lowe, 1949, 1950).

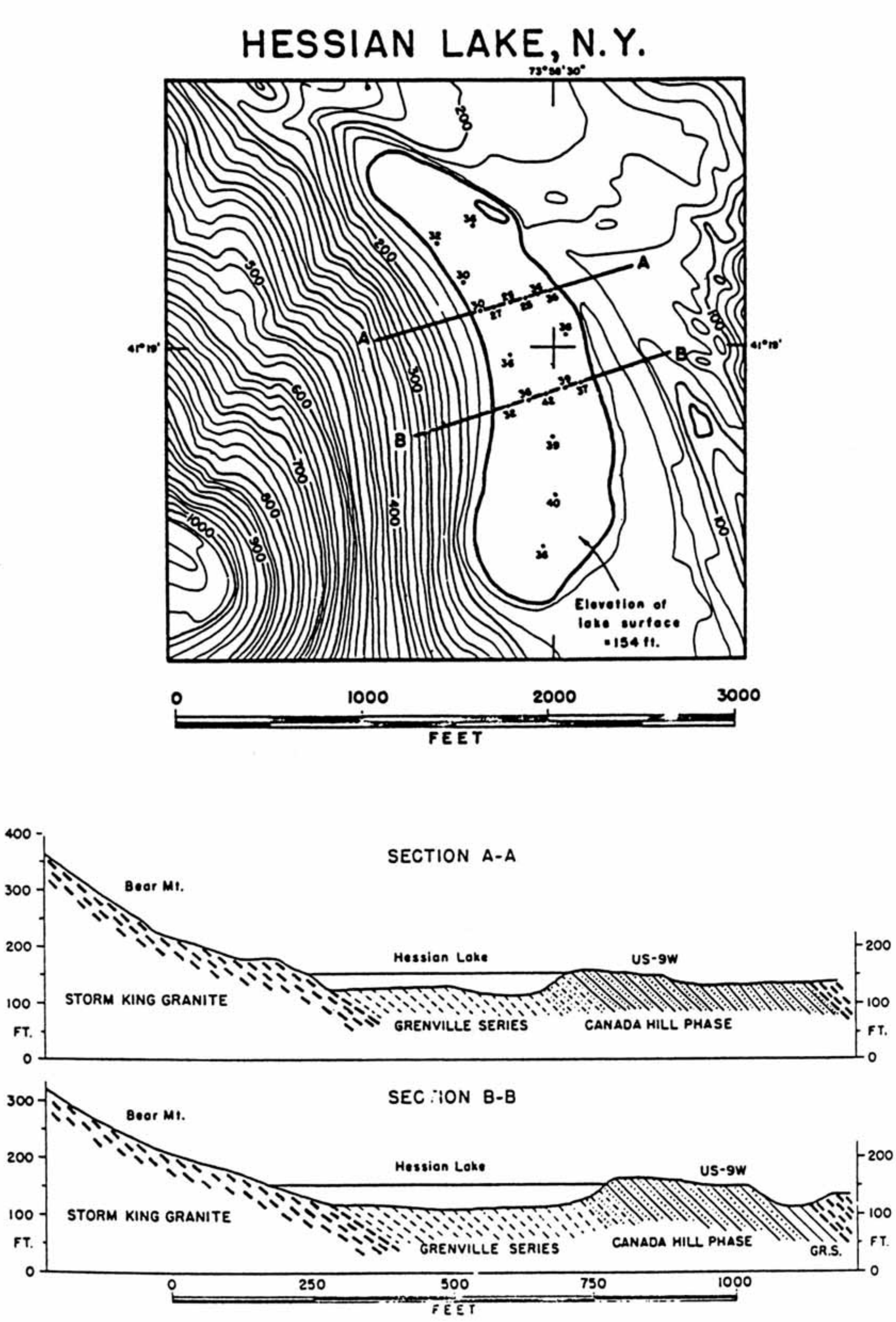


Figure 43. Topographic map and geologic sections across Hessian Lake, immediately north of the Bear Mountain Inn. (Lowe, 1949).

A geologic fault map of the Hudson Highlands (Figure 44) shows the multitude of northeast-trending shear zones (many reactivated during the Mesozoic) that were formed in the Hudson Highlands. Many of these formed during various stages of the Taconic orogeny. Reactivation of these crustal weaknesses along the Ramapo-Canopus fault zone form a linear array of earthquake epicenters (Figure 45) that show reverse-fault first motions. Such motions are inferred to be the result of compression in the North American plate related to modern sea-floor spreading away from the mid-ocean ridge of the Atlantic. (This is somewhat anomalous; eastern North America is supposed to be part of a passive margin that is just going along for the ride. Nevertheless, measurements of strain in the bedrock of eastern North America are about the same as those in California--not at all what one would expect.)

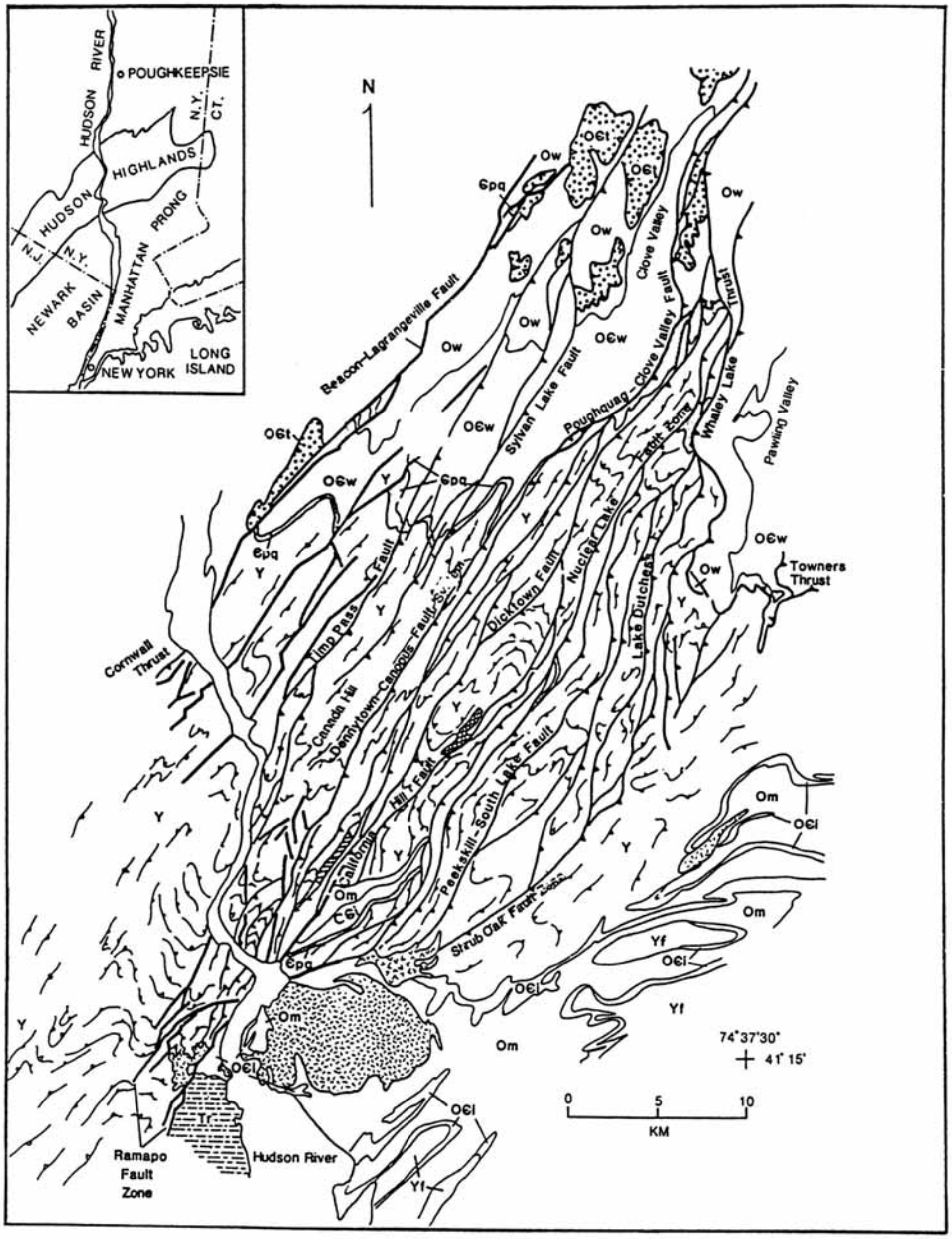


Figure 44. Geologic fault map of the Hudson Highlands.

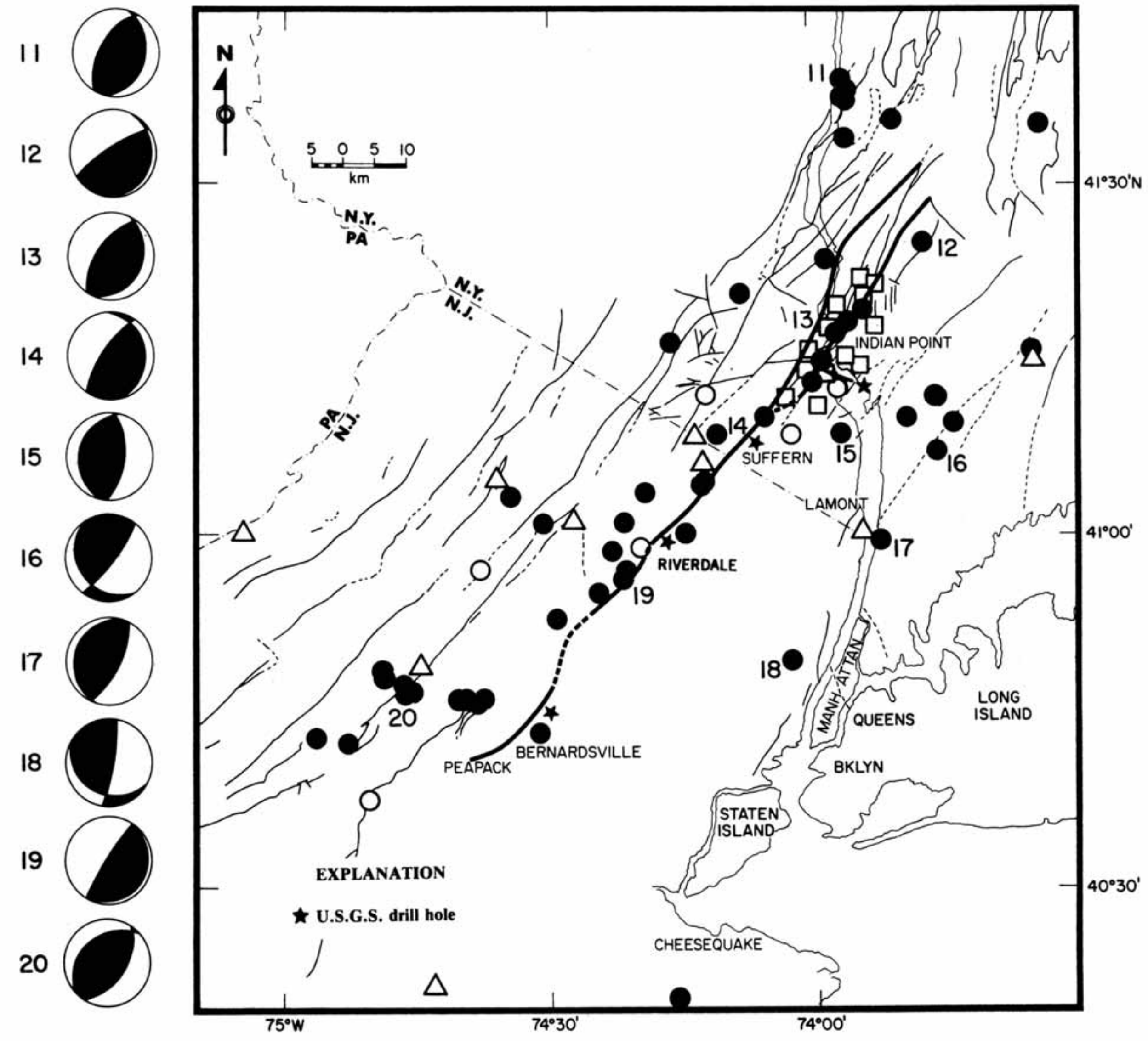


Figure 45. Location of earthquake epicenters and fault-plane solutions for the Ramapo seismic zone. From Ratcliffe, 1980.

Glacial Features

All around us are rounded knolls of Proterozoic gneiss that have been sculpted by glaciers that flowed across the Hudson Highlands. The usual two directions are indicated: from NNE to SSW and from NW to SE. Here, the pattern matches that found in northern Manhattan. The older glacier flowed from the NNE to SSW and shaped rock drumlins and roche moutonnées. The younger glacier came from the NW and flowed SE. This glacier formed the many crescentic marks and smoothed any jagged southern ends of roche moutonnées made by the earlier glacier.

Both glaciers flowed across the Highlands as if they were not a serious obstacle. This implies that these glaciers were very thick (say 8 to 10 km). By contrast, the most-recent Wisconsinan glacier (the Woodfordian) did not leave many traces up here. For other reasons, we can infer that the thickness of the Woodfordian ice was much less than that of the earlier glaciers.

When we leave the top of Bear Mountain, we will drive southward and encounter various units of the highlands complex. Beyond Dunderberg Mountain (Jones Point), we pass across the Ramapo-Canopus fault zone into Mesozoic rocks of the Newark Basin. See if, during our drive southward, you can detect the place where soil color changes from whatever to the characteristic reddish brown of the Newark Supergroup.

43.5 Back at road junction for exit. Bear L then R to exit.
43.55 Bear R for exit downhill on Perkins Drive.
43.8 Sensational view of Hudson River zig-zagging through Highlands on R. Locate Anthonys Nose, Beacon Mountain, the Bear Mountain Bridge, etc.).
45.5 Rejoin Seven Lakes Drive, turn L, headed E.
45.95 Leave Popolopen Lake quadrangle, enter Peekskill quadrangle.
46.7 Splendid view to R of Hudson River at the south end of Iona Island and view of old river course occupied by Snake Hole Creek in Salisbury Meadow.
47.5 Back at traffic circle. Go half way around, following sign for US 9W southbound.
48.2 Stop sign at US 9W and 202. You are now travelling alongside abandoned course of river.
48.5 View of Dunderberg Mountain ahead.
50.5 View of the Indian Point power plant on L. Proterozoic gneiss all along the road for the next 0.2 milies.
50.8 In flatlands along river.
51.2 View to L and Proterozoic gneiss on R.
51.9 Large exposure of gneiss on R with pink feldspar pegmatite cutting felsic- and mafic gneiss. One or more mafic dikes cut the sequence here.
52.5 Steam-power plant owned by Orange-Rockland Utilities on L and gneiss on R.
52.7 Sign for Tompkins Cove village.
53.1 Road junction by Public Library. Along the side street is a cut showing the contact between a mafic dike and the felsic gneiss.
53.6 Powerline crossing overhead.
53.7 Road to Tompkins Cove quarry on L. The quarry removes carbonate rocks of Inwood Marble; a few granitic pegmatite dikes have been uncovered.
53.8 Leave Peekskill quadrangle, enter Haverstraw quadrangle.
53.9 Paleozoic carbonates with vertical dip on L.
54.1 Paleozoic carbonates with vertical dip on L.
54.4 Turn L on Park Road for Stony Point Battlefield and Stop 6.
54.55 Turn L at T-intersection and follow road around to the R.
55.0 Park in front of the wooden bridge to Stony Point Park.

STOP 6 - Stony Point Battlefield and west edge of Cortlandt intrusives (Optional). [UTM Coordinates: 585.62E / 4565.8N, Haverstraw quadrangle.]

We plan to make three small traverses at Stony Point State Park; one south of along the railroad cut to see conglomerate of the Newark Basin, one along the railroad cut that exposes intrusive rocks of the Stony Point-Cortlandt Complex and, a walk through the famous Stony Point battleground.

Along the east side of the CONRAIL tracks south of the entrance to the Stony Point State Historic Park, in a low knoll are exposed red-colored rudites forming the near-basal part of the sedimentary fill of the Newark Basin. Here, in a deeply iron-stained exposure, angular clasts of gray-colored Wappinger Limestone, 3 to 6 cm in size, are set in a reddish sandstone matrix. Crudely developed beds strike roughly N60°W and dip 35°SW. Compared to the basin-marginal rudites exposed near Suffern, New York, which consist of rounded- to angular boulders of Proterozoic gneiss together with quartzite, Green Pond Conglomerate, limestone, reddish shale, and -arkose, the clasts in this exposure are essentially monomict except for rare, but important, clasts of contact-metamorphosed Manhattan A and fine-grained Stony Point dike rocks (Nick Ratcliffe, personal communication 4/94). A likely explanation for this exposure is that during the early Mesozoic episode of uplift, erosion, and deposition in what is now preserved as the northern part of the Newark Basin, the adjacent elevated area had not yet been denuded below the stratigraphic level of the Cambro-Ordovician carbonate rocks that formerly covered the Proterozoic basement complex and that at this locality the clasts travelled a very small distance.

Walk back on the tracks beneath the bridge at the entrance to Stony Point Park. Here, dike rocks and two stock-like masses of mafic- to ultramafic plutonic rock, representing westerly appendages of the Cortlandt Complex across the Hudson River, cut across isoclinally folded, probable lower Paleozoic rocks of the Annsville Phyllite and Inwood Marble (Figures 19, 20). Regionally, the country rocks are less-metamorphosed equivalents of the Manhattan Schist and Inwood Marble, respectively, as suggested by stratigraphic- and paleontologic data from the Tompkins Cove and Verplanck quarries on either side of the Hudson River (Figure 46). Here, the Annsville contains sillimanite (a very high-grade metamorphic index mineral) near the contact with the hornblende pyroxenite (Cortlandtite) intrusives. Poikiloblastic muscovite (related to post-intrusive regional cooling) overgrows the sillimanite contact assemblages (Ratcliffe and others, 1983). This is the type locality for poikilitic Cortlandtite as described by Williams (1885).

Deformational features related to regional folding episodes mapped in the lower Paleozoic country rocks are truncated by the earliest pluton of biotite diorite (Pluton II of the Cortlandt Complex). The diorite and the country rocks are further cut by the cortlandtitic rocks which are correlative and probably continuous with Pluton IV of the eastern "funnel" of the Cortlandt Complex. Dating of these intrusive rocks at 435 Ma established a Taconian age for deformation of the bedrock sequences.

Afterward, walk through the gate to the Stony Point Battlefield exhibit (Figure 47) and walk through the outdoor exhibit in order to relive the important battle that took place here in

July, 1779 (Refer to the historical timeline in Part I). Note the glaciated knolls of diorite that show many crosscutting fine-grained dike rocks. Here, glacial grooves are oriented N3°W.

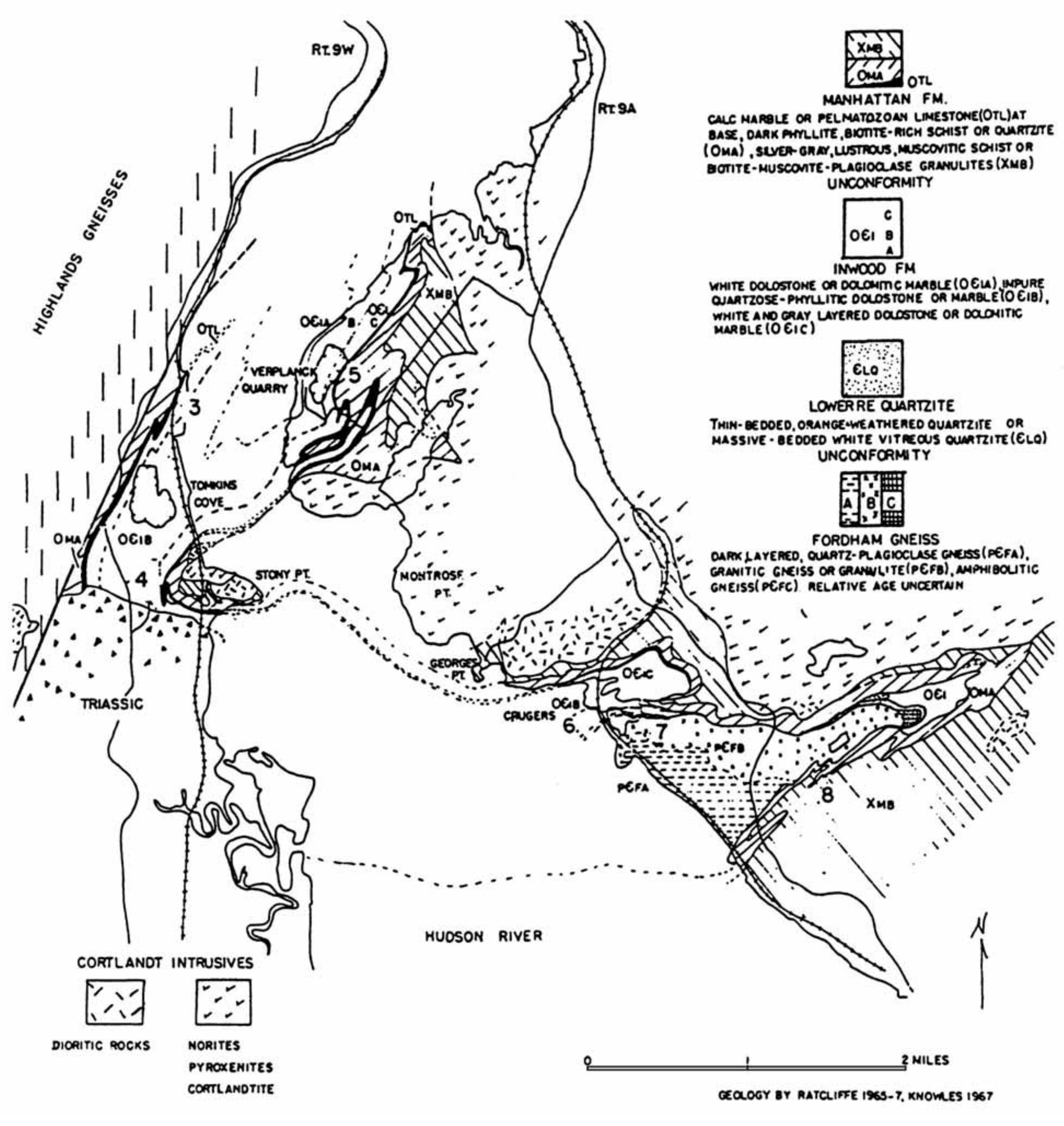
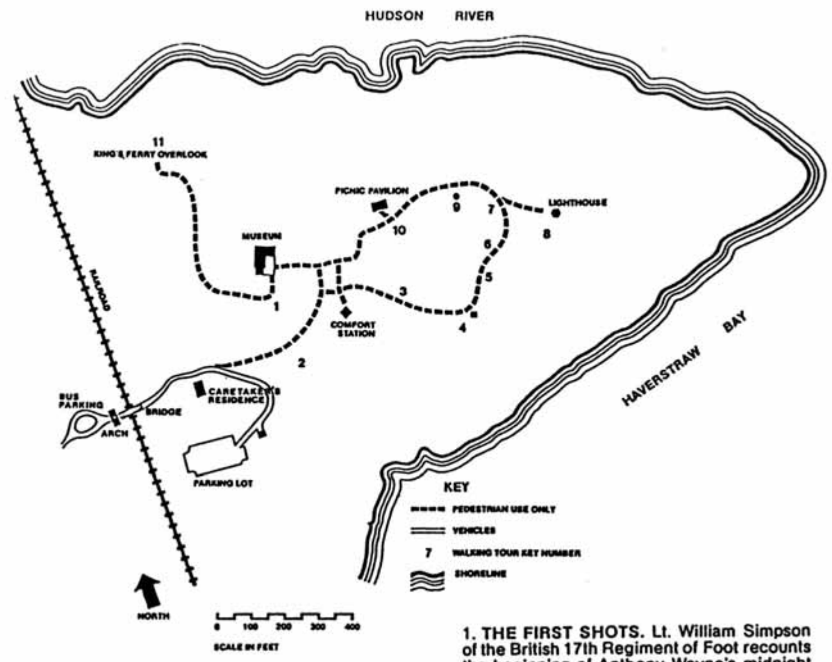


Figure 46. Geologic map of the west edge of the Cortlandt intrusives showing the lithic subdivisions of the Manhattan and Inwood Formations. From Ratcliffe, 1968.



STONY POINT BATTLEFIELD WALKING TOUR

Signs located at various points on Stony Point explain the value of this peninsula as a military fortification, the difficulties encountered by General "Mad Anthony" Wayne and his light infantry during their attack on the night of July 15-16, 1779, and the importance of the small lighthouse on the summit to ships on the Hudson River. The first sign is on the knoll just west of the museum building, and each sign includes a map of the park

1. THE FIRST SHOTS. Lt. William Simpson of the British 17th Regiment of Foot recounts the beginning of Anthony Wayne's midnight assault on Stony Point.

2. WORK H. From this hilltop, Lt. William Horndon of the Royal Artillery vainly tried to stop the right column of American light infantry with cannon fire and grapeshot.

COMMERCE AND THE HUDSON RIVER. This river has been a major avenue of New York's commerce for more than three hundred years.

3. A FLAW IN THE BRITISH DEFENSE. The British learned too late that their troops were divided ineffectually to stop the American attack.

4. WORK F. Had the British gunners arrived at their posts in time, the eight-inch howitzer posted here behind an earthen fortification might have proved devastating to the American attackers.

5. THE UPPER WORKS. Here, you see the remains of the earthen walls which, combined with the natural landscape, formed part of the summit fortifications, the strongest point of what the British commander called his "little Gibraltar."

6. THE FINAL COMBAT. Crying out their watchword "The fort's our own!" the American light infantry overwhelmed the British in the upper works in brief but bloody hand-to-hand combat.

7. HOW DID THE LIGHT INFANTRY SUCCEED? The Americans' victory was nothing short of remarkable, considering the natural and man-made obstacles that they faced. The British, however, had committed several critical blunders.

8. THE BRITISH CAMPAIGN OF 1779. Stony Point was at the center of British plans to draw the Americans into a final and decisive battle, which would finish the rebellion in the colonies. The failure of this strategy marked the end of major British activities in the north.

STONY POINT LIGHT. For one hundred years, the lighthouse on the summit of Stony Point warned ships of hazards on the Hudson River.

9. STONY POINT BECOMES A PARK. This peninsula has been a recreational area since its opening in 1902, under the jurisdiction of the American Scenic and Historic Preservation Society.

10. THE REPERCUSSIONS OF STONY POINT. Anthony Wayne's victory boosted American morale, and journalists seized the opportunity to promote the cause of independence. The British viewed the matter differently.

11. KING'S FERRY. Stony Point was the western side of an important river crossing for American troops and supplies. Its loss to the British hampered transportation and communication between New England and the states to the south.

Figure 47. Sketch map of Stony Point State Park showing the walking tour of the battlefield.

55.0 Reboard vans and drive out the way we came.
55.6 Turn L onto Routes 9W and 202 Southbound.
55.9 Park Road again on L.
56.5 Traffic light in village of Stony Point at junction with East Main Street.
56.6 Bridge over Cedar Pond Brook that flows in a large strike valley near the base of the Newark Supergroup.
56.7 Traffic light and road junction with Central Highway on R. Turn R on Central Highway to join with Palisades Interstate Parkway for return trip option; road log continues on US 9W)
57.4 Road junction with Rockland County Route 98 (Filors Lane).
57.8 Entering West Haverstraw village.
58.0 Traffic light and road junction with Railroad Avenue.
58.7 Entering Haverstraw village.
58.8 US 202 veers off to R toward Suffern, New York. Continue ahead on US 9W Southbound.
59.2 Traffic light and road junction with Westside Avenue on L.
59.6 Traffic light and road junction with New Main Street.
60.3 View of Hudson River on L.
60.8 Palisades Sill exposed on R. At traffic light, bear L on 9W.
61.4 Red sandstone at base of sill exposed on R.

61.8 Junction with Route 304 on R. Stay on 9W. Textbook example of columnar joints in sill on L.
62.4 Bear L to follow 9W. Junction on R for Route 303.
64.2 Traffic light and junction with County Route 80 (Lake Road).
65.5 Blinker light. Entrance on L to Rockland State Park.
66.4 Palisades dolerite exposed on L and R.
66.9 Upper Nyack. Red sandstone and dolerite behind building on R.
67.1 Traffic light at junction with Christian Herald Road.
68.3 Traffic light in Nyack, New York.
68.4 Turn R for NYS Thruway (I-87) Southbound by Gallick Auto Body Works (before Nyack Jeep Eagle).
68.5 Pass under Thruway.
68.8 Traffic light in central Nyack. Turn R for Thruway ramp for I-87, I-287, and Tappan Zee Bridge.
68.85 Turn R again onto I-87 Southbound.
73.8 Toll gate at east end of Tappan Zee Bridge.

END OF ROAD LOG

ACKNOWLEDGEMENTS

We sincerely hope that you have enjoyed today's field trip into the Hudson River Valley. We are indebted to **Don Loprieno** of the Stony Point Historic Site and **Gerry Culliton** of the FDR Hospital at Montrose for granting access for our trips. As always, **Matt Katz** and **Marcie Brenner** have been most helpful in handling the registration of field trip participants.

TABLES

Table 01 - GEOLOGIC TIME CHART

(with selected major geologic events from southeastern New York and vicinity)

ERA **Periods (Epochs)**	**Years (Ma)**	**Selected Major Events**
CENOZOIC		
(Holocene)	0.1	Rising sea forms Hudson Estuary, Long Island Sound, and other bays. Barrier islands form and migrate.
(Pleistocene)	1.6	Melting of last glaciers forms large lakes. Drainage from Great Lakes overflows into Hudson Valley. Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley. Repeated continental glaciation with five? glaciers flowing from NW and NE form moraine ridges on Long Island.
(Pliocene)	6.2	Regional uplift, tilting and erosion of coastal-plain strata; sea level drops. Depression eroded that later becomes Long Island Sound.
(Miocene)	26.2	Fans spread E and SE from Appalachians and push back sea. Last widespread marine unit in coastal-plain strata.
MESOZOIC	66.5	
(Cretaceous)		
	96	Passive eastern margin of North American plate subsides and sediments (the coastal-plain strata) accumulate.
	131	(**Begin Atlantic Passive-Margin Stage II**).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
		Atlantic Ocean starts to open. Newark basins deformed, arched, eroded.
(Triassic)	190	Continued filling of subsiding Newark basins and mafic igneous activity both extrusive and intrusive. Newark basins form and fill with non-marine sediments.

PALEOZOIC	245	
(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line and St. Nicholas Thrusr Zone). Arc-continent collision. Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata.
(Ordovician)		Ultramafic rocks (oceanic lithosphere) sliced off and transported structurally above deposits of continental shelf.
(Cambrian)		Shallow-water clastics and carbonates accumulate in west of basin. (= **Sauk Sequence**; protoliths of the Lowerre Quartzite, Inwood Marble, Walloomsac Schist). Transitional slope/rise sequence (Manhattan Schist) and deep-water terrigenous strata (Hartland Formation) form to east. (= **Taconic Sequence**).
PROTEROZOIC		
	570	Period of uplift, rifting,and erosion followed by subsidence of margin and development of **Iapetan Passive-Margin Stage I**.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).
ARCHEOZOIC		
	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 02 - Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity

This geologic table is a tangible result of the On-The-Rocks Field Trip Program conducted by Drs. John E. Sanders and Charles Merguerian between 1988 and 1998. In Stenoan and Huttonian delight, we here present the seven layer cake model that has proved so effective in simplifying the complex geology of the region. Under continual scrutiny and improvement, we provide this updated web-based information as a public service to all students and educators of geology. We encourage any comments, additions, or corrections. References cited can be sought by following this link.

LAYER VII - QUATERNARY SEDIMENTS

A blanket of irregular thickness [up to 50 m or more] overlying and more or less covering all older bedrock units. Includes four or five tills of several ages each of which was deposited by a continental glacier that flowed across the region from one of two contrasting directions: (1) from N10°E to S10°W (direction from Labrador center and down the Hudson Valley), or (2) from N20°W to S20°E (direction from Keewatin center in Hudson's Bay region of Canada and across the Hudson Valley). The inferred relationship of the five tills is as follows from youngest [I] to oldest [V]. [I] - Yellow-brown to gray till from NNE to SSW, [II] - red-brown till from NW to SE, [III] - red-brown till from NW to SE, and [IV] - yellow-brown to gray till from NNE to SSW, and [V] - red-brown till from NW to SE containing decayed stones (Sanders and Merguerian, 1991a,b, 1992, 1994a, b; Sanders, Merguerian, and Mills, 1993; Sanders and others, 1997; Merguerian and Sanders, 1996). Quaternary sediments consist chiefly of till and outwash. On Long Island, outwash (sand and gravel) and glacial lake sediment predominates and till is minor and local. By contrast, on Staten Island, tills and interstratified lake sediments predominate and sandy outwash appears only locally, near Great Kills beach.

[Pliocene episode of extensive and rapid epeirogenic uplift of New England and deep erosion of major river valleys, including the excavation of the prominent inner lowland alongside the coastal-plain cuesta; a part of the modern landscape in New Jersey, but submerged in part to form Long Island Sound].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER VI - COASTAL-PLAIN STRATA (L. Cretaceous to U. Miocene; products of Passive Continental Margin II - Atlantic).

Marine- and nonmarine sands and clays, present beneath the Quaternary sediments on Long Island (but exposed locally in NW Long Island and on SW Staten Island) and forming a wide outcrop belt in NE New Jersey. These strata underlie the submerged continental terrace. The basal unit (L. Cretaceous from Maryland southward, but U. Cretaceous in vicinity of New York City) overlaps deformed- and eroded Newark strata and older formations. Also includes thick (2000 m) L. Cretaceous sands and shales filling the offshore Baltimore Canyon Trough. At the top are Miocene marine- and coastal units that are coarser than lower strata and in many localities SW of New Jersey, overstep farther inland than older coastal-plain strata. Capping unit is a thin (<50 m) sheet of yellow gravel (U. Miocene or L. Pliocene?) that was prograded as SE-directed fans from the Appalachians pushed back the sea. Eroded Newark debris is present in L. Cretaceous sands, but in U. Cretaceous through Miocene units, Newark-age redbed debris is conspicuously absent. This relationship is considered to be proof that the coastal-plain formations previously buried the Newark basins so that no Newark-age debris was available until after the Pliocene period of great regional uplift and erosion. The presence of resistant heavy minerals derived from the Proterozoic highlands part of the Appalachians within all coastal-plain sands indicates that the coastal-plain strata did not cover the central highlands of the Appalachians.

[Mid-Jurassic to Late Jurassic episode of regional arching of Newark basin-filling strata and end of sediment accumulation in Newark basin; multiple episodes of deformation including oroclinal "bending" of entire Appalachian chain in NE Pennsylvania (Carey, 1955), and one or more episodes of intrusion of mafic igneous rocks, of folding, of normal faulting, and of strike-slip faulting (Merguerian and Sanders, 1994b). Great uplift and erosion, ending with formation of Fall-Zone planation surface].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER V - NEWARK BASIN-FILLING STRATA (Upper Triassic and Lower Jurassic)

Newark-age strata unconformably overlie folded- and metamorphosed Paleozoic strata of Layer II and some of the Proterozoic formations of Layer I; are in fault contact with other Proterozoic formations of the Highlands complex. Cobbles and boulders in basin-marginal rudites near Ramapo Fault include mostly rocks from Layers III, IIB, and IIA(W), which formerly blanketed the Proterozoic now at the surface on the much-elevated Ramapo Mountains block. The thick (possibly 8 or 9 km) strata filling the Newark basin are nonmarine.

In addition to the basin-marginal rudites, the sediments include fluvial- and varied deposits of large lakes whose levels shifted cyclically in response to climate cycles evidently related to astronomic forcing. A notable lake deposit includes the Lockatong Formation, with its analcime-rich black argillites, which attains a maximum thickness of about 450 m in the Delaware River valley area. Interbedded with the Jurassic part of the Newark strata are three extrusive complexes, each 100 to 300 m thick, whose resistant tilted edges now underlie the curvilinear ridges of the Watchung Mountains in north-central New Jersey. Boulders of vesicular basalt in basin-marginal rudites prove that locally, the lava flows extended northwestward across one or more of the basin-marginal faults and onto a block that was later elevated and eroded. The thick (ca. 300 m) Palisades intrusive sheet is concordant in its central parts, where it intrudes the Lockatong at a level about 400 m above the base of the Newark strata. To the NE and SW, however, the sheet is discordant and cuts higher strata (Merguerian and Sanders, 1995a). Contact relationships and the discovery of clastic dikes at the base of the Palisades in Fort Lee, New Jersey, suggest that the mafic magma responsible for the Palisades was originally intruded at relatively shallow depths (roughly 3 to 4 km) according to Merguerian and Sanders (1995b).

Xenoliths and screens of both Stockton Arkose and Lockatong Argillite are present near the base of the sill. Locally, marginal zones of some xenoliths were melted to form granitic rocks (examples: the trondhjemite formed from the Lockatong Argillite at the Graniteville quarry, Staten Island, described by Benimoff and Sclar, 1984; and a "re-composed" augite granite associated with pieces of Stockton Arkose at Weehawken and Jersey City, described by J. V. Lewis, 1908, p. 135-137).

[**Appalachian terminal orogeny**; large-scale overthrusts of strata over strata (as in the bedding thrusts of the "Little Mountains east of the Catskills" and in the strata underlying the NW side of the Appalachian Great Valley), of basement over strata (in the outliers NW of the Hudson Highlands, and possibly also in many parts of the Highlands themselves), and presumably also of basement over basement (localities not yet identified). High-grade metamorphism of Coal Measures and intrusion of granites in Rhode Island dated at 270 Ma. Extensive uplift and erosion, ending with the formation of the pre-Newark peneplain].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

Mostly nonmarine coarse strata, about 6 km thick, including thick coals altered to anthracite grade, now preserved only in tight synclines in the Anthracite district, near Scranton, NE Pennsylvania; inferred to have formerly extended NE far enough to have buried the Catskills and vicinity in eastern New York State (Friedman and Sanders, 1982, 1983).

[**Acadian orogeny**; great thermal activity and folding, including metamorphism on a regional scale, ductile deformation, and intrusion of granites; dated at ~360 Ma].

LAYER III - MOSTLY MARINE STRATA OF APPALACHIAN BASIN AND CATSKILLS (Carbonates and terrigenous strata of Devonian and Silurian age)

(Western Facies)	**(Eastern Facies)**
Catskill Plateau, Delaware Valley monocline, and "Little Mountains" NW of Hudson-Great Valley lowland.	SE of Hudson-Great Valley lowland in Schunnemunk-Bellvale graben.
Kaaterskill redbeds and cgls.	Schunnemunk Cgl.
Ashokan Flags (large cross strata)	Bellvale Fm., upper unit
Mount Marion Fm. (graded layers, marine)	Bellvale Fm., lower unit (graded layers, marine)
Bakoven Black Shale	Cornwall Black Shale

Onondaga Limestone	
Schoharie buff siltstone	Pine Hill Formation
Esopus Formation	Esopus Formation
Glenerie Chert	
Connelly Conglomerate	Connelly Conglomerate
Central Valley Sandstone	
Carbonates of Helderberg Group	Carbonates of Helderberg Group
Manlius Limestone	
Rondout Formation	Rondout Formation
Decker Formation	
Binnewater Sandstone	Poxono Island Formation
High Falls Shale	Longwood Red Shale
Shawangunk Formation	Green Pond Conglomerate

[**Taconic orogeny**; 480 Ma deep-seated folding, dynamothermal metamorphism and mafic- to ultramafic (alkalic) igneous intrusive activity (dated in the range of 470 to 430 Ma) across suture zone (Cameron's Line-St. Nicholas thrust zones). Underthrusting of shallow-water western carbonates of Sauk Sequence below supracrustal deep-water eastern Taconic strata and imbrication of former Sauk-Tippecanoe margin. Long-distance transport of strata over strata has been demonstrated; less certain locally is proof of basement thrust over strata and of basement shifted over basement. In Newfoundland, a full ophiolite sequence, 10 km thick, has been thrust over shelf-type sedimentary strata]. In NYC and throughout New England, dismembered ophiolite is common (Merguerian 1979; Merguerian and Moss 2005, 2007).

~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~

LAYER II - CAMBRO-ORDOVICIAN CONTINENTAL-MARGIN COVER (Products of Passive Continental Margin I - Iapetus). Subdivided into two sub layers, IIB and IIA. Layer IIA is further subdivided into western- and eastern facies.

LAYER IIB - TIPPECANOE SEQUENCE - Middle Ordovician flysch with basal limestone (Balmville, Jacksonburg limestones).

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Walloomsac Schist
Normanskill Fm. / Annsville Phyllite

Subaerial exposure; karst features form on Sauk (Layer IIA[W]) platform.

~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~

LAYER IIA [W] - SAUK SEQUENCE	**LAYER IIA [E] - TACONIC SEQUENCE**
Western shallow-water platform (L. Cambrian - M. Ordovician)	**Eastern deep-water zone** (L. Cambrian-M. Ordovician)
Copake Limestone (Stockbridge,	
Rochdale Limestone (Inwood Marble)	
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm.
Stissing Dolostone	
Poughquag Quartzite	
Lowerre Quartzite	
Ned Mtn Fm.	

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). In New Jersey, metamorphosed rift facies rocks are mapped as the Chestnut Hill Formation of A. A. Drake, Jr. (1984)].

~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~

LAYER I - PROTEROZOIC BASEMENT ROCKS

Many individual lithologic units including Proterozoic Z and Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks identified, but only a few attempts have been made to decipher the stratigraphic relationships; hence, the three-dimensional structural relationships remain obscure. Followed by a period of uplift and erosion.

~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~

[**Grenville orogeny**; deformation, metamorphism, and plutonism dated about 1,100 Ma. After the orogeny, an extensive period of uplift and erosion begins. Grenville-aged (Proterozoic Y) basement rocks include the Fordham Gneiss of Westchester County, the Bronx, and the subsurface of western Long Island (Queens and Brooklyn Sections, NYC Water Tunnel #3), the Hudson Highland-Reading Prong terrane, the Franklin Marble Belt and associated rocks, and the New Milford, Housatonic, Berkshire, and Green Mountain Massifs.]

~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~

In New Jersey and Pennsylvania rocks older than the Franklin Marble Belt and associated rocks include the Losee Metamorphic Suite. Unconformably beneath the Losee, in Pennsylvania, Proterozoic X rocks of the Hexenkopf Complex crop out.
~~~~~~~~~~~~~~~~~~~~

Table 03 – Proposed new classification of the Pleistocene deposits of New York City and vicinity (Sanders and Merguerian, 1998, Table 2)

Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	I	NNE to SSW	Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.
Mid-Wisconsinan (?)			Paleosol on Till II, SW Staten Island.
Early Wisconsinan(?)	II	NW to SE	Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.
Sangamonian(?)			Wantagh Fm. (in Jones Beach subsurface).
Illinoian(?)	IIIA	NW to SE	Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).
	IIIB		Manhasset Fm. of Fuller (with middle Montauk Till Member; in lower member, coarse delta foresets (including debris flows) deposited in Proglacial Lake Long Island dammed in on S by pre-Ronkonkoma terminal moraine.
	IIIC		
Yarmouthian			Jacob Sand, Gardiners Clay.
Kansan(?)	IV	NNE to SSW	Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.
Aftonian(?)			No deposits; deep chemical decay of Till V.
Nebraskan (?)	V	NW to SE	Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.
			Pre-glacial (?) Mannetto Gravel fills subsurface valleys.

REFERENCES CITED

Abdel-Monem, A. A., and Kulp, J. L., 1968, Paleogeography and the source of sediments of the Triassic basin, New Jersey, by K-Ar dating: Geological Society of America Bulletin, v. 79, no. 9, p. 1231-1241.

Adams, A. G., 1977, A guide to the Catskills and the region around: Sun Publications

Adams, A. G., 1981, A guidebook to the river: Albany, NY, State University of New York PRess, 424 p.

Adams, A. G., ed., 1980, The Hudson River in literature: An anthology: Albany, NY, State University of New York Press, xxx p.

Agron, S. L., 1980, Environmental geology of the Hackensack meadowlands, p. 215-241 in Manspeizer, Warren, editor, Field studies of New Jersey geology and guide to field trips: New York State Geological Association, Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, New Jersey, Rutgers University, Newark College of Arts and Sciences, Geology Department, 398 p.

American Association of Petroleum Geologists Bulletin, v. 15, p. 657-683.

Anonymous, 1965, Bridges: New Yorker Magazine, 27 November 1965, 41:51.

Arctander, E. H., 1953, Port called New York: Travel, v. 99, p. 15-16 (March 1953).

Averill, S. P., Pardi, R. R., Newman, W. S., and Dineen, R. J., 1980, Late Wisconsin-Holocene history of the lower Hudson region: new evidence from the Hackensack and Hudson River valleys, p. 160-186 in Manspeizer, Warren, editor, Field studies of New Jersey geology and guide to field trips: New York State Geological Association, Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, New Jersey, Rutgers University, Newark College of Arts and Sciences, Geology Department, 398 p.

Balk, R., 1927, Die primare struktur des noritmassivs von Peekskill am Hudson Nordlich, New York: Neues Jahrbuch fur Mineralogy, Berlageband, v. 57, p. 249-303.

Berkey, C. P., 1908, The acid extreme of the Cortlandt series near Pekskill, N. Y. (abs.): Science, n.s., v. 28, p. 575.

Bopp, R. F., and Simpson, H. J., 1989, Contamination of the Hudson River. The sediment record, p. 401-416 in Hamlet, K. S., chm., Contaminated marine sediments--assessment and remediation: U. S. National Research Council, Commission on Engineering and Technical Systems, Marine Board, Committee on Contaminated Marine Sediments: Washington, D. C., National Academy Press, 493 p.

Bopp, R. F., Simpson, H. J., Deck, B. L., and Kostyk, N., 1984, The persistence of PCB components in sediments of the lower Hudson: Northeastern Environmental Science, v. 3, p. 180-184.

Bopp, R. F., Simpson, H. J., Olsen, C. R., and Kostyk, N., 1981, Polychlorinated biphenyls in sediments of the tidal Hudson River, New York: Environmental Science and Technology, v. 15, p. 210-216.

Bopp, R. F., Simpson, H. J., Olsen, C. R., Trier, R. M., and Kostyk, N., 1982, Chlorinated hydrocarbons and radionuclide chronologies in sediments of the Hudson River and estuary, New York: Environmental Science and Technology, v. 16, p. 666-676.

Boyle, R. H., 1969, The Hudson River. A natural (sic) and unnatural history: New York, N. Y., W. W. Norton and Company, Inc., 304 p.

Brock, P. J. C., 1989, Stratigraphy of the northeastern Manhattan Prong, Peach Lake quadrangle, New York-Connecticut, p. 1-27 in Weiss, Dennis, ed., New York State Geological Association Annual Meeting, 61st, Field trip guidebook: Middletown, NY, Orange County Community College, Department of Science and Engineering, 302 p.

Brock, P. J. C., 1993 ms., Geology of parts of the Peach Lake and Brewster quadrangle, southeastern New York and adjacent Connecticut, and basement blocks of the north-central Appalachians: New York, NY, City University of New York Graduate Faculty in Earth and Environmental Sciences, Ph. D. Dissertation, 494 p., 6 plates.

Bruce, Wallace, 1982, The Hudson: New York, NY, Walking News, Inc., 280 p.

Bucher, W. H., 1948, The Cortlandt intrusive: in Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America, 61st Annual Meeting, New York City, p. 33-38.

Burmeister, W. F., 1974, Appalachian waters. 2: The Hudson River and its tributaries: Oakton, VA, Appalachian Books, xxx p.

Busby, M. W., and Darmer, K. I., 1970, A look at the Hudson River Estuary: Water Resources Bulletin, v. 6, no. 5, p. 802-812.

Dana, J.D., 1881, Origin of rocks of the Cortlandt series: American Journal of Science, v. 22, p. 103-112.

Dana, J.D., 1884, Note on the Cortlandt and Stony Point hornblendic (sis) and augitic rock [N. Y.]: American Journal of Science, v. 28, p. 384-386.

Darmer, K. I., 1987, Overview of Hudson River hydrology: New York, N. Y., Hudson River Foundation for Science and Environmental Research, Inc., Report prepared under Grant No. 005/86A/016, 174 p.

Davis, W. M., 1888a, The topographic map of New Jersey: Science, v. 12, p. 206-207.

Davis, W. M., 1888b, Synclinal mountains and anticlinal valleys: Science, v. 12, p. 320.

Davis, W. M., 1890, The rivers of northern New Jersey, with notes on the classification of rivers in general: National Geographic Magazine, v. 2, p. 81-ll0.

Davis, W. M., 1892, The Catskill delta in the postglacial Hudson estuary: Boston Society of Natural History, Proceedings, v. 25, p. 318-335.

Davis, W. M., 1894, The ancient outlet of Lake Michigan: Popular Science Monthly, v. 46, p. 217-229.

Davis, W., M., and Wood, J. W., Jr., 1890, The geographic development of northern New Jersey: Boston Society of Natural History, Proceedings, v. 24, p. 365-423.

Diamant, L., 1983, First trip up the Hudson: Columbia (The Magazine of Columbia University), v. 8, no. 6, p. 22-23, 34-35.

Dunwell, Frances F., 1991, The Hudson River Highlands: New York, NY, Columbia University Press, 264 p.

Encyclopedia Britannica, 11th ed., 1910, Henry Hudson, p. 849-850, Volume XIII: New York, NY, The Enclopaedia Britannica Company, 960 p.

Flint, R. F., 1945, Glacial map of North America: Geological Society of America Special Paper No. 60, p.

Flint, R. F., 1971, Glacial (sic) and Quaternary geology: New York-London-Sydney-Toronto, John Wiley and Sons, Inc., 892 p.

Friedman, G. M., 1956, The origin of the spinel-emery deposits with particular reference to those of the Cortlandt Complex, New York: New York State Museum Bulletin 351, 68p.

Friedman, G. M., and Sanders, J. E., 1978, Principles of sedimentology: New York, John Wiley and Sons, Inc., 792 p.

Giese, G. L., and Barr, J. W., 1967, The Hudson River Estuary--A preliminary investigation of flow and water quality (sic) characteristics: New York State Department of Conservation, Water Resources Commission, Bulletin 61, 36 p.

Gilbert, G. K., 1906, Crescentic gouges on glaciated surfaces: Geological Society of America Bulletin, v. 17, p. 303-306.

Glaeser, J. D., 1966, Provenance, dispersal and depositional environments of Triassic sediments in the Newark-Gettysburg basin: Pennsylvania Geological Survey Report G-43, 168 p.

Haeni, F. D., and Sanders, J. E., 1974, Contour map of the bedrock surface, New Haven-Woodmont quadrangles, Conn.: United States Geological Survey Map, MF 557A.

Hall, L. M., 1968, Times of origin and deformation of bedrock in the Manhattan Prong, in Zen, E-an, White, W., S., Hadley, J. B., and Thompson, J. B., eds., Studies of Appalachian geology, northern and Maritime: Wiley-Interscience, New York, p. 117-127.

Harris, S. E., 1943, Friction cracks and the direction of glacial movement: Journal of Geology, v. 51, p. 244-258.

Helenek, H. L. and Mose, D. G., 1984, Geology and geochronology of Canada Hill granite and its bearing on the timing of Grenvillian events in the Hudson Highlands, New York: p. 57-73 in M. J. Bartholomew, ed., The Grenville event in the Appalachians and related topics, Geological Society of America Special Paper 194, 287 p.

Howell, W. T., 1982, The Hudson Highlands: New York, NY, Walking News, Inc., 488 p.

Jaffe, H. W., and Jaffe, E. B., 1973, Bedrock geology of the Monroe quadrangle, Orange County, New York: New York State Museum and Science Service, Map and Chart Series No. 20, 74 p.

Jones, S. E., 1954, Here's New York harbor: National Geographic Magazine, v. 106, no. 12, p. 773-813 (with map). (Dec 1954)

Kaye, C. A., 1982, Bedrock (sic) and Quaternary geology of the Boston area, Massachusetts, p. 25-40 in Legget, R. F., ed., Geology under cities: Boulder, Colorado, The Geological Society of America, Reviews in Engineering Geology, v. 5, 131 p.

Kazin, A., 1962, Greatest harbor: Holiday, v. 31, p. 42-45 + (Feb 1962)

Kempner, M. J., 1964, Greatest bridge of them all: Verrazano-Narrows bridge: Harper, v. 229, p. 70-76. (Nov. 1964)

Klein, G. deV., 1969, Deposition of Triassic sedimentary rocks in separate basins, eastern North America: Geological Society of America Bulletin, v. 80, no. 9, p. 1825-1832.

Langbein, W. B., 1978, Hydrology (sic) and environmental aspects of Erie Canal (1817-99): U. S. Geological Survey Water-Supply Paper 2038, 92 p.

Leet, L. D., and Judson, S., 1965, Physical geology, 3rd ed.: Englewood Cliffs, New Jersey, Prentice Hall, Inc., 406 p.

Leverett, F., and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: United States Geological Survey Monograph 53, 529 p.
Levorsen, A. I., 1931, Pennsylvanian overlap in United States:

Levorsen, A. I., 1933, Studies in paleogeology: American Association of Petroleum Geologists Bulletin, v. 17, p. 1107-1132.

Levorsen, A. I., 1934, Relation (sic) of oil (sic) and gas pools to unconformities in the Mid-Continent region, p. 761-784 in Wrather, W. E., and Lahee, F. H., eds., Problems of petroleum geology--a symposium (Sydney Powers memorial volume): Tulsa, Oklahoma, American Association of Petroleum Geologists, 1073 p.

Levorsen, A. I., 1943, Discovery thinking: American Association of Petroleum Geologists Bulletin, v. 27, p. 887-928.

Levorsen, A. I., 1960, Paleogeologic maps: San Francisco, W. H. Freeman and Company, 174 p.

Lewis, J. V., 1924, Fissility of shale and its relations (sic) to petroleum: Geological Society of America Bulletin, v. 35, no. 3, p. 557-590.

Longwell, C. R., Flint, R. F., and Sanders, J. E., 1969, Physical geology: New York, John Wiley and Sons, Inc., 685 p.

Lowe, K. E., 1949, The granite problem in the Hudson Highlands: Transactions of the New York Academy of Sciences, Series II, v. 12, p. 49-54.

Lowe, K. E., 1950, Storm King granite at Bear Mountain, New York: Geological Society of America Bulletin, v. 61, no. 3, p. 137-190.

MacClintock, P., 1953, Crescentic crack, crescentic gouge, friction crack, and glacier movements: Journal of Geology, v. 61, no. 2, p. 186.

Mack, A. C., 1982, The Palisades of the Hudson: New York, NY, Walking News, INc., 64 p.

McCrone, A. W., 1966, The Hudson River estuary: hydrology, sediments, and pollution: Geographical Review, v. 56, p. 175-189.

McCrone, A. W., and Schafer, C., 1966, Geochemical (sic) and sedimentary environments of Foraminifera in the Hudson River estuary, New York: Micropaleonotology, v. 12, p. 505-509.

McNeer, May, 1962, The Hudson: River of history: Westport, CT, Gerrard Publishing Company, xxx p.

Merguerian, C., 1983a, The structural geology of Manhattan Island, New York City (NYC), New York (abs.): Geological Society of America Abstracts with Programs, v. 15, p. 169.

Merguerian, C., 1983b, Tectonic significance of Cameron's Line in the vicinity of the Hodges Complex - an imbricate thrust model for Western Connecticut: American Journal of Science, v. 283, p. 341-368.

Merguerian, C., 1986a, Tunnel vision - a deep view of the bedrock geology of New York City (NYC) (abs.): Geological Society of America Abstracts with Programs, v. 18, p. 54-55.

Merguerian, C., 1986b, The bedrock geology of New York City (NYC) (abs.): in Symposium on the Geology of Southern New York, Abstracts with Programs, Hofstra University, New York, p. 8.

Merguerian, C., and Baskerville, C., 1987, The geology of Manhattan Island and the Bronx, New York City, New York: in D.C. Roy, ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, p. 137-140.

Merguerian, C., Baskerville, C. A., and Okulewicz, S., 1982, Cameron's Line in the vicinity of New York City (abs.): Geological Society of America Abstracts with Programs, v. 14, p. 65.

Merguerian, Charles, 1994, Stratigraphy, structural geology, and ductile- and brittle faults of the New York City area: Geology of Long Island and Metropolitan New York, Long Island Geologists Meeting, State University of New York at Stony Brook, 23 April 1994, p. 49-56.

Merguerian, Charles; and Sanders, J. E., 1994a, Danbury anticline of Sanders (1960) revisited: post-depositional structural explanation for northeast end of Newark basin, Rockland Co., NY (abs.): Geological Society of America, Abstracts with Programs, v. 26, no. 3, p. 62.

Merguerian, Charles; and Sanders, J. E., 1994b, Post-Newark folds and -faults: implications for the geologic history of the Newark basin: Geology of Long Island and Metropolitan New York, Long Island Geologists Meeting, State University of New York at Stony Brook, 23 April 1994, p. 57-64.

Millington, B. R., 1930, Glacial topography and agriculture in central Massachusetts: Economic Geography, v. 6, no. 4, p. 1-8.

Multhauf, R. P., 1971, The French crash program for saltpeter production, 1776-96: Technology and Culture, v. 12, p. 163-181.

Newman, W. S., Thurber, D. L., Krinsley, D. H., and Sirkin, L. A., 1968, Trip F: The Pleistocene geology of the Montauk Peninsula, p. 155-173 in Finks, R. M., ed., New York State Geological Association, Annual Meeting, 40th, May 1968, Flushing, New York: Queens College of the City University of New York, Department of Geology, 253 p.

Newman, W. S., Thurber, D. L., Zeiss, H. S., Rokach, A., and Musich, L., 1969, Late Quaternary geology of the Hudson River estuary--a preliminary report: New York Academy of Sciences, Transactions, series 2, v. 31, no. 5, p. 548-569.

O'Brien, R. J., 1981, America sublime: Landscape and scenery of the Lower Hudson Valley: New York, NY, Columbia University Press, 336 p.

Olsen, C. R., Cutshall, N. H., Larsen, I. L., Simpson, H. J., Trier, R. M., and Bopp, R. F., 1985, An estuarine fine-particle budget determined from radionuclide tracers: Geo-Marine Letters, v. 4, p. 157-160.

Olsen, C. R., Simpson, H. J., Bopp, R. F., Williams, S. C., Peng, T.-H., and Deck, B. L., 1978, A geochemical analysis of the sediments and sedimentation in the Hudson estuary: Journal of Sedimentary Petrology, v. 48, p. 401-418.

Olsen, C. R., Simpson, H. J., Peng, T.-H., Bopp, R. F., and Trier, R. M., 1981, Sediment mixing (sic) and accumulation rate (sic) effects on radionuclide depth profiles in Hudson estuary sediments: Journal of Geophysical Research, v. 86, p. 11020-11028.

Olsen, P. E., 1980, Triassic and Jurassic formations of the Newark basin, p. 2-39 in Manspeizer, Warren, editor, Field studies of New Jersey geology and guide to field trips: New York State Geological Association, Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, New Jersey, Rutgers University, Newark College of Arts and Sciences, Geology Department, 398 p.

Owens, J. P., Stefannson, Karl, and Sirkin, L. A., 1974, Chemical (sic), mineralogic (sic), and palynologic character (sic) of the Upper Wisconsinan-Lower Holocene fill in parts of Hudson, Delaware, and Chesapeake estuaries: Journal of Sedimentary Petrology, v. 44, no. 2, p. 390-408.

Paige, S., 1956, Cambro-Ordovician age of the "Inwood" limestone and "Manhattan" schist near Peekskill, New York: Geological Society of America Bulletin, v. 67, no. 3, p. 391-394.

Price, Willard, 1962, Henry Hudson's river: National Geographic Magazine, v. 121, no. 3, p. 364-403. (Photographs by Wayne Miller).

Ransom, J. M., 1966, Vanishing ironworks of the Ramapos: New Brunswick, NJ, Rutgers University Press, 382 p.

Ratcliffe, N. M., 1968a, Trip H: Stratigraphic and structural relations (sic) along the western border of the Cortlandt intrusives, in Finks, R. M., ed., Guidebook to field excursions: New York State Geological Association, 40th Annual Meeting, Queens College, Flushing, New York, p. 197-220.

Ratcliffe, N. M., 1968b, Contact relations (sic) of the Cortlandt complex at Stony Point, New York, and their regional implications: Geological Society of America Bulletin, v. 79, p. 777-786.

Ratcliffe, N. M., 1971, The Ramapo fault system in New York and adjacent northern New Jersey: a case of tectonic heredity: Geological Society of America Bulletin, v. 82, no. 1, p. 125-142.

Ratcliffe, N. M., 1981, Cortlandt-Beemerville magmatic belt: a probable late Taconian alkalic cross trend in the central Appalachians: Geology, v. 9, no. 7, p. 329-335.

Ratcliffe, N. M., Armstrong, R. L., Mose, D. G., Seneschal, R., Williams, R., and Baramonte, M. J., 1982, Emplacement history and tectonic significance of the Cortlandt Complex and related plutons, and dike swarms in the Taconide zone of southeastern New York based on K-Ar and Rb-Sr investigations: American Journal of Science, v. 282, p. 358-390.

Ratcliffe, N. M., Bender, J. F., and Tracy, R. J., 1983, Tectonic setting, chemical petrology and petrogenesis of the Cortlandt Complex and related rocks of southeastern New York State: Guidebook for field trip 1, Northeastern Section, Geological Society of America Meeting, Kiamesha Lake, New York, 101p.

Reeds, C. A., 1926, The varved clays at Little Ferry, New Jersey: American Museum Novitates, No. 209, p. 1-16.

Reeds, C. A., 1927, Glacial lakes and clays (sic) near New York City: Natural History, v. 27, p. 55-64.

Reeds, C. A., 1933, The varved clays and other glacial features in the vicinity of New York City: International Geological Congress, 16th, U. S. A., Guidebook 9, p. 52-63.

Reineck, H.-E., and Singh, I. B., 1980, Depositional sedimentary environments, with reference to terrigenous clastics, 2nd revised and updated ed.: Berlin-Heidelberg-New York, Springer-Verlag, 549 p.

Rogers, G. S., 1910, The character (sic) of the Hudson gorge at New York City: School of Mines Quarterly, v. 32, p. 26-42.

Rogers, G. S., 1911a, Original gneissoid structure in the Cortlandt series: American Journal of Science (4), v. 31, p. 125-130.

Rogers, G. S., 1911b, Geology of the Cortlandt series and it emery deposits: Annals of the New York Academy of Sciences, v. 21, p. 11-86.

Sanders, J. E., 1963, Late Triassic tectonic history of northeastern United States: American Journal of Science, v. 261, p. 501-524.

Sanders, J. E., 1974a, Geomorphology of the Hudson Estuary, p. 4-38 in Roels, Oswald, ed., Hudson River colloquium: New York Academy of Sciences, Annals, v. 250, 185 p.

Sanders, J. E., 1974b, Guidebook to field trip in Rockland County, New York: New York, New York, Petroleum Exploration Society of New York, 87 p.

Sanders, J. E., 1981, Principles of physical geology: New York, John Wiley and Sons, Inc., 624 p.

Sanders, J. E., 1989 ms., Sediment-filled deep V-shaped, bedrock-walled valleys underlying New Haven Harbor, Connecticut, revealed by continuous seismic-reflection profiling using sparker- and compressed-air sound sources: 75 p., 16 figs.

Sanders, J. E., 1989a, The PCB-pollution problem in the upper Hudson River: from environmental disaster to "environmental gridlock": Northeastern Environmental Science, v. 8, no. 1, p. iii-iv, 1-86.

Sanders, J. E., 1989b, PCB pollution in the upper Hudson River, p. 365-400 in Hamlet, K. S., chm., Contaminated marine sediments--assessment and remediation: U. S. National Research Council, Commission on Engineering and Technical Systems, Marine Board, Committee on Contaminated Marine Sediments: Washington, D. C., National Academy Press, 493 p.

Sanders, J. E., and Merguerian, Charles, 1994a, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island: Geology of Long Island and Metropolitan New York, Long Island Geologists Meeting, State University of New York at Stony Brook, 23 April 1994, p. 103-116.

Sanders, J. E.; and Merguerian, Charles, 1992a, Directional history of Pleistocene glaciers inferred from features eroded on bedrock, New York metropolitan area, SE NY (abs.): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 72.

Sanders, J. E.; Merguerian, Charles; and Mills, H. C., 1993, "Port Washington Deltas" of Woodworth (1901) revisited: pre-Woodfordian Gilbert-type delta revealed in storm-eroded coastal bluff, Sands Point, New York (abs.): Geological Society of America, Abstracts with Programs, v. 25, no. 6, p. A-308.

Shand, S., 1942, Phase petrology of the Cortlandt Complex: New York: Geological Society of America Bulletin, v. 53, p. 409-428.

Shear, W. G., 1977, Panorama of the Hudson: 200 photos showing both sides of the river from New York to Albany: New York, NY, Gordon Press, xxx p.

Shrock, R. R., 1948, Sequence in layered rocks. A study of features and structures useful for determining top and bottom or order of succession in bedded (sic) and tabular rock bodies: New York-Toronto-London-McGraw-Hill Book Company, Inc., 507 p.

Simpson, H. J., Olsen, C. R., Williams, S. C., and Trier, R. M., 1976, Man-made radionuclides and sedimentation in the Hudson River estuary: Science, v. 194, p. 179-183.

Simpson, Jeffrey, 1981, The Hudson River Eighteen Fifty to Nineteen Eighteen: A photographic portrait: Tarrytown, NY, Sleepy Hollow Press, 208 p.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, no. 2, p. 93-114.

Sloss, L. L., Krumbein, W. C., and Dapples, E. C., 1949, Integrated facies analysis, p. 91-124 in Longwell, C. R., chm., Sedimentary facies in geologic history: Geological Society of America Memoir 39, 171 p.

Steenland, N. C., and Wollard, G. P., 1952, Gravity and magnetic investigation of the structure of the Cortlandt Complex, New York: Geological Society of America Bulletin, v. 63, p. 1075-1104.

Stewart, H. B., Jr., 1958, Upstream bottom currents in New York harbor: Science, v. 127, p. 1113-1115 (09 May 1958).

Thompson, H. D., 1936, Hudson gorge in the Highlands: Geological Society of America Bulletin, v. 47, no. 12, part 1, p. 1831-1848.

van Zandt, Roland, 1971, Chronicles of the Hudson: Three centuries of travelers accounts: New Brunswick, NJ, Rutgers University Press, xxx p.

Vaux, M., 1983, A strong brown god: Columbia (The Magazine of Columbia University, v. 8, no. 6, p. 9-15, 40-41.

Weiss, D., 1974, Late Pleistocene stratigraphy and paleoecology of the lower Hudson River estuary: Geological Society of America Bulletin, v. 85, no. 10, p. 1561-1570.

Williams, G. H., 1884, On the parametamorphism of pyroxene to hornblende in rocks: American Journal of Science, 4th Series, v. 31, p. 125-130.

Williams, G. H., 1885, Hornblende aus St. Lawrence Co., N. Y.; Amphibol-anthophyllite aus der Gegend von Baltimore; uber das Vorkommen des von Cohen als "Hudsonit" bezpichneten Gesteines am Hudson-Fluss: Neues Jahrbuch, v. II, p. 175-177.

Williams, G. H., 1886, The peridotites of the Cortlandt series on the Hudson River near Peekskill: American Journal of Science, v. 31, p. 26-31.

Williams, G. H., 1888a, The gabbros and diorites of the "Cortlandt series" on the Hudson river near Peekskill, N. Y.: American Journal of Science (3), v. 35, p. 438-448.

Williams, G. H., 1888b, The contact metamorphism produced in the adjoining mica schists and limestones by the massive rocks of the "Cortlandt series" near Peekskill, N. Y.: v. 36, p. 254-259.

Williams, G. H., 1888c, The massive rocks and contact phenomena of the Cortlandt series near Peekskill, N. Y.: Johns Hopkins University Circular, v. 7, p. 63-65.

Williams, S. C., Simpson, H. J., Olsen, C. R., and Bopp, R. F., 1978, Sources of heavy metals in sediments of the Hudson River estuary: Marine Chemistry, v. 6, p. 195-213.

Wyckoff, Jerome, 1971, Rock scenery of the Hudson Highlands and Palisades: Glenns Falls, NY, Adirondack Mountain Club, Inc., xxx p.

Filename: DL OTR02 Hudson Highlands.doc