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TRIPS ON THE ROCKS

Guide 09: Geology of Croton Point and Peekskill Hollow, NY

Trip 10: 12 May 1990; Trip 25: 21 November 1992

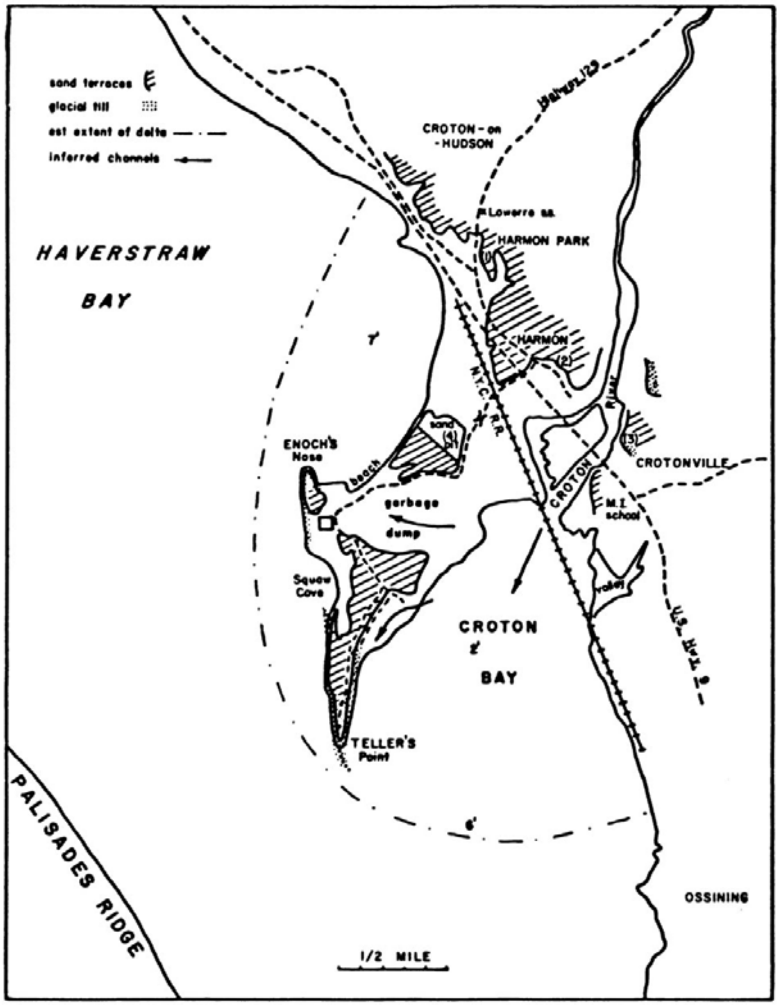

Figure 1 – Location map of Croton Point Park showing the probable extent of deltaic deposits and inferred sediment transport directions. (Markl, 1971, fig. 1, p. 506.)

Field Trip Notes by:

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INTRODUCTION

As a result of our collaboration in preparing for and carrying out these On-The-Rocks field trips, which began in 1988, we have arrived at an interpretation of the glacial history of southeastern New York that differs considerably for what has come to be accepted as the "conventional wisdom" or "revealed truth" or whatever names one cares to apply to the currently fashionable dogma. Our ideas differ so profoundly from the accepted versions that all we can say is that both interpretations could be wrong, but only one of them can be correct. The ultimate test as to whether our new interpretation or the current-consensus interpretation is correct will come from stratigraphic relationships among the Pleistocene glacial- and interglacial sediments. In that connection, Croton Point Park is a key locality. One of the reasons for revisiting Croton Point so soon after our previous trip (May 1990) is to consider how the significant stratigraphic relationships that we have discovered at Croton Point fit with the relationships based on our studies elsewhere (Sanders and Merguerian, 1991, 1992).

According to our interpretation, Croton Point was under seige during numerous discrete advances of Pleistocene continental glaciers. As each glacier advanced, it brought along distinctive boulders set in a matrix of finely pulverized rock flour (together forming a glacial sediment named till) that takes on the average color of the parent rocks from which the glacier eroded the debris. We argue that three and probably four separate Pleistocene glaciations left their mark on this part of New York State in the form of glacial striae, tills, outwash, interglacial marine, and proglacial deltaic- and -lake deposits.

Today's On-The-Rocks field trip to Croton Point Park and Peekskill Hollow is intended to familiarize participants with the glacial- and bedrock geology of the Peekskill area of southeastern New York. See Table 1 for a geologic time chart for the names of the geologic eras and periods, the estimated times of their boundaries, and selected events in the greater New York City region; and Table 2, Generalized descriptions of major geologic "layers," southeastern New York State and vicinity. An expanded section on the Glacial Geology and Drainage History is provided for your reading enjoyment.

We will spend the first half of the day examining glacial-, deltaic-, and lacustrine deposits at Croton Point Park (Figure 1, cover). We will examine the variously colored tills and find them to harbor distinctive suites of boulders that can be traced to regions to the northwest (Newark Basin strata) and to the north-northeast (New England). We will expend considerable effort in trying to identify and categorize the kinds and sizes of the glacial boulders that the river has conveniently washed out of the till and cleaned off for our study, thus affording us an excellent opportunity for a vigorous exercise course in boulder bashing and rock identification. We will spend the afternoon examining nearby parent areas of some very distinctive boulders left by two glaciers that flowed from NNE to SSW (the New England source for ice that flowed down the Hudson Valley). Based on geologic relationships exposed at Croton Point Park and New York City, the older of these two New England glaciers antedated and the younger postdated the widely recognized glacial deposits that resulted from ice that flowed one or more times from NNW to SSE across the Hudson Valley (the Newark source). Thus, by the end of our day, we will have seen the effects of glaciation and have traced back the distinctive glacial boulders parallel to the striae developed on their parent bedrock areas.

Independently of how the glacial stratigraphy of Croton Point is interpreted, two other fascinating topics will be addressed on today's trip. These are (1) the relationship between distinctive indicator stones washed out of the till(s), and their bedrock parent areas, and (2) the postglacial history implied by the results of borings made in connection with the landmark litigation over Westchester County's use of the low central area of Croton Point Park for a landfill. We include a brief summary of this litigation and of Westchester's County's responses to the court orders directed to the County. This summary follows the Geologic Background section.

GEOLOGIC BACKGROUND

Under this heading, we discuss the physiographic setting, bedrock units, the glacial deposits, the drainage history, and local geologic summaries of our field-trip route. Refer to Tables 1 and 2 for details not fully explained in text. Figure 2 offers a panoramic geological/physiographic bird's-eye-view of the Manhattan Prong, Hudson Valley, Newark Basin, and adjacent areas.

Physiographic Setting

The crystalline bedrock exposed in New York City is part of the Manhattan Prong (Figures 2, 3), a terrane that widens northward into the New England Upland physiographic province of the Appalachian mountain belt. The Manhattan Prong is composed of a complexly deformed, northeastly trending sequence of metamorphosed Proterozoic to Lower Paleozoic rocks. Under the heading Bedrock Units - Layers I and II, we describe these rocks in some detail. Suffice it to say here that northeastward, the crystalline bedrock of the region continues extends into Connecticut and Massachusetts; southwestward, near Staten Island, the units plunge beneath younger rocks and -sediments but in the vicinity of Philadelphia, Pennsylvania, they come to the surface again. To the west, this crystalline basement terrane is truncated and unconformably overlain by gently dipping strata consisting of interlayered igneous- and sedimentary units of the Newark Basin (Figures 2, 3). The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, forming the Palisade cliffs, from Stony Point southward to Staten Island. As shown on the diagonal cut-away slice in Figure 2, the Newark strata generally dip about 15° to the northwest and are truncated against the Ramapo fault in New Jersey and New York.

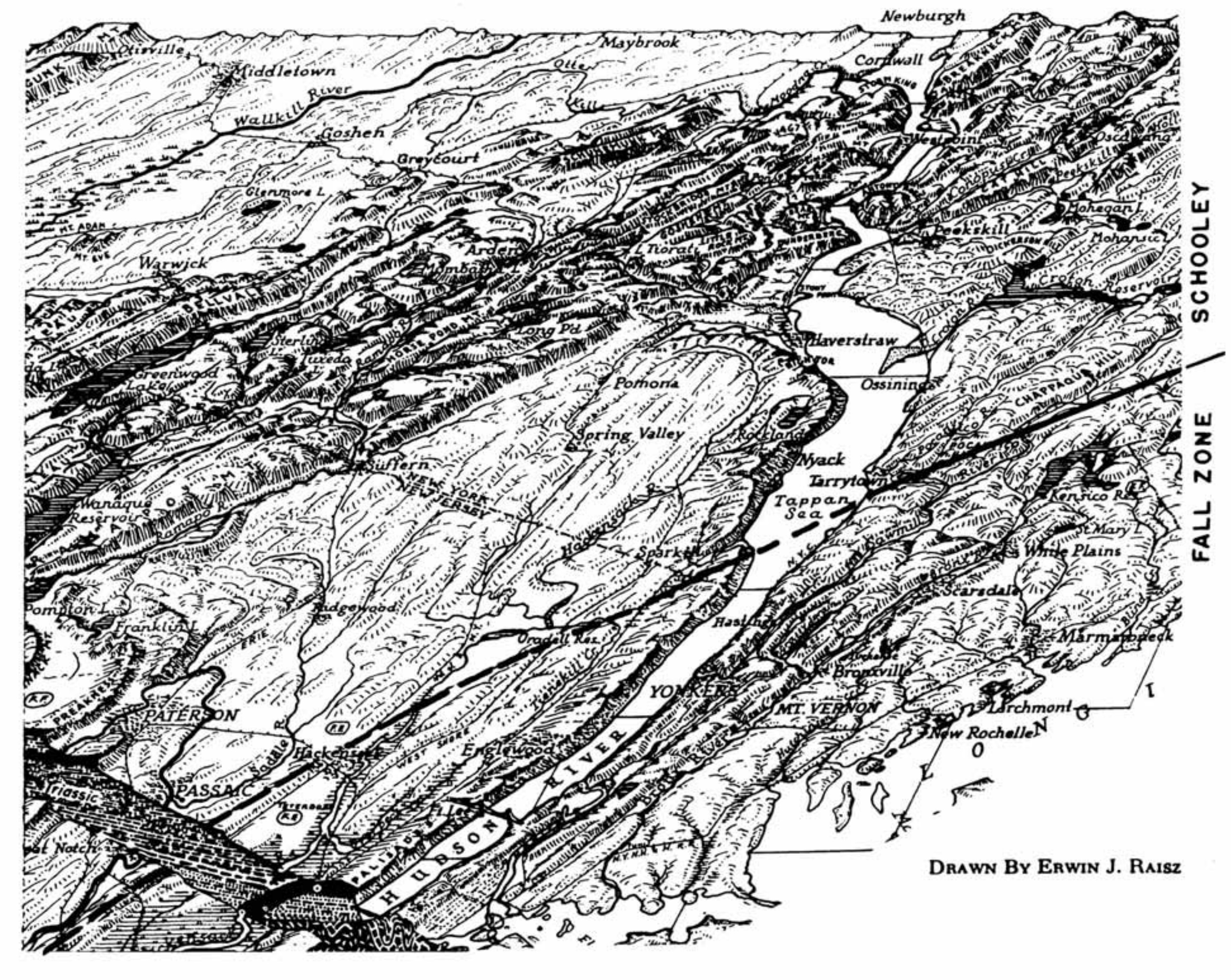


Figure 2 - Oblique, aerial physiographic diagram of a part of the Manhattan Prong, Newark Basin, Hudson-Reading Prong, and Atlantic Coastal Plain of the Appalachians. The vertical slice is oriented NW-SE to illustrate the generalized across-strike structural relations among major geologic "Layers" as outlined in Table 2. (E. Raisz.)

The Proterozoic and Paleozoic metamorphic rocks of the Manhattan Prong are in ductile- and brittle fault contact with the Hudson Highland-Reading Prong, an ancient elongate hilly terrane of moderate relief that shows the effects of significant uplift and protracted Pleistocene glaciation. These billion-year-old and older rocks trend northeastward from Reading, Pennsylvania through westernmost New Jersey onward through SE New York State. They cross the Hudson River just north of today's prime objectives near Peekskill, New York. Beyond eastern New York State, the Hudson-Reading Prong is continuous in the subsurface with exposed Proterozoic rocks forming the New Milford, Housatonic, Berkshire, Green, and Long Mountain massifs throughout New England and Newfoundland.

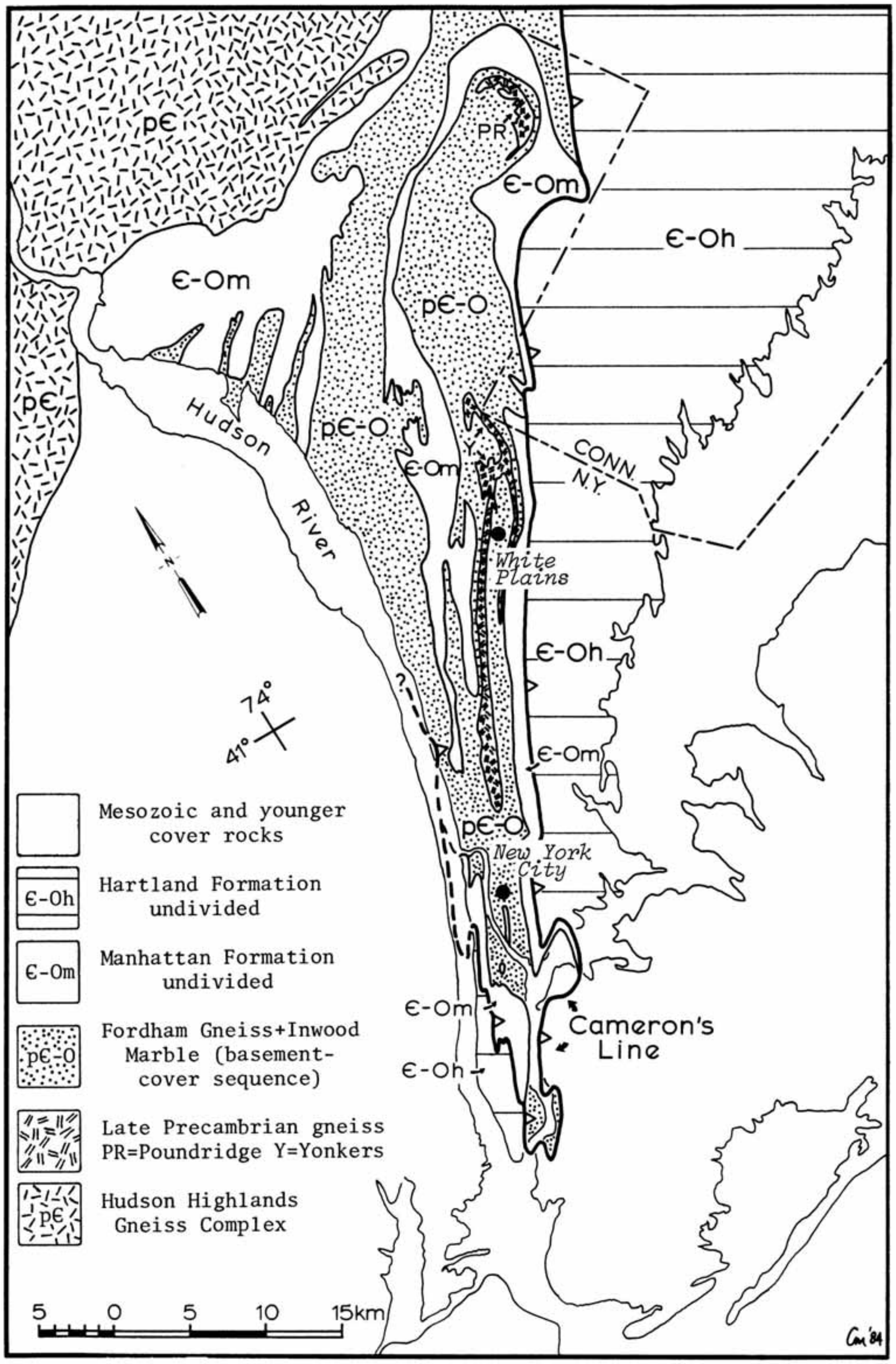


Figure 3 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted. (Mose and Merguerian, 1985.)

The region north of Peekskill, New York is traversed by numerous northeast-trending sub-parallel ridges and valleys. Peekskill Hollow is a northeast-trending valley stretching from the Hudson River northeastward for about 9 km; its average width is 0.8 km. Gallows Hill is a prominent ridge ending at Peekskill Bay in the Hudson River near Annsville, New York. This ridge separates Peekskill Hollow and Sprout Brook Valley to the northwest. Here, Sprout Brook is continuous with Canopus Creek to the northwest of Cortlandt Lake. These valleys and the intervening ridge are lithologically controlled by phyllite (Gallows Hill) and easily erodable rocks (carbonate rocks) and/or faults as described below. Northwest of Gallows Hill, the rocks of the Manhattan Prong and the Hudson Highlands are in contact. As described in detail under the heading Geology of Peekskill Hollow, the carbonate unit at the boundary of these disparate terranes shows abundant evidence for ductile- and brittle faulting and controls the position of Sprout Brook.

In its course through the Hudson Highlands, the Hudson River follows numerous orthogonal bends which produce an unusual zig-zag path in comparison to the Hudson's "normal" straight-line course to the north and south of the Highlands. We address this point later in the text and provide a full discussion in our guidebook on the Hudson Highlands (On the Rocks Trip 14 - October 1990).

Bedrock Units

Layers I (The Proterozoic Basement Complex) and Metamorphosed Parts of Layer II (the Lower Paleozoic Shelf Sequence and Allochthonous Rocks)

As we begin Trip 25 from the New York Academy of Sciences, let us express a few thoughts about the rocks beneath our feet. Before Paleozoic metamorphism and deformation, the New York City strata were sedimentary strata that for the most part, had been deposited on an eroded, complexly deformed cratonic sequence of layered feldspathic gneiss, schist, amphibolite, calc-silicate rock, and massive granitoid gneiss of uncertain stratigraphic relationships known as the Fordham, Yonkers, and Pound Ridge gneisses (Layer I).

These complexly deformed, dominantly felsic rocks are of Precambrian age, and are assigned to the alphabetical-letter scheme of Precambrian rocks designated as Proterozoic by the United States Geological Survey. Present in southeastern New York are representatives of Proterozoic Y and Z (Tables 1 and 2). These rocks are inferred to represent the ancient continental crust of proto-North America that were involved in the Grenville orogeny (Proterozoic Y) and post-Grenville, pre-Iapetus extensional tectonic activity (Proterozoic Z).

Early in the Paleozoic Era, this region became the trailing edge of a continental plate, a passive continental margin (Figure 4) adjacent to the ancestral Atlantic Ocean (Iapetus). This tectonic setting persisted until the Taconic orogeny late in the Ordovician Period (Figure 5). Interestingly, the current plate-tectonic passive-continental-margin setting of eastern North America [deformed Paleozoic and older basement covered by essentially nondeformed Mesozoic and younger sediments that were (and continue to be) deposited as the margin subsides toward an ocean basin to the east] more or less duplicates that of Early Paleozoic time!.

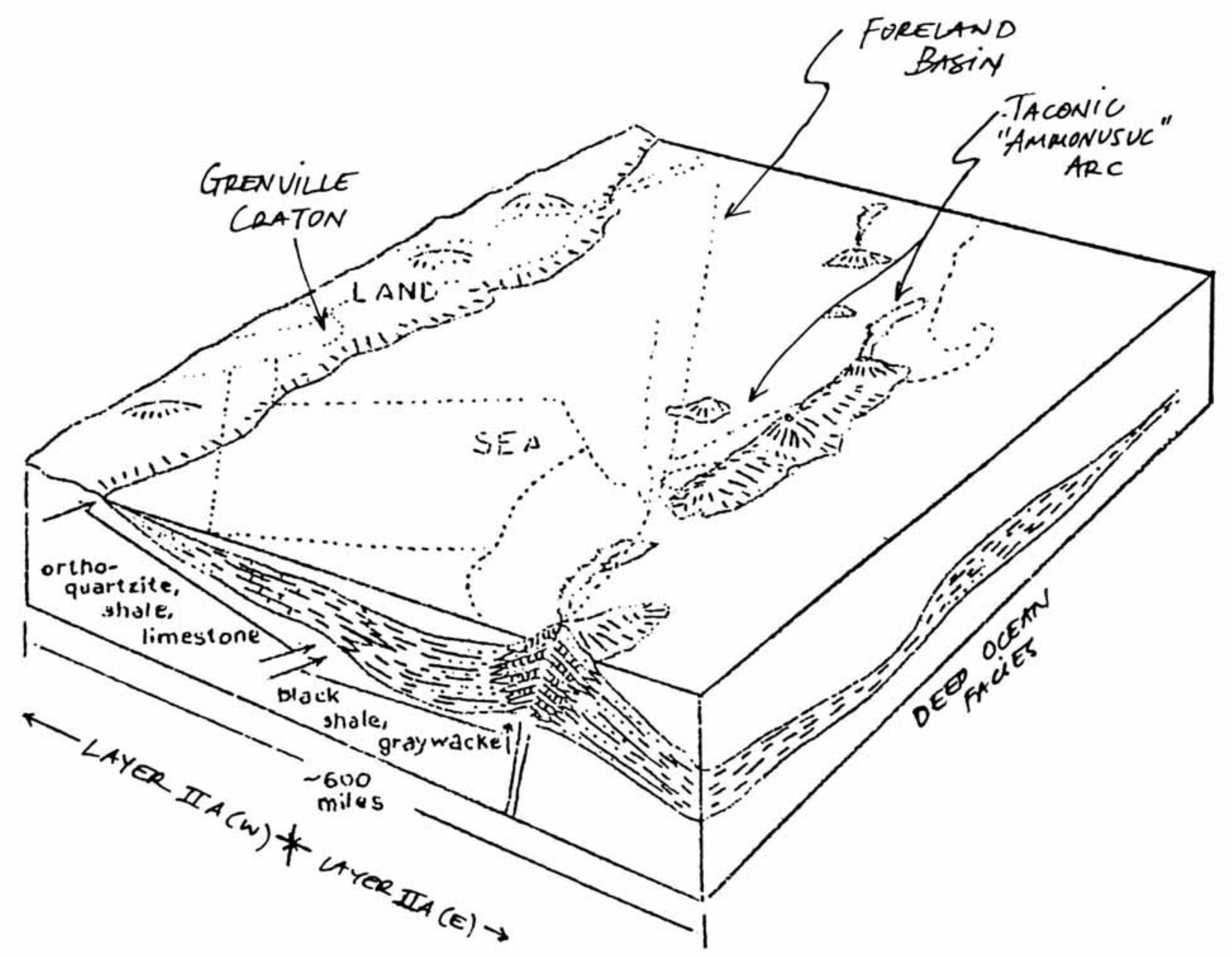


Figure 4 - Block diagram showing the Lower Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

The Cambrian and Ordovician bedrock units (Layer II) underlying the Manhattan Prong and adjacent parts of western Connecticut consist of sedimentary- and igneous rocks that formed near the Earth's surface. They began their geologic lives approximately 550 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America (Figure 5).

Layer II can be divided into two sub-layers, IIA and IIB. The older of these, IIA, represents the ancient passive-margin sequence of the proto-Atlantic (Iapetus) ocean. In turn, these rocks can be subdivided into two facies that differ in their original geographic positions with respect to the shoreline and shelf. A nearshore-shelf facies [Layer IIA(W)] was deposited in shallow water and is designated as the Sauk Sequence. The local representatives of the Sauk Sequence are from base upward, the Lower Cambrian Lowerre Quartzite and Cambro-Ordovician Inwood Marble in New York City (Poughquag Quartzite and Wappinger Group carbonates in Westchester County; Cheshire Quartzite and Woodbridge and Stockbridge marbles in western Connecticut and Massachusetts). These Sauk strata were deposited as sandy- and limey sediments in an environment closely similar to that of the present-day Bahama Banks. The chief difference is that the salinity of the Early Paleozoic seas exceeded that of normal seawater (inferred from the features of the Cambro-Ordovician dolostones).

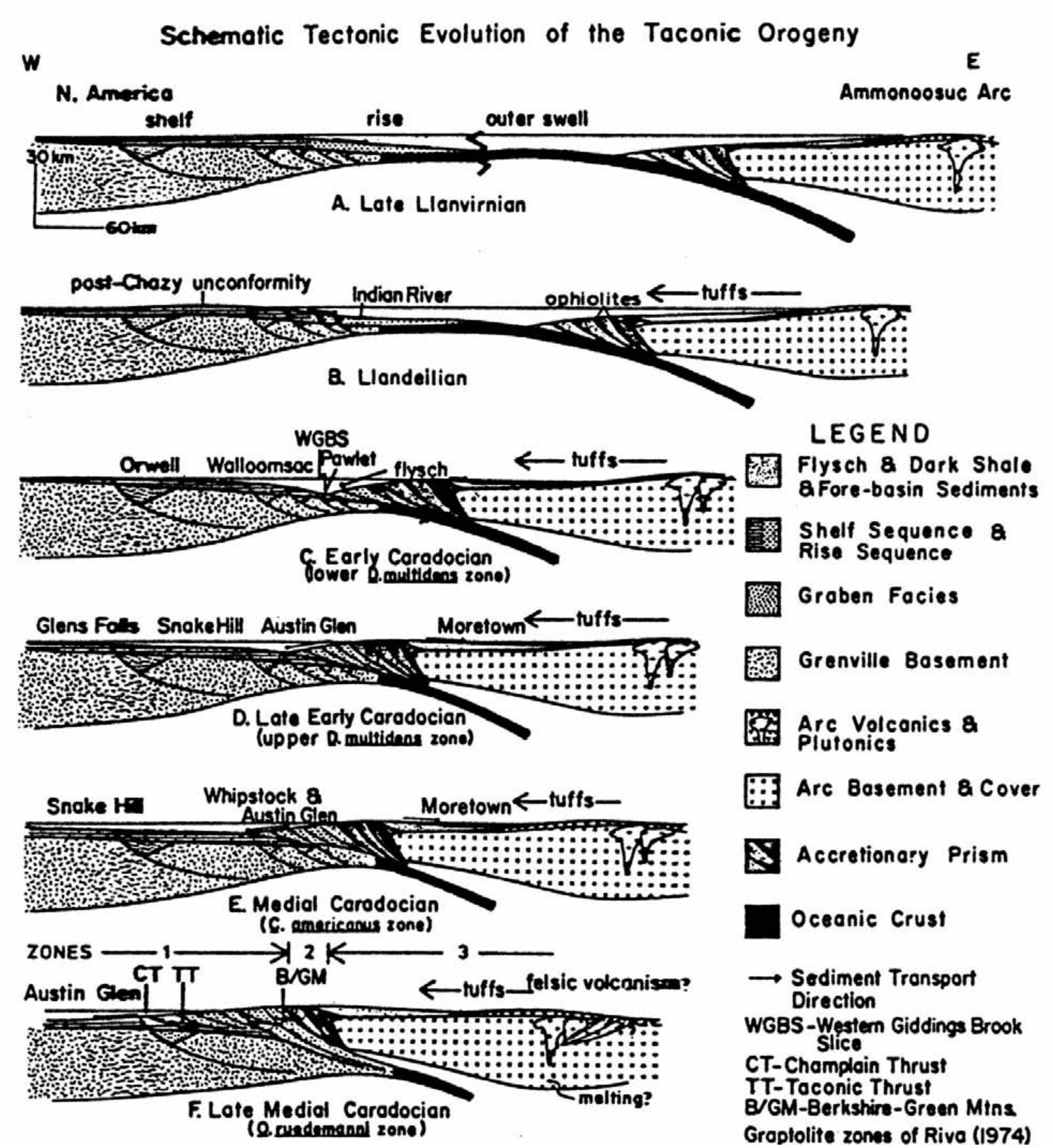


Figure 5 - Sequential tectonic cross-sections for the Taconic orogeny in New England. (Rowley and Kidd, 1981.)

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water Sauk strata were evidently deposited under deep water on oceanic crust [Layer IIA(E)]. This sequence is also of Cambrian to Ordovician age and is known as the Taconic Sequence in upstate New York, as units Ꞓ-Ot and Ꞓ-Oh of the Manhattan Schist(s) in New York City and vicinity (Figure 6). In western Connecticut, the deep-water sequence includes the Waramaug (or Manhattan B and C of Hall, 1968) and the Hartland formations (Merguerian, 1983).

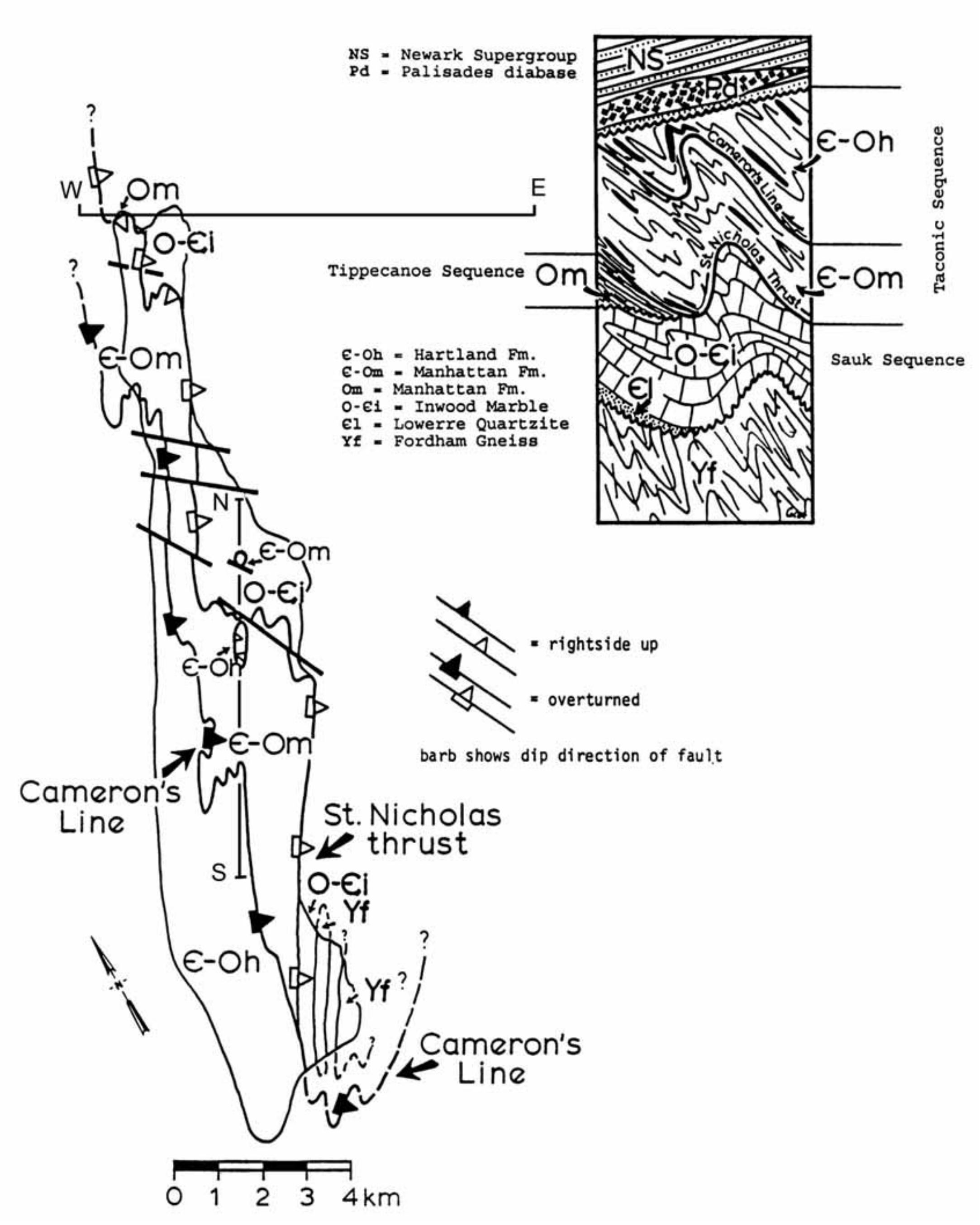


Figure 6 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. (Geologic mapping and drawing by C. Merguerian.)

Layer IIB consists of younger, mostly terrigenous, strata with thin basal Balmville Limestone, which unconformably overlie the Sauk Sequence [Layer IIA(W)]. These are now collectively designated as the Tippecanoe Sequence. The depositional setting for the basal Tippecanoe limestones was somewhat analogous to that of the Sauk Sequence, but with the exception that the salinity of the waters was normal rather than hypersaline. (This is inferred from the limestones of the basal Tippecanoe as contrasted with the dolostones of the Sauk.) After the basal Tippecanoe limestones had been deposited, the depositional setting shifted drastically. The former passive continental margin gave way to a foreland basin, which subsided deeply in response to the loads on the lithosphere being imposed by the advancing overthrust sheets and -adjacent volcanic arc from the east. The sedimentary fill of the foreland basin contains thick units of terrigenous sediments that were deposited under anoxic (low-oxygen) conditions and thus are dark colored as a result of finely disseminated pyrite and/or organic matter. In this respect, they differ notably from the fine-textured sedimentary strata of the older Taconic Sequence, which were deposited under oxidizing conditions.

In eastern New York State, the metamorphosed equivalents of the dark-colored terrigenous Tippecanoe Sequence rocks are mapped as the Walloomsac Schist, Annsville Phyllite, and parts of the Manhattan Formation (Unit Om in Figure 6, Manhattan A of Hall (1968)).

The schists originally named as the Manhattan Schist by Merrill and others (1902) were thought to be entirely younger than the Inwood Marble (Layer IIB) and thus to be the metamorphosed equivalents of units now assigned to the Tippecanoe Sequence. As a result of mapping by CM, large parts of this body of schist are now recognized as correctly belonging to rock units that are the same age or older than Manhattan Schist unit Om and the Inwood Marble, and thus their protoliths belong to the Taconic Sequence. According to CM, at Inwood Hill Park in Manhattan (NYAS On-The-Rocks Rain Trips 3 and 16), this Manhattan Schist Unit Om is demonstrably interlayered with the Inwood Marble and at its base and contains thin layers of calcite marble (Balmville equivalent). Such stratigraphic evidence is used to indicate that unit Om of the Manhattan Schist is in place where found and is therefore belongs to the Tippecanoe Sequence. This unit is probably younger than most of Manhattan units Ꞓ-Ot and Ꞓ-Oh whose protoliths belong to the Taconic Sequence. The upper part of the Taconic Sequence spans the same age range as the lower Tippecanoe Sequence but the main body of the Taconic Sequence is the same age as the Sauk Sequence.

During the middle of the Ordovician Period, roughly 450 million years ago, after the foreland basin had begun started filling very rapidly with anoxic sediments and prior to the main events of the Taconic orogeny, vast overthrust sheets began to move westward along the floor of the foreland basin. The first of these broke loose inboard of the former shelf edge. In northwestern Vermont, the these thrusts involve rocks no older than the base of the Sauk Sequence (the Champlain family of overthrusts). From Dutchess County, NY southwestward into New Jersey, however, these thrust sheets include continental-type basement rocks and the overlying Sauk Sequence. In this New York-New Jersey segment of the Appalachians, these mid-Ordovician overthrusts involving continental-type basement rocks have been recognized only recently. (See summaries in On-The-Rocks guidebooks to Franklin Mines, Delaware Water Gap, Stokes Forest, and Bellvale Mountain and the Shawangunks.) Next came sheets involving only the older eastern, deep-water formations of the Taconic Sequence [Layer IIA(E)] that were stripped away from their presumed oceanic basement crust and shifted into positions above the Inwood (Sauk Sequence) and its younger overlying terrigenous sediment of the Tippecanoe Sequence (all of the Manhattan Schist as originally conceived, but only Manhattan Schist unit Om, according to CM). In other words, the Taconic allochthon (On-the-Rocks Trips 8 and 22), is present as one or more overthrust slices in the Manhattan Prong and extends into New York City (Figure 7). (In much of the tectonic literature of the Taconic region, the term allochthon is reserved for the displaced Taconic Sequence. The strata that compose the earlier overthrusts that broke loose inboard of the former shelf edge and that may or may not involve continental-type basement rocks have been referred to as parautochthonous. "Para" means "almost." We think these older, pre-Taconic-allochthon thrusts are just as allochthonous as the displaced rocks of the Taconic Sequence. The overthrust Sauk strata include non-metamorphosed protoliths of the Inwood Marble.

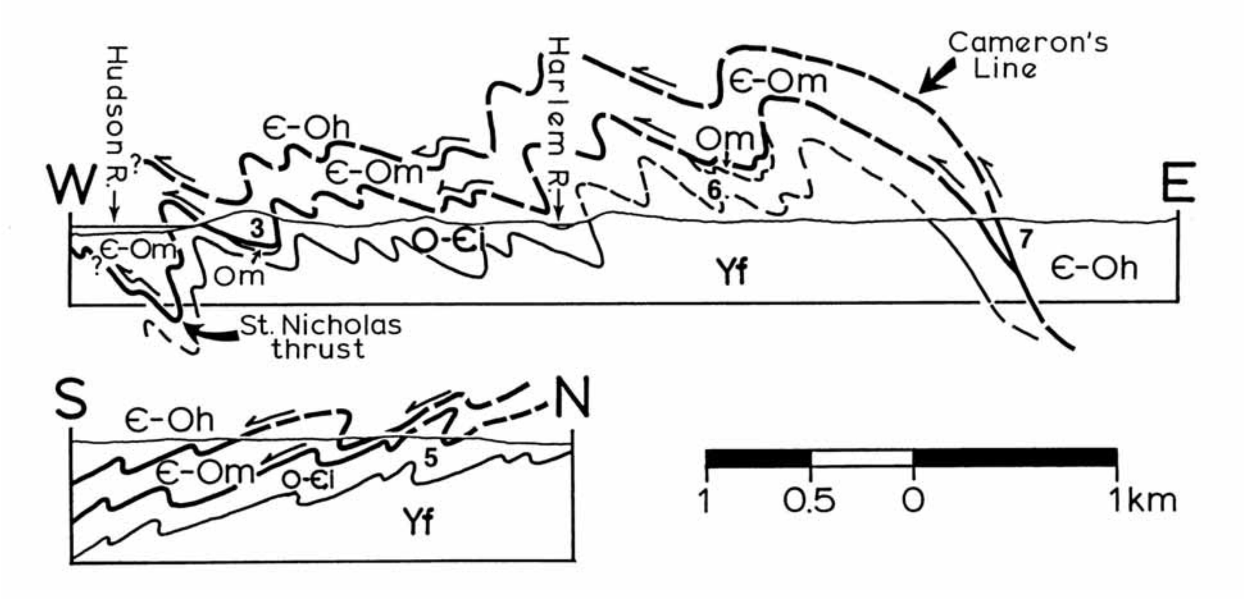


Figure 7 - Geologic cross section across northern Manhattan and the Bronx showing folded overthrusts (Cameron's Line and the St. Nicholas thrust), New York City. Symbols defined on Figure 6. (C. Merguerian.)

The root zone of the overthrust involving the Taconic Sequence is thought to be Cameron's Line (See Figures 3, 7.), a feature widely known in western Connecticut (Merguerian, 1983). CM interprets Cameron's line as a fundamental plate-tectonic boundary along which rocks belonging in place on the North American continent were overridden by materials from the former continental margin when the plate-tectonic regime changed from a passive margin to a convergent margin featuring an active subduction zone.

During and after the overthrusting, the rocks of the Manhattan Prong were crowded together in complex folds and metamorphosed under medium- to high-grade Barrovian conditions. This can be inferred from the presence of such "indicator" minerals as kyanite, staurolite, sillimanite, hornblende, and garnet. Such diagnostic metamorphic minerals suggests that rocks now exposed at the modern land surface of New York City formerly were at depths of

25 to 40 km. Rocks north of the city in the Manhattan Prong were buried by 25 to 30 km of overburden. If this is correct, it indicates that 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, enormous uplift and vast erosion took place. A simplified geologic section showing the relationships between the folded New York City rocks, at the former land surface, and the Newark Supergroup drawn along an east-west line at the George Washington Bridge (GWB) is shown in Figure 8. The overturned anticlines and synclines of the New York City metamorphic rocks are unconformably overlain by the west-dipping strata of the Newark Supergroup (Layer V, Table 2). The unconformity surface projects out of the Hudson River over the Manhattan Prong and New York City. On the west side of the Hudson River, this surface dips westward at the same angle as the overlying strata of the Newark Supergroup.

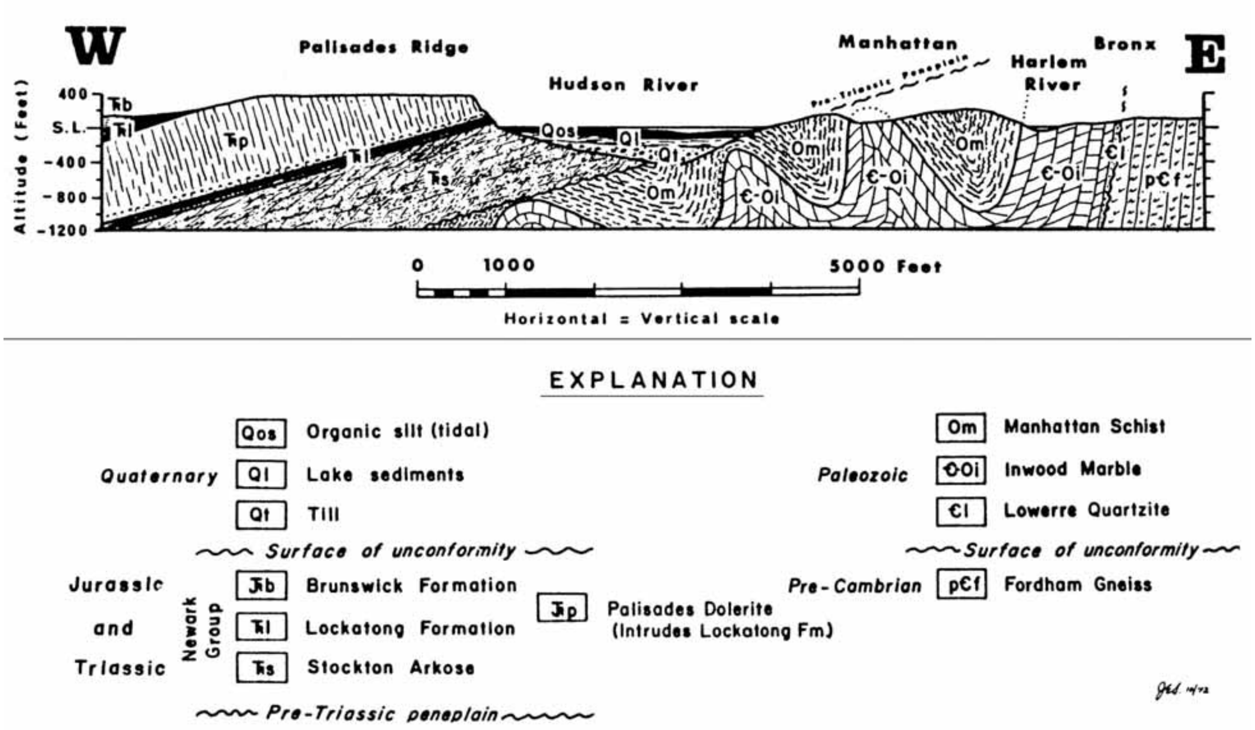


Figure 8 - Profile-section across Hudson River at George Washington Bridge. Topography from U. S. Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974, fig. 3, p. 11.)

The foregoing paragraphs imply that all the bedrock in New York City has been involved in overthrusting and that some of it is even allochthonous in the Taconic-Sequence-only sense referred to above. (See CM's cross section of Figure 7.) It may not have occurred to you in these terms, but as you observe outcrops in New York City and the Manhattan Prong, you are doing two contrasting things. First, you are vicariously walking backward in time. And second, you are figuratively descending deep within a former mountain zone.

Layer V - Newark Basin-filling Strata

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 Figure 2, the Newark strata generally dip about 15° to the northwest.

The formal stratigraphic name for the dominantly red-brown colored Newark strata is Newark Supergroup (Olsen, 1980). 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 sheet 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 ridges known as the Watchungs. The age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of Early Jurassic age (Cornet, 1977; Cornet and Travers, 1975, Olsen, 1980).

The Newark sedimentary strata were deposited in a fault-bounded basin (the Ramapo Border fault in Figure 2) to which the sea never gained access. In this basin, the filling strata were deposited in various oxygen-enriched nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate (Olsen, 1986) and produced hematite-stained clastic sediments or "redbeds".

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities (Sanders, 1963). They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited.

Geology of Peekskill Hollow

The region north of Peekskill, New York is traversed by numerous northeast-trending sub-parallel ridges and valleys. The region has been studied by many geologists including Berkey (1907, 1933), Berkey and Rice (1919), Berkey and Colony (1933), Gordon (1911), Paige (1956), Bucher (1957), Lowe (1958), Schaffel (1958), and Ratcliffe (1971, 1980). Simon Schaffel's paper is the last to summarize the important stratigraphic-structural problems related to Peekskill Hollow, a northeast-trending valley stretching from the Hudson River for roughly 9 km with an average width of 0.8 km. Gallows Hill is a prominent ridge ending near the Hudson River at Annsville, New York bifurcated by Peekskill Hollow and Sprout Brook Valley to the northwest. These valleys and intervening ridge are structurally and lithologically controlled by faults and easily differentially eroded rocks as described below and at Stops 8 and 9.

The Peekskill Hollow section was first diagrammed by Berkey (Figure 9) who interpreted Gallows Hill as a syncline of Hudson River Phyllite (now called the Annsville Phyllite). The syncline is bounded to the northwest and southeast by faults and carbonate rocks of various ages ranging from Proterozoic through Cambro-Ordovician. Proterozoic gneisses (Reservoir Granite) crop out on the northwest side of Gallows Hill and also to the southeast, beyond the outcrop belt of Wappinger Limestone and Poughquag Quartzite. Berkey's interpretation of a Proterozoic limestone belt beneath Sprout Brook was challenged by Bucher (1957) who suggested (Figure

10) that the Paleozoic strata are transgressive against the Precambrian gneiss which results in a pinch-out of the infolded basal Paleozoic section beneath the syncline of black shale (phyllite). In his view, the western limestone ("a" = black unit in Figure 10) was "Trentonian" (late Middle Ordovician = Balmville limestone) in age and thus separated from the limestone beneath the Annsville syncline (actually an inlier) by a steep reverse fault.

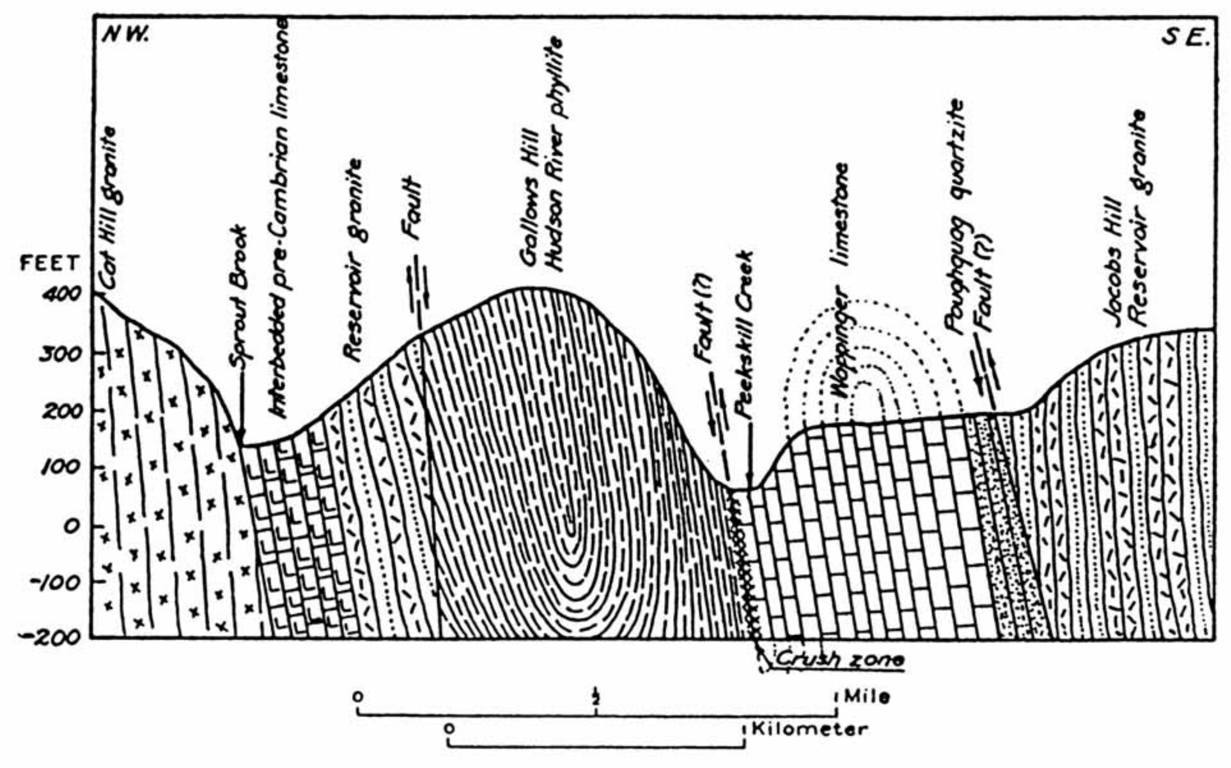


Figure 9 - Geologic section at Peekskill Hollow showing the structure across Gallows Hill. (Berkey, 1933.)

Paige (1956) attempted to correlate the Manhattan Schist and Inwood Marble at Verplanck Point with the Cambro-Ordovician Annsville Phyllite-Wappinger Limestone succession in Peekskill Hollow. His geologic map and cross section are shown in Figure 11. Note section B-B' from the Cortlandt Complex in Peekskill northwestward to Sprout Brook Creek wherein Paige interprets the Annsville cut as forming a normal-faulted overturned limb of an anticline cored by Precambrian rocks (Reservoir Gneiss). More recently, in reversing his earlier opinion published in 1971, Ratcliffe (1980) has suggested that Berkey's Precambrian call on the limestone belt to northwest of the Annsville syncline the model is more correct. According to Ratcliffe, the unusual marble, which contains rounded inclusions of gneiss, is actually Proterozoic limestone that has been intensely sheared to form a tectonic-mylonite breccia. The Annsville Phyllite (in the Annsville cut) is in fault contact with the flow-banded mylonitic Proterozoic marble along the N40°E-trending Annsville fault located adjacent to Sprout Brook. Fault textures superimposed upon the Proterozoic mylonite indicate right-lateral oblique thrusting of probable Late Ordovician age according to Ratcliffe (1980). The Annsville fault may mark an extension of the northeast-trending Theills fault on the west side of the Hudson River.

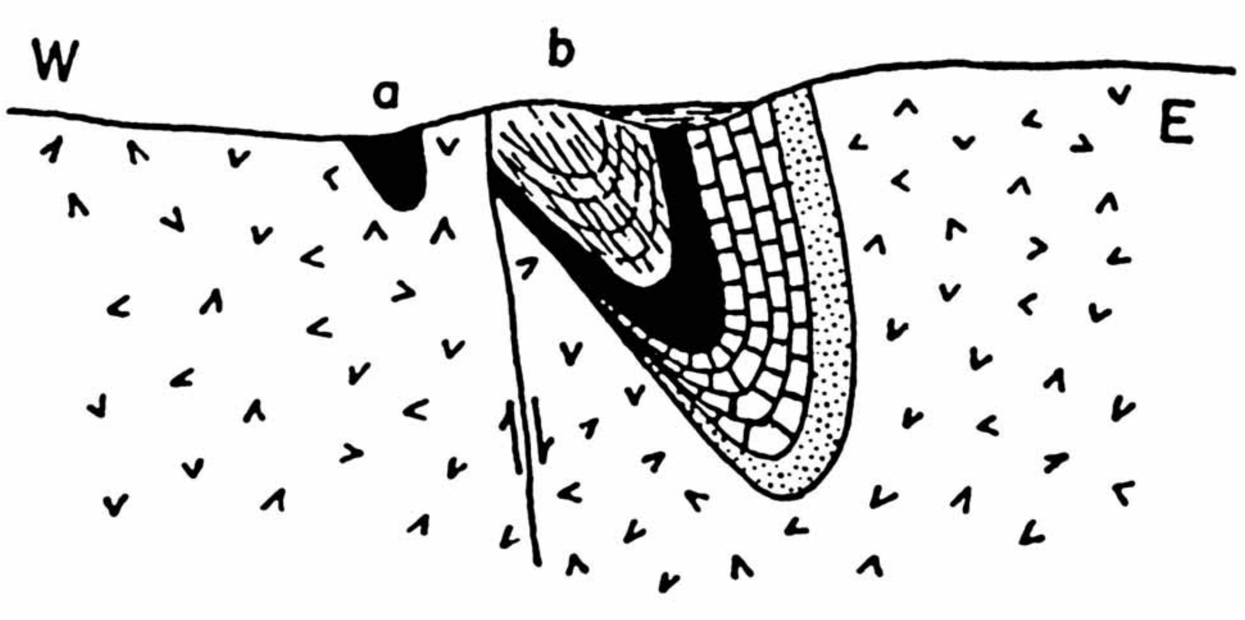


Figure 10 - Diagrammatic cross section of Paleozoic sediments infolded into Precambrian (Proterozoic Y) gneiss northwest of Peekskill, New York. The section shows the westward overlap of the young Trentonian limestones and shales (eroded at left of fault) onto the gneiss. The Annsville cut (Stop 8) is at "b". Poughquag quartzite (dotted); Ꞓ-O dolostone-limestone (blocks); Trenton limestone (black); and Annsville (Hudson River) Phyllite in center of syncline. (W. H. Bucher, 1957.)

Structural interpretations may vary but it is clear that the positions of Peekskill and Sprout Brook Creeks are controlled by both lithology and structure. As discussed at Stops 8 and 9, CM and JES offer a new interpretation of the structure based on the presence of very low dips in the metamorphic- and sedimentary layering of the Poughquag Quartzite southeast of Peekskill Creek. Stay tuned to the text for further developments.

Geology of the Cortlandt Complex

The Cortlandt Complex is one of many mafic-ultramafic plutons that were emplaced in the general vicinity of Cameron's Line (the inferred Taconic suture) in Mid-Ordovician time. As has been noted by many workers, the structural settings, mineral compositions, and ages of these composite plutons, 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.

Since late in the nineteenth century, geologists interested in igneous rocks have studied the various aspects of the Cortlandt pluton near Peekskill, New York. Work by Dana (1881) and Williams (1884, 1886) helped set the stage for early twentieth-century studies by Rogers (1911) (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 Woollard (1952; Figure 14), and work by Friedman (1956) provided data on which new models of the crustal structure of the Cortlandt Complex could be conceived. A summary diagram (Figure 15) shows the various structural models proposed for the complex by this time. Compare these with the gravity anomalies displayed on the gravity map of New York State (Figure 16).

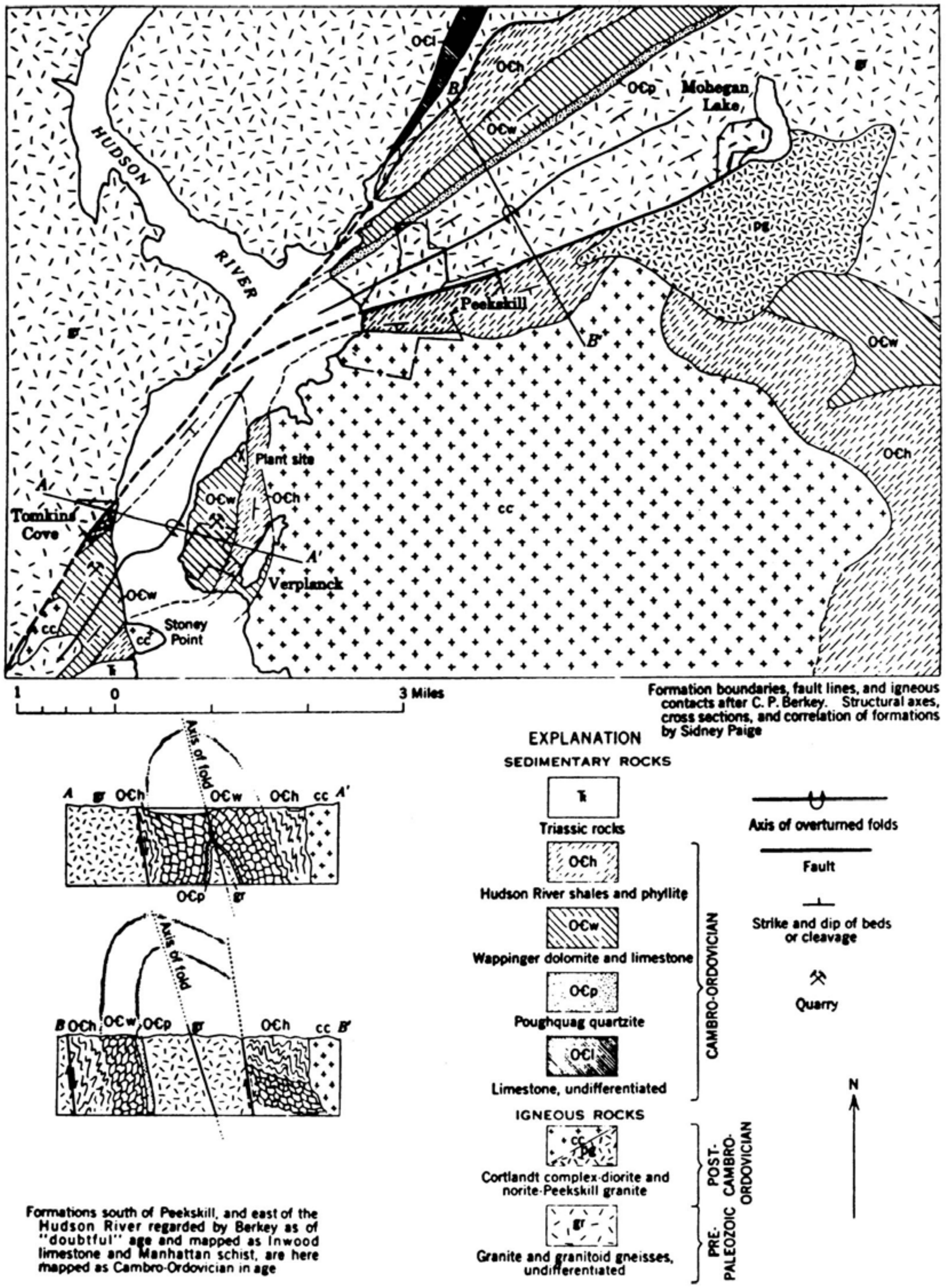


Figure 11 - Geologic and structural map of the southwest portion of the West Point quadrangle, New York. (Sidney Paige, 1956.)

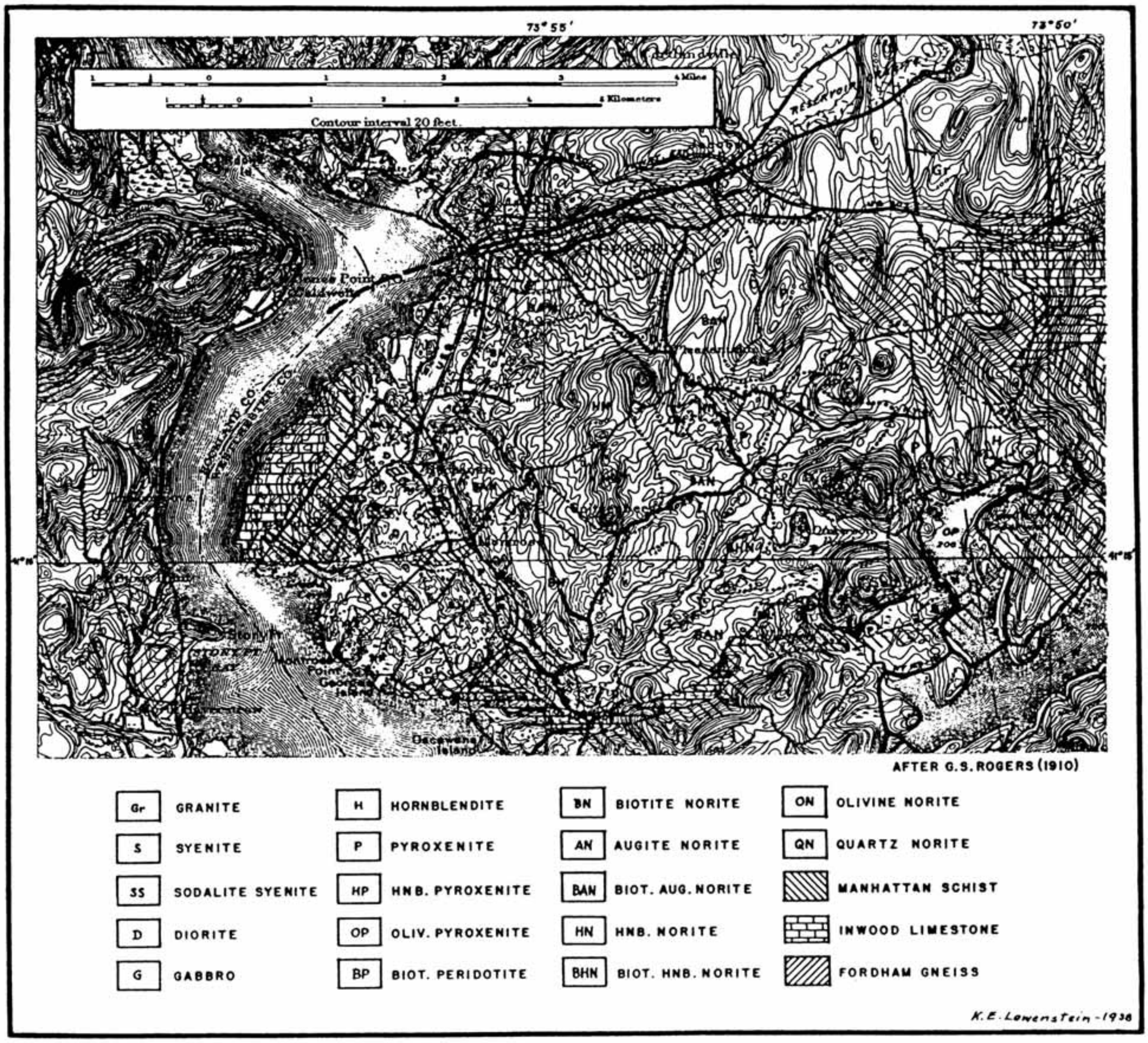


Figure 12 - Geologic map of the Cortlandt Series according to Rogers (1911) as redrafted by K. E. Lowe in 1938.

Modern studies since the 1950's have built upon the geological data of earlier workers. Using geochemical- and geochronologic data, Ratcliffe (1968, 1971, 1981) and Ratcliffe and others (1982, 1983) have defined the ages of intrusion, contact-metamorphic relationships, and internal configurations of the Cortlandt pluton(s). The Cortlandt Complex is a lopolithic (inverted mushroom shaped) mass consisting of six temporally related plutons of varying compositions (Figures 17-19). Intrusive into the metamorphic rocks of the Manhattan Prong, the oldest pluton (Pluton 1) is a kaersutite (alkali amphibole) hornblendite, gabbro, and pyroxenite grading internally into norite. It is internally well layered; aligned primary amphiboles define a flow layering. Pluton 2 is a green hornblende gabbro, a diorite, and a biotite quartz diorite that are correlative with identical rocks at Stony Point on the west side of the Hudson. (See Figure 17.) Pluton 3 cuts across the core of Pluton 1, sends apophyses into Pluton 2, and consists of clinopyroxenite and hornblende pyroxenite (websterite). Pluton 4 consists of hornblende pyroxenite, peridotite, and cortlandtite displaying cumulate layering. These four plutons form the western "funnel" of Balk but are now interpreted (See Figure 19.) as separate intrusives along the west edge of the Cortlandt lopolithic mass.

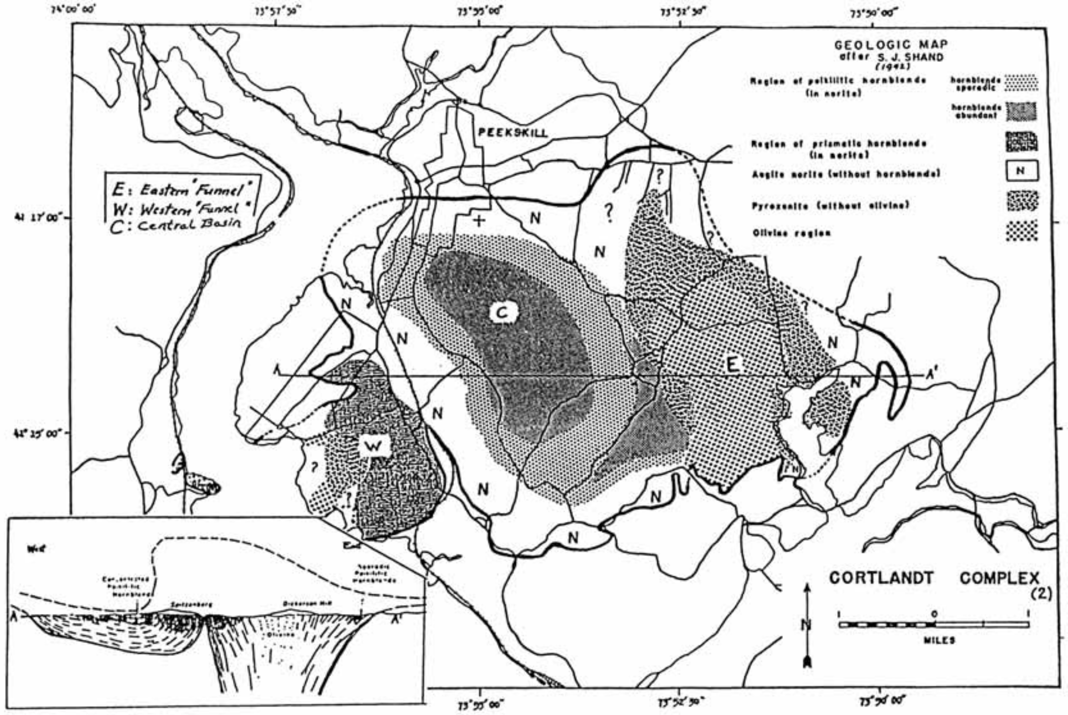


Figure 13 - Geologic map of the Cortlandt Complex after Shand (1942) showing "critical phases." (W. H. Bucher, 1948.)

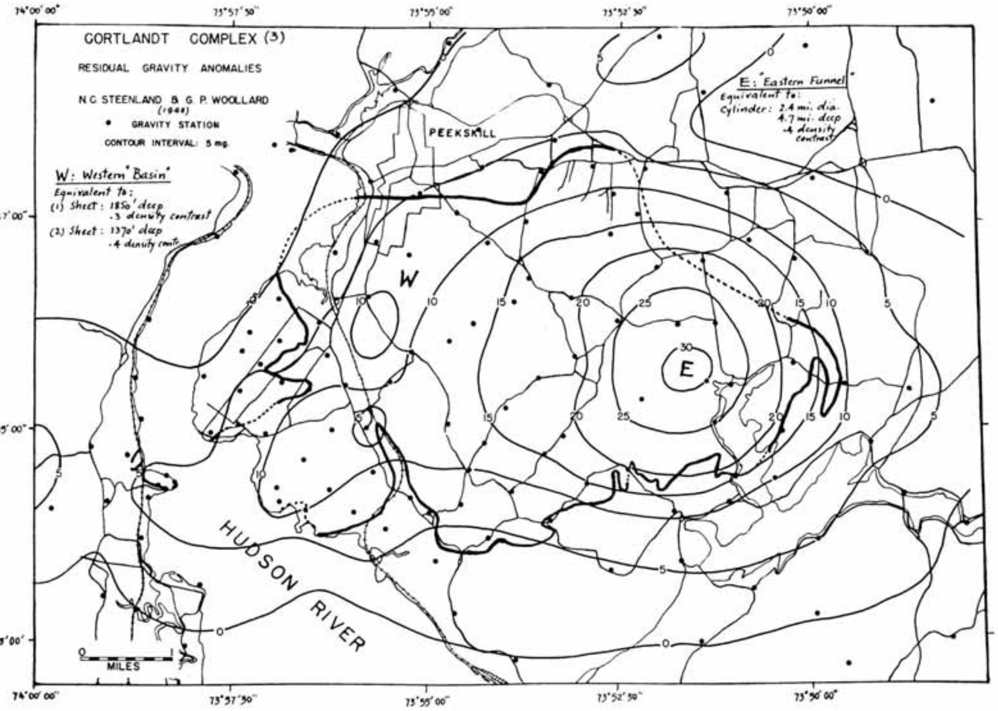
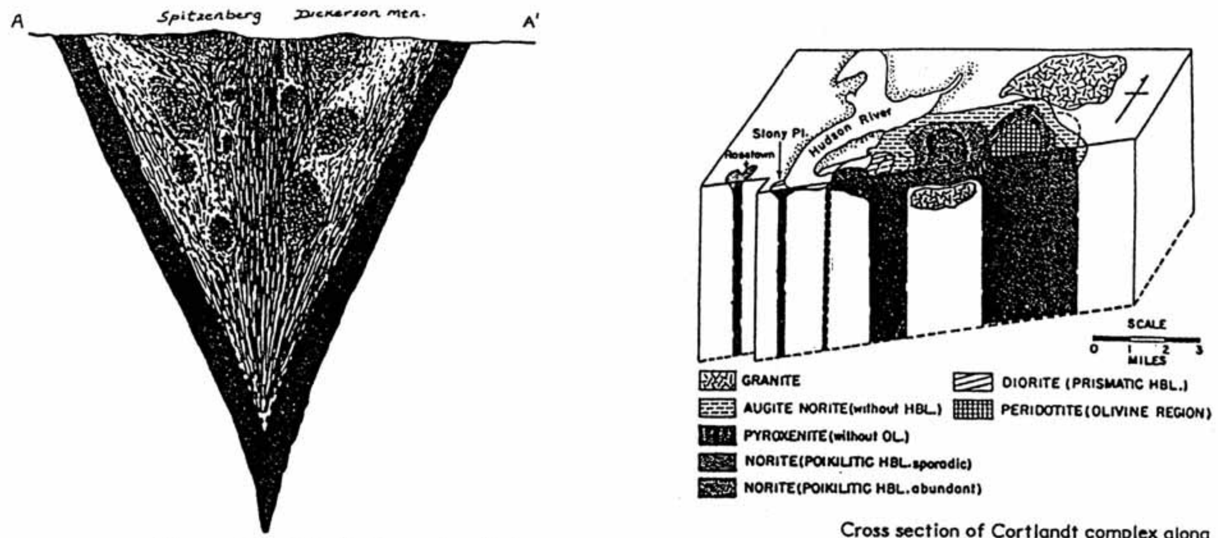
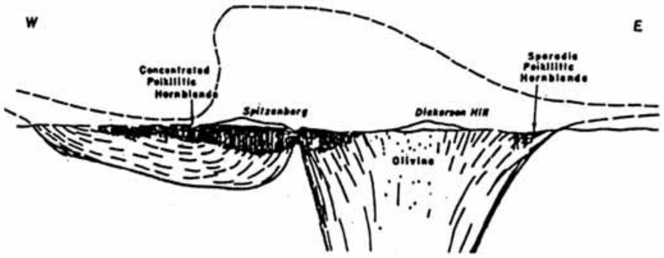


Figure 14 - Gravity map of Cortlandt Complex. (Steenland and Woollard, 1952.)



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

The central basin is underlain by Pluton 5 that consists of biotite-hornblende norite and gabbro, and coarse poikilitic kaersutite norite. This pluton, which contains abundant xenoliths of Manhattan Schist and calc-silicate rock (Inwood Marble?), shows evidence in the form of bent crystals of plagioclase and biotite and delicate folds in igneous flow layers of the norite that it was intruded while compressive forces were active. The eastern "funnel" is composed of hornblende pyroxenite and hornblende peridotite of Pluton 6 that engulf abundant cognate xenoliths of Pluton 5.

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). The igneous rocks of these plutons contact metamorphosed rocks of the Manhattan Prong that already possessed a regional-metamorphic fabric related to the Taconic orogeny. Therefore, this date of intrusion sets a medial Ordovician minimum age for the Taconic orogeny. This corroborates estimates from structural- and paleontologic studies along the sole thrusts of the Taconic Mountains. The fact that the Cortlandt rocks have not been deformed indicates that they were intruded during the waning stages of the Taconic orogeny. In addition, studies of the contact-metamorphic minerals in the 20- to 50-meter-thick aureole of the Cortlandt Complex allows the interpretation that the complex was intruded into the rocks of the Manhattan Prong at depths of 25 kilometers.

In retaining radiometric ages of 430 to 470 Ma, the rocks near Peekskill contrast with those farther south, in Manhattan and surroundings, for instance. In Manhattan, all radiometric ages fall in the range of 350 to 365 Ma, reflecting regional heating and "resetting of isotopic clock" by the Acadian orogeny (mid-Devonian). Clearly, the rocks around Peeksill escaped the effects of the mid-Devonian heating that affected the rocks farther south.

This brief summary of the bedrock geology is to provide a solid basis for understanding some of the distinctive boulders that have been eroded out of the Pleistocene till at Croton Point.

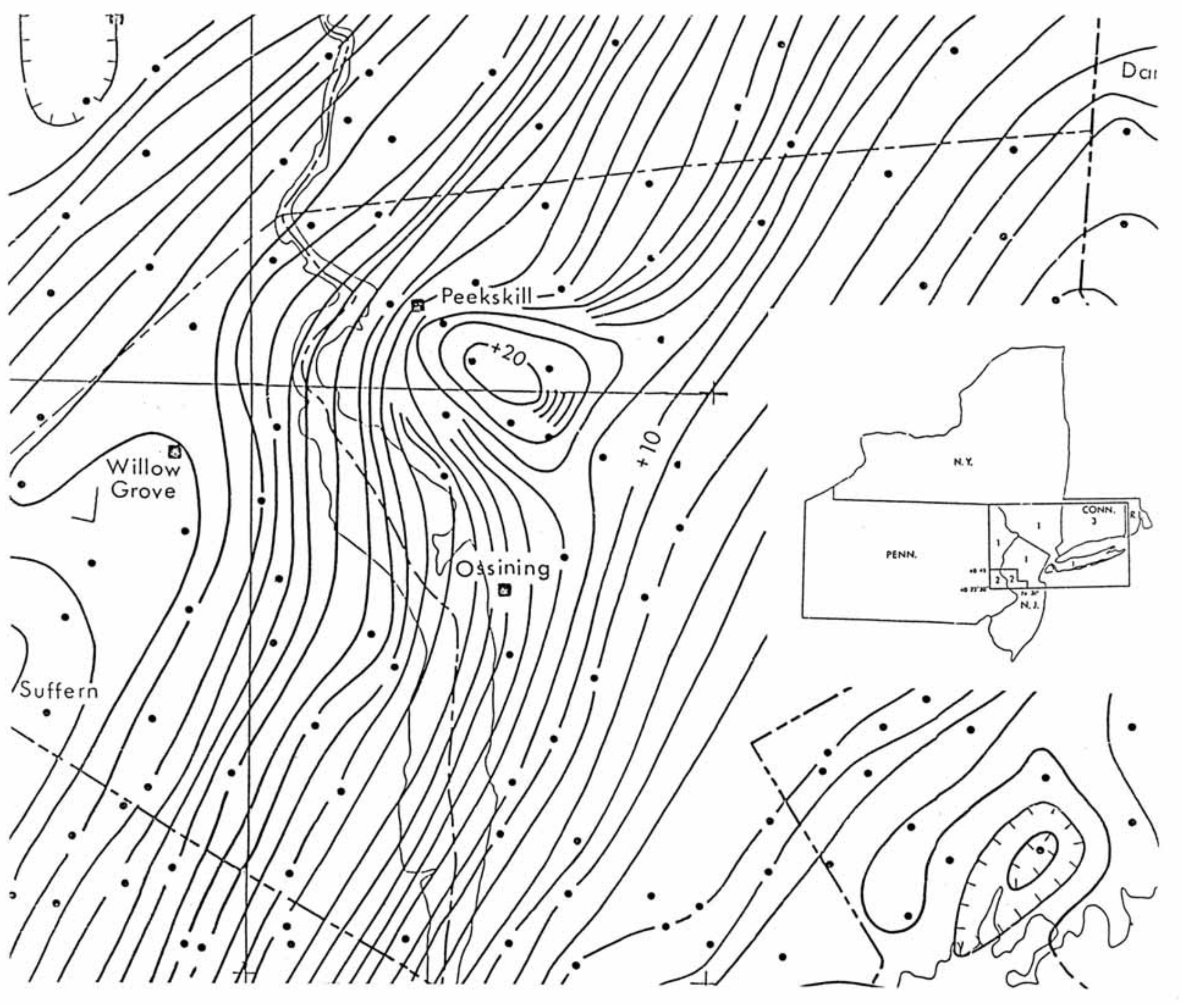


Figure 16 - Simple Bouguer gravity-anomaly map of part of southeastern New York State and contiguous states showing localized positive anomaly SE of Peekskill. (T. C. Urban, R. W. Bromery, F. A. Revetta, and W. H. Diment, 1973.)

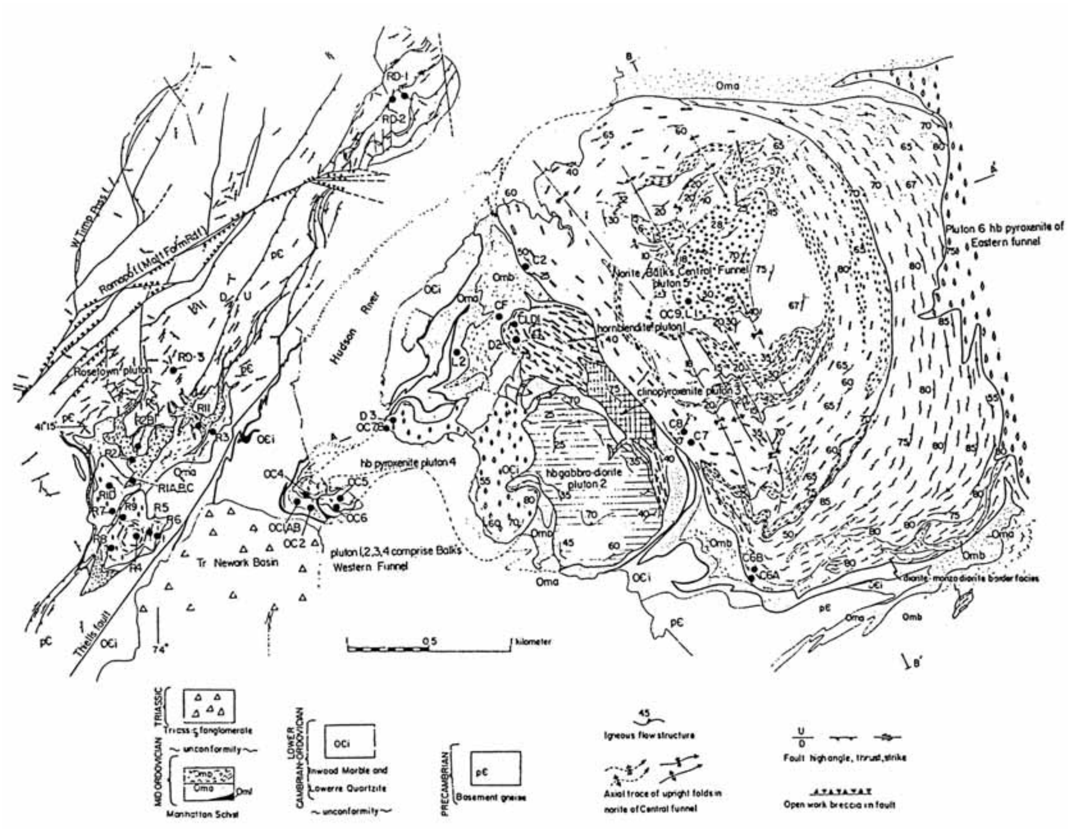
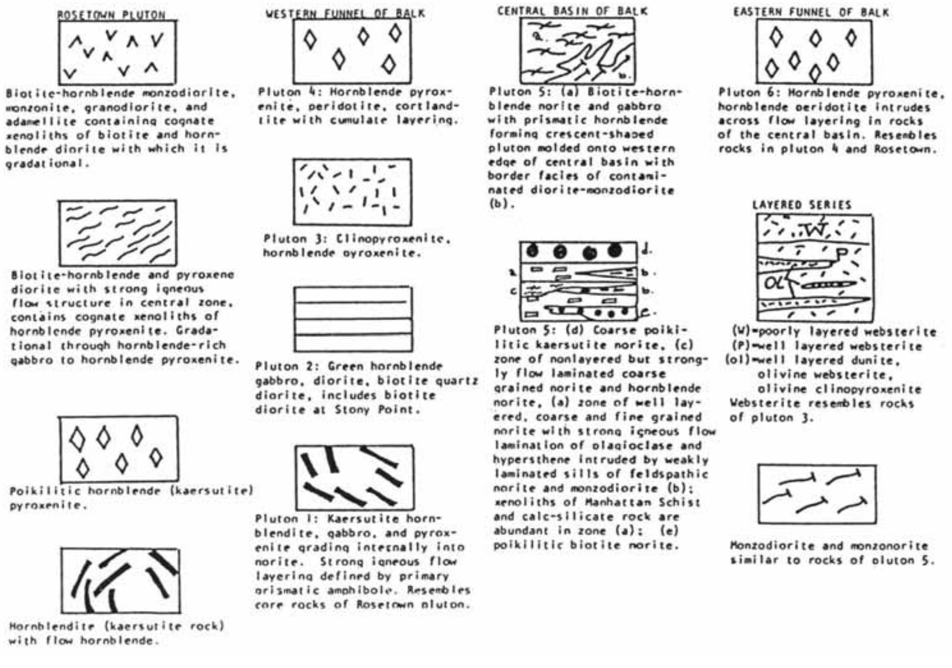


Figure 17 - Geologic map of the western and central funnels of the Cortlandt Complex and the Stony Point and Rosetown extensions of the Cortlandt. (Ratcliffe and others, 1982, 1983.)



ROSETOWN PLUTON

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.

WESTERN FUNNEL OF BALK

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

Pluton 3: Clinopyroxenite, hornblende pyroxenite.

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 prismatic amphibole. Resembles core rocks of Rosetown pluton.

CENTRAL BASIN OF BALK

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.

EASTERN FUNNEL OF BALK

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

LAYERED SERIES

(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 pluton 5.

Figure 18 - Explanation and lithologic descriptions of rocks of the Cortlandt Complex. (Ratcliffe and others, 1983.)

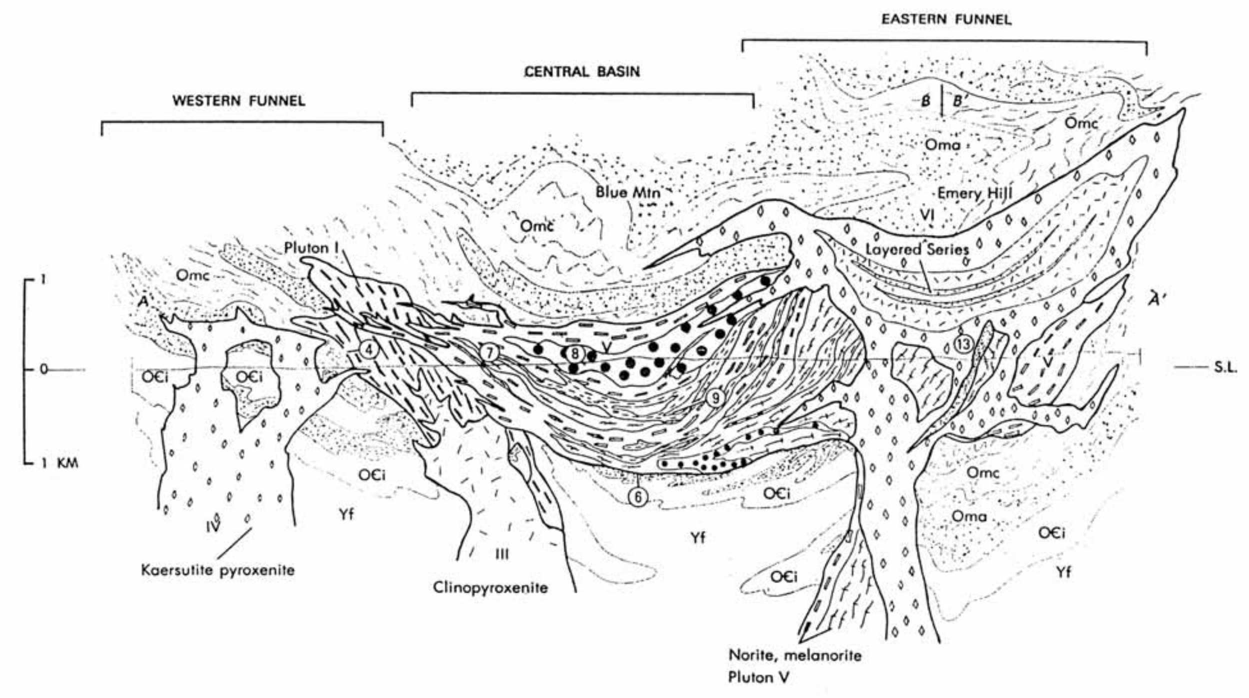


Figure 19 - Geologic section oriented SW to NE of the Cortlandt Complex (Section A-A' on Figure 17) showing internal flow structure, cross-cutting relationships, and general lopolithic form of the intrusive. (Ratcliffe and others, 1983.)

GLACIAL GEOLOGY

As mentioned under the description of Layer VII, the Quaternary sediments in Table 2, the glacial deposits, include several contrasting varieties. We will be especially interested in the characteristics of till and outwash. Till is a general name for any sediment deposited directly by the flowing ice of the 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/gravels and lake clays. The key point about distinguishing outwash is the stratification that resulted from the action of water.

Direction(s) of Flow of Ancient Glacier(s)

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. The directions of flow of a former glacier can be determined easily and unambiguously in the field by recording the azimuths of features eroded on bedrock by the flowing ice (such as striae and grooves, and the long axes and slope asymmetry of roche moutonnées and rock drumlins), by plotting the distribution of distinctive clasts, and by recording certain asymmetrical properties of glacial deposits (such as directions of orientations of elongate clasts and the long axes of drumlins).

Direction of flow based on distribution of distinctive clasts comes under the heading of provenance studies; that is, where the clasts (= large particles) in a deposit come from. Because glaciers can transport stones long distances, one commonly finds a collection of clasts in a glacial deposit that are 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. Use of striae and indicator stones shows that glaciers flowed across the New York region from several directions. You will share in this type of analysis on today's trip!

The distribution of erratics derived from as far away as the anthracite district in eastern Pennsylvania and pebbles of the distinctive maroon-matrix, white pebble rock in the Green Pond Formation (Lower Silurian -- the "Braunschweiger-sausage rock" of the late Barnard biology Professor Donald Ritchie) in the red- brown tills and outwashes in New York City (Figure 20) lends strong support to the interpretation that the striae and other directional indicators oriented NW-SE indicate regional ice flow from that direction, rather than a local SE deviation of a glacier whose main axis of flow was from NNE to SSW.

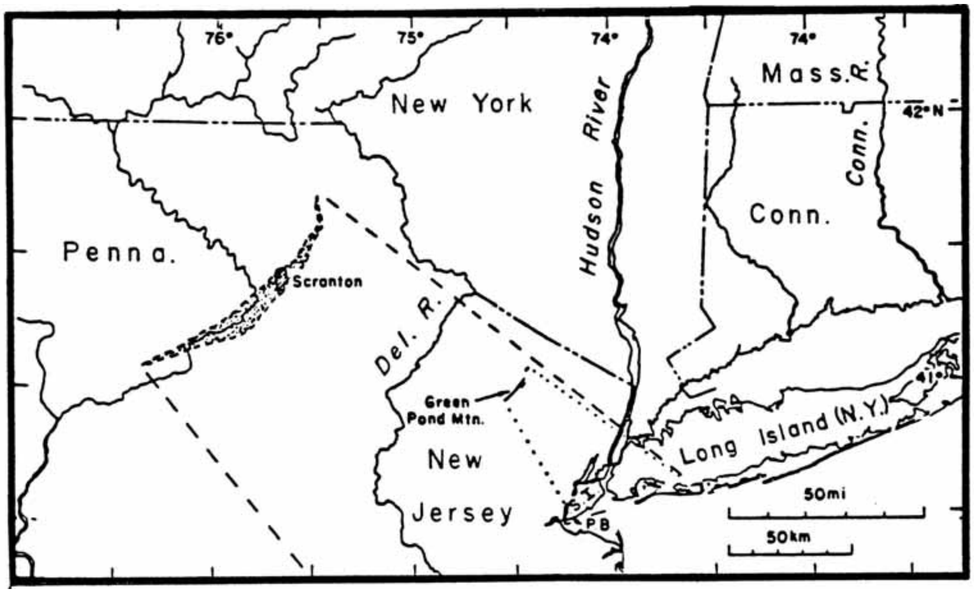


Figure 20 - Distinctive erratics found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (JES in Friedman and Sanders, 1978, fig. 2-1, p. 27; Friedman, Sanders, and Kopaska-Merkel, 1992, Box 2.2 fig.1, p. 48.)

L. D. Gale's Geological Survey of Manhattan Island (1828-1830)

The easiest method for tracking the directions of flow of an ancient glacier is to record directions of striae and grooves on the bedrock. In New York City, such a survey was first carried out in 1828-29 by L. D. Gale (in Mather, 1843). As was common in his day, Gale supposed that the grooves and scratches had been made by water currents, perhaps assisted by icebergs. The presumed significance of water is implied in the use of the term diluvial.

Gale's extensive observations clearly demonstrate that on Manhattan Island, one can see the effects of two contrasting flow directions. Nearly all the "diluvial scratches and furrows" recorded by Gale indicate flow (1) from the NW to the SE. By contrast, the displacement of indicator erratics (the anthophyllite-bearing rock and the white limestone) show transport (2) from the NNE to the SSW.

Despite his compilation of data implying two contrasting flow directions, Gale interpreted all of his evidence in terms of a single event, which he expressed as "the diluvial current." Gale tried to show how the changes in flow of a single such current could account for both the regional trends of the scratches and furrows on the smoothed bedrock and the displaced indicator erratics.

By appealing to a single transport event to account for the evidence of two transport directions, Gale began a pattern that would be followed by most subsequent students of the "diluvial" deposits. But Gale's single transport event differed significantly from the one favored by later investigators. Gale concluded that his single "diluvial current" had flowed from NW to SE and he sought aberrations in this flow direction to account for the displacement from NNE to SSW of indicator erratics. In contrast, the single flow event for most later workers was taken to be from the NNE to the SSW; they invoked aberrations to explain the scratches and furrows that trend NW-SE.

The idea that the features Gale referred to as "Diluvial" had been made by a now-vanished continental glacier was proposed later in the ninenteenth century. T. C. Chamberlin (1895) argued that only one Late Pleistocene ice sheet had invaded the New York City region. Chamberlin's view was reinforced by R. D. Salisbury and assistants (1902), and is implicit in all recent papers where the term "lobe" is used with respect to the margin of the ice sheet (for example, Connally and Sirkin, 1970, 1973; Sirkin, 1982).

One Glacier, Several Flow Directions

Salisbury and assistants (1902) found that the predominance of ice-flow indicators showed glacial flow from the NNW to the SSE over the Palisades whereas by contrast, such indicators demonstrated that glacial flow over the Watchung ridges had been predominantly from the NNE to the SSW. In his interpretation of these indicators of contrasting directions of ice flow, Salisbury argued that within the margins of an ice sheet are localized zones within which the ice-flow paths are faster than elsewhere. Accordingly, the ice-flow "streamlines" are thought to be crowded close together (Figure 21). On either side of such supposed zones of concentrated flow, the ice tends to spread out toward each side.

In applying this concept to the New York metropolitan area, Salisbury inferred that during the latest glaciation of the New York City region, the axis of fastest-flowing ice had not been down the Hudson Valley, as one might expect on the basis of valley size, but rather had followed the Hackensack Valley to the west (Salisbury and assistants, 1902). From this inferred zone of concentrated flow down the Hackensack Valley, they thought that the ice had flowed toward the SSE over the Palisades ridge and Manhattan, and toward the SSW over the crests of the Watchung Ridges in New Jersey (Figure 22).

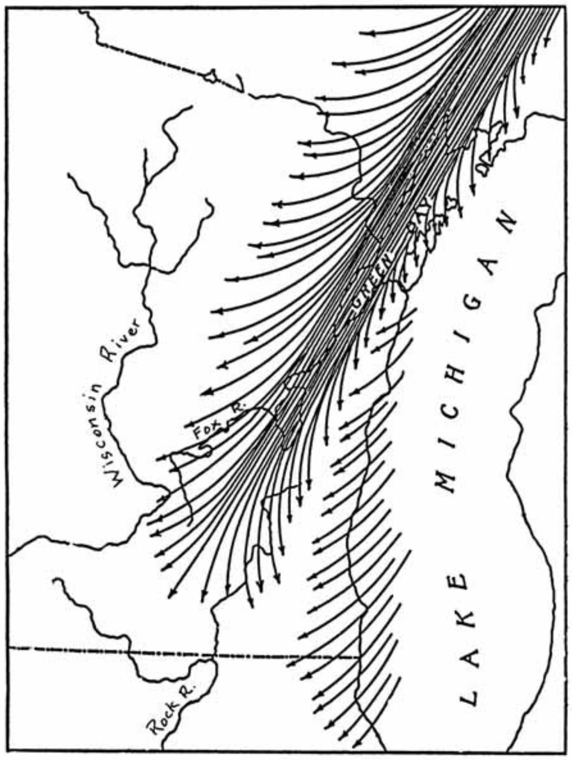


Figure 21 - A divergent system of striae found west of Lake Michigan. (Salisbury, 1902, fig. 31.)

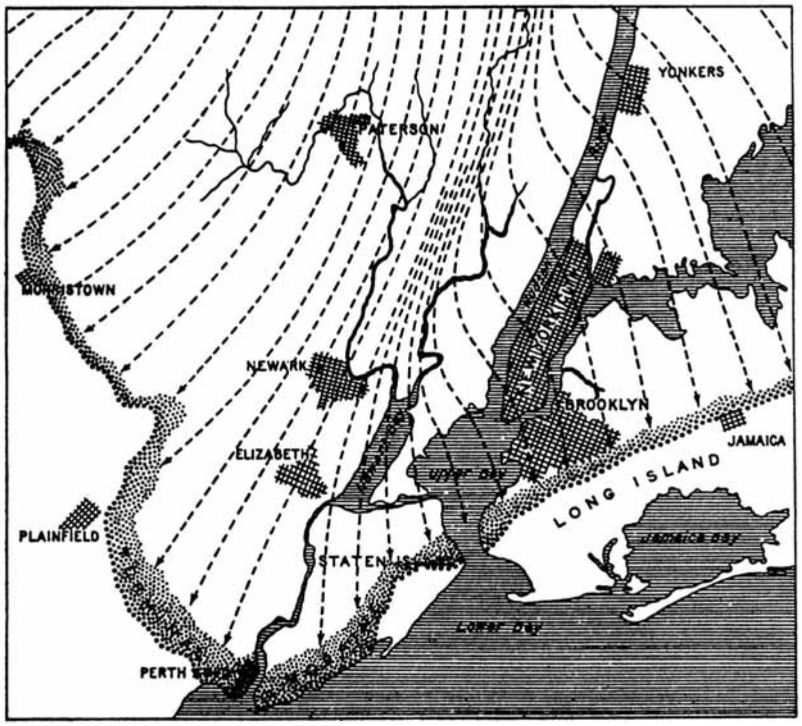


Figure 22 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, fig. 11, 1908, rendering of R. D. Salisbury).

Salisbury admitted that the regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from NW New Jersey constituted an anomaly to this explanation of marginal-flow divergence within a single glacier as the cause of the divergent orientations of the glacial grooves and scratches. Salisbury acknowledged that another succession of events which could explain the distribution of erratics of Green Pond Conglomerate involved two glaciations:

> "No single Green Pond mountain conglomerate bowlder has been found on the ridge. West of Hackensack, such bowlders are found in abundance, and this in spite of (sic) the fact that in New Jersey the movement of the ice along the Green Pond mountain range was to the southwest, approximately parallel to the range itself. Glacial movement in this direction could not have carried bowlders from the New Jersey part of the Green Pond mountain formation to the Hackensack valley. It would seem that the conglomerate ledges which furnished the Hackensack valley bowlders must have lain somewhere north of New Jersey, in the axis of the ice lobe, or perhaps a little to the west of it, and that the bowlders derived from this ledge were carried southward in the direction of ice movement, and finally out of the valley onto the highlands to the west by the westerly-diverging currents, but that they were not brought within the influence of easterly diverging currents, and therefore were not carried eastward upon the Palisades ridge. Another hypothesis which would equally well explain the distribution of the Green Pond mountain conglomerate bowlders, but for which there is no demonstrative evidence at hand, is that these bowlders were carried southeastward from their parent ledges by an earlier ice movement, the movement in the last epoch being to the southwest over or along the Green Pond mountain formation. (A good deal may be said for this suggestion). The distribution of these bowlders has not been studied beyond the State of New Jersey" (Salisbury and Peet, 1894, p. 180).

Ice Lobes

Another version of how a single glacier could create flow indicators having several directions is based on the behavior of ice lobes. Such lobes characterize the terminus of a valley glacier that has spread beyond the confining bedrock valley walls. Although the main flow direction of ice in a valley glacier is parallel to the trend of the valley, within the terminal lobe, the spreading ice creates divergent flow paths.

Flow Determined by Ice Domes on Top of Glacier

The theoretical background in support of the concept that one and the same continental ice sheet could display multiple flow directions was proposed at the time when the modern version of the Laurentide Ice Sheet was advocated (Flint, 1943). According to Flint, the Laurentide Ice Sheet began as one or more snowfields in the highlands of northeastern Canada. With continued additions of snow, an ice cap appeared and it began to spread southward and westward. The azimuth from the northeastern Canadian highlands to New York City is 195° or along a line from N15°E to S15°W. After this ice cap had become a full-fledged ice sheet and had attained something close to its full thickness, it is presumed to have itself become a factor in localizing where additional snow would fall. Flint inferred that the ice sheet could divert the flow of moisture-bearing winds from the Gulf of Mexico and thus would have acted as an orographic source of precipitation. In other words, the ice sheet forced the air to rise and to be cooled and thus to drop its moisture. Enough snow is therefore thought to have been heaped up at various localities near the outer margin of the ice sheet and thus to have formed ice domes whose relief may have altered the direction of glacial flow. Thus, the initial direction of regional rectilinear flow toward the SSW as a result of snow supply from northeastern Canada, could change locally to centers of quasiradial flow under of the influence of the ice domes each of which could display divergent flow patterns, including zones of flow from NNW to SSE. During meltback and retreat of the ice front, the above-described situation would be reversed. The factors responsible for radial ice-dome flow, including sectors from NNW toward the SSE, would cease to operate and those causing rectilinear flow toward the SSW to resume their former pre-eminence. The predicted pattern of flow for each advance of such an ice sheet, therefore, would involve three phases in the following order: (1) rectilinear flow from the NNE toward the SSW; (2) quasi-radial flow from the glacier-marginal ice domes, but locally from the NNW toward the SSE; and (3) rectilinear from the NNE toward the SSW.

Flint opposed the multiple-glacier hypothesis because he was convinced that if two glaciers had flowed over an area and both had extended their influence deep enough to polish and scratch the bedrock, then the younger glacier would obliterate all traces of the older one. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one.

Multiple Flow Directions, Multiple Glaciers: Boston Area, MA

After he had analyzed the Pleistocene stratigraphy of the Boston area, Kaye (1982) wrote the following paragraph under the headings of directions of glacial flow:

> "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° 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, the mean direction being S23°E +/- 1° for Till I; S64°E +/- 18° for Till II; and S31°E +/- 2° for Till III.

Our View of the Situation

The regional geologic relationships in the New York City region are especially helpful with regard to ice-flow recon-structions. The distribution of the reddish-brown bedrock in the strata filling the Newark basin lying west of the Hudson River provides an especially valuable indicator with respect to ice flow across the Hudson Valley in contrast to ice flow down the Hudson Valley. In many localities east of the Hudson River, color of the glacial sediments alone suffices for distinguishing source-distinctive tills and -outwash sediments. Any reddish-brown sediments resulted from action of ice that flowed across the Hudson River. By contrast, sediments that are yellowish brown or gray were deposited as a result of glaciation by ice that flowed down the Hudson Valley. This interpretation is not valid on parts of Long Island because red-colored sediments of the Connecticut River Valley basin may have been distributed southwestward by ice flow from the NNE (See our On-The-Rocks Trip 15 guidebook for Long Island.)

According to us, several interpretations of these two sets of ice-flow indicators are possible. These are: (1) that various changing conditions caused the direction of flow of a single ice sheet to shift with time, and (2) each set of flow directions was made by a single glacier having only one dominant flow direction.

(1) Almost without exception, geologists who have studied the Pleistocene deposits in the New York metropolitan area have accepted T. C. Chamberlin's viewpoint that a single ice sheet of Late Wisconsinan age created all the flow indicators observed. We agree that the various mechanisms that have been proposed (deviated flow related to change of speeds of ice streamlines, lobes at the margin, and peripheral ice domes) are valid concepts. Our main dispute is with the ways in which these concepts have been proposed and that the proposers have ignored the evidence of glacial erosion of the bedrock, provenance, and stratigraphic relationships of the tills.

(2) We think that the evidence in the New York City region is best interpreted by multiple glaciations, several of which displayed what C. A. Kaye referred to as "rectilinear" flow. Our interpretation of the relationships in New York City almost exactly mataches those described by C. A. Kaye from the Boston area.

Contrasting Glacial Effects on Valleys as a Function of Valley Trend: Valleys Trending NE-SW vs. Those Trending NW-SE

Although room for doubt may still exist in the minds of some readers on the subject of the relationship between the contrasting azimuths of the glacially sculpted striae and other features on the bedrock and the stratigraphy of the Quaternary sediments, glacial ice flowing in two contrasting directions [at whatever time(s) it may have done so] has affected valleys differently according to the angle between valley trend and ice-flow direction. For example, ice flowing from NNE to the SSW has tended to deepen and clean out valleys trending NE-SW and to fill but not otherwise change valleys trending NW-SE. By contrast, ice flowing from NW to SE has deepened and cleaned out valleys trending NW-SE and filled valleys trending NE-SW. These relationships between glacial-flow direction and valley trend have affected the preservation of stratigraphic units associated with each glacial episode, may have been significant factors in determining the course of the Hudson River across the Hudson Highlands, and affect the application of the correct use of the term fjord for valleys along the New England coast. (For further discussion, see our On-The-Rocks guidebook for the Hudson Highlands trip.)

Preservation of Stratigraphic Units

The direction of flow of the last (youngest) glacier to spread into the New York City region was from NNE to SSW, a direction that is down the Hudson Valley, the Hackensack Valley, and other valleys having this trend, and is close to the regional strike of many bedrock formations. The last glacier deepened these valleys that trend NE-SW. The ice dug down to bedrock and thus removed most traces of sedimentary units deposited by older glaciers.

Engineering borings in the Hudson and Hackensack valleys, for example, show a succession from brownish gravel (probable till) resting on bedrock and overlain by brownish sand and brownish varved clay that shows but slight resistance to penetration of the drilling tools. Clasts from gravels associated with these deposits tend to be well rounded.

Course of the Hudson River across the Hudson Highlands

The fact that the major river of the region, the Hudson, flows across the largest topographic barrier in the region, the Hudson Highlands, has attracted the attention of several geomorphologists. Two contrasting interpretations have been proposed: (1) superposition, and (2) headward erosion along zones of weakness. The most-recent analysis (by Thompson, 1936) emphasized the close relationship between zones of weakness in the bedrock and the zig-zag course of the Hudson River. Closely spaced joints and faults trending NW-SE have been followed by dikes; these fracture provide ready-made zones of weakness in that direction.

All previous students of the subject of the course of the Hudson across the Highlands have acknowledged that the history includes continental glaciation, but all have presumed that only one glacier was involved, that it flowed from NNE to SSW, and that glacial effects were not significant factors in determining the river's location. Our proposed new interpretation of the glacial history introduces many new dimensions to the subject of the course of the river across the highlands. For example, each of the two flow directions is parallel to one of the two zig-zag segments of the river. The regional joint patterns and structural trends break up the bedrock into blocks cut by NE-SW- and NW-SE-trending fractures and structural fabrics. The edges of these blocks would be easily eroded by flowing water or ice scour across the region. Glacial flow from the NW would erode and enlarge valleys trending NW-SE. Glacial flow from the NE would erode and enlarge valley segments trending NE-SW. The proposed order of ice flow (as explained below) is: (1) from NNE, (2) from NW; (3) from NW; and (4) from NNE. Thus, the end result of erosion associated with these four glacial advances could easily have been a bedrock-controlled path across the highlands. Significant pieces of this path could have been eroded one at a time by a single glacier: the zigs being cut by ice flow from one direction at one time and the zags, by ice flowing from another direction at another time. Such zig-zag erosion need not have been the only influence of the glaciers on drainage history. Clearly, the glacial striae and crescentic marks that we have detected on top of Bear Mountain indicate flow by two glaciers, one from the NW and another from the NNE. The thick glaciers passed over this rugged landscape without ever blinking an eye; they were not impressed.

We know from the effects of glacial erosion on the highest peaks that ice completely covered the highlands probably to a depth of several kilometers. Therefore, streams of meltwater that began to flow southward on the top of the melting glacier would have been flowing across the highlands from a still-higher elevation associated with the glacier. To some degree, drainage across a resistant mass that was established on a wasting glacier at a higher elevation would qualify it as being a special kind of superposition, that is a lowering of a downcutting stream so that it flows across a buried resistant rock mass after having been established at a higher elevation. As first defined and widely applied, superposition involves the lowering by downcutting of a drainage network which began on a younger stratigraphic unit that unconformably overlies the resistant feature.

Fjords on the New England coast?

Fjords are glaciated valleys that have been drowned by the sea. Typically, the glacier involved was a valley glacier and it flowed down the valley, deepening it into a typical U-shaped cross section. Because the valleys on the rugged Maine coast have been glaciated, some geologists suggested that they should be referred to as fjords. Despite the combination of glaciation and coastal valleys, Douglas Johnson objected to the designation of coastal-Maine valleys as fjords. His chief reason for doing so was that the direction of glacial flow (from NW to SE) had been across the valleys (that trended NE-SW) rather than along their axes. But, if any glacier had flowed down the axes of Maine's coastal valleys (that is, from NE to SW), then whatever merit may have attended Johnson's argument virtually disappears.

Because the direction of flow of the last glacier to overspread the New York City region was down the Hudson and Hackensack valleys, and subsequently these valleys have been drowned by the sea, we think it is appropriate to refer to these valleys as fjords. Although the Hackensack valley is situated in an area of low relief and has been nearly completely filled with sediment, it would still qualify as being a fjord. In addition to its other fjord-like characteristics, the slope of the thalweg (defined as the line joining the deepest points of a stream channel or more generally, valley profile) of the Hackensack valley reverses at the southern limit of the ice (Lovegreen, 1974). This reversal is from the usual NNE to SSW gradient to a steep slope from SSW to NNE.

Glacial Geology of Southeastern New York

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 City, glacial deposits may be 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 (1934, p. 1), of Harvard, once described this relationships between "deployments" of glacial ice and the water of the oceans as one of "robbery" and of "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 has been firmly established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

Figure 23 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 23 - 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 24). 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.

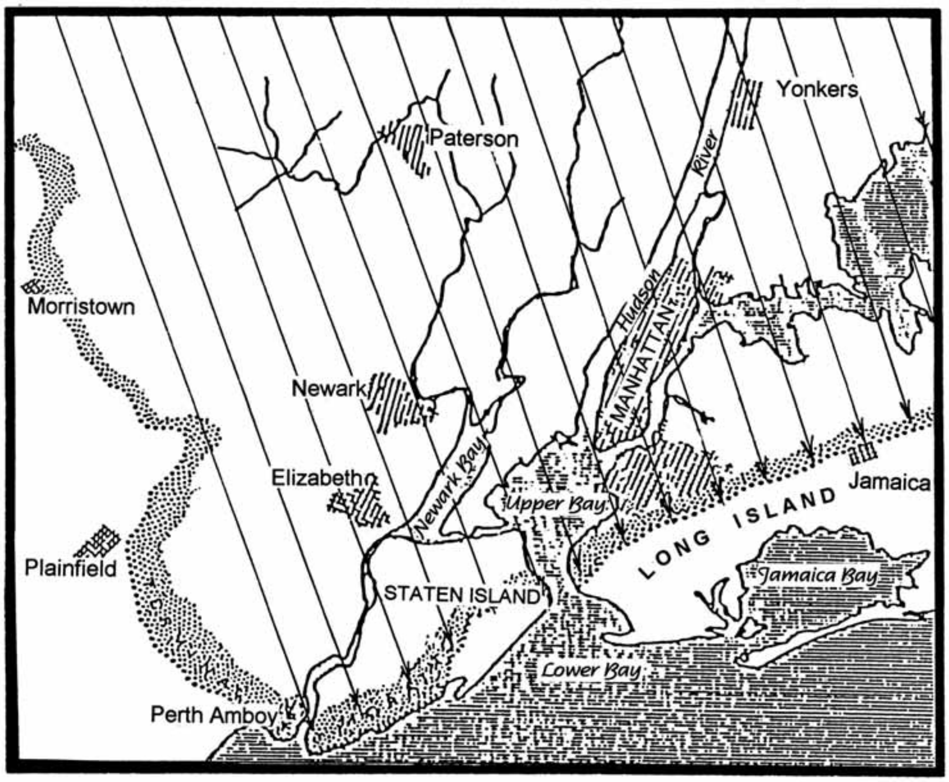


Figure 24 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders.)

From studying the stratigraphic relationships, provenance of indicator stones, and grooves on the bedrock, we propose an alternative view. In the our scheme of things, the flow indicated in Figure 22 is not the product of one glacier, but of more than three (possibly four).

The oldest glacier advanced from the NNE and is responsible for the basal till exposed at Teller's Point in Croton Point Park (Stop 2 of today's trip) and roche moutonnée sculpting of bedrock ridges in New York City that were subsequently scratched by a later NW-trending glacial advance. Following this earliest glacier, for which evidence is scarce and obscure (younger glaciers have removed most of the evidence for it), a second and possibly third glaciation took place from the NW direction.

The distribution of erratics derived from as far away as the anthracite district in eastern Pennsylvania (See Figure 20.) in the red-brown tills and outwashes in New York City lends strong support to the interpretation shown in Figure 24, as contrasted to Figure 22. In Figure 24, the ice is shown as having 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 ice gradient on the top of the glacier. Local red-colored outwash sandwiched between two red-brown tills suggests an interglacial (or short-term interstadial?) period within the NW-trending advance. At Stop 4, two red-brown tills are indeed separated by stratified red-brown sand which we interpret as glacial outwash. Interestingly, pebbles in the lower red-brown till show a higher degree of decomposition compared to those in the upper red-brown till.

Figure 25 shows the regional flow from NNE to SSW as resulting from a later (youngest or Woodfordian) glacier. According to our view, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 24 and not from the Woodfordian glacier! The latest glacier, shown in Figure 25, did not reach much of Long Island. This conclusion is based on our studies of glacial stratigraphy and provenance of till boulders. The Woodfordian glacier covered parts of Queens and Brooklyn, Manhattan, and Staten Island and was responsible for the yellow-brown till that caps the drumlin at Enoch's Nose in Croton Point Park (Stop 4). The extent and nature of its terminal moraine is not as yet known.

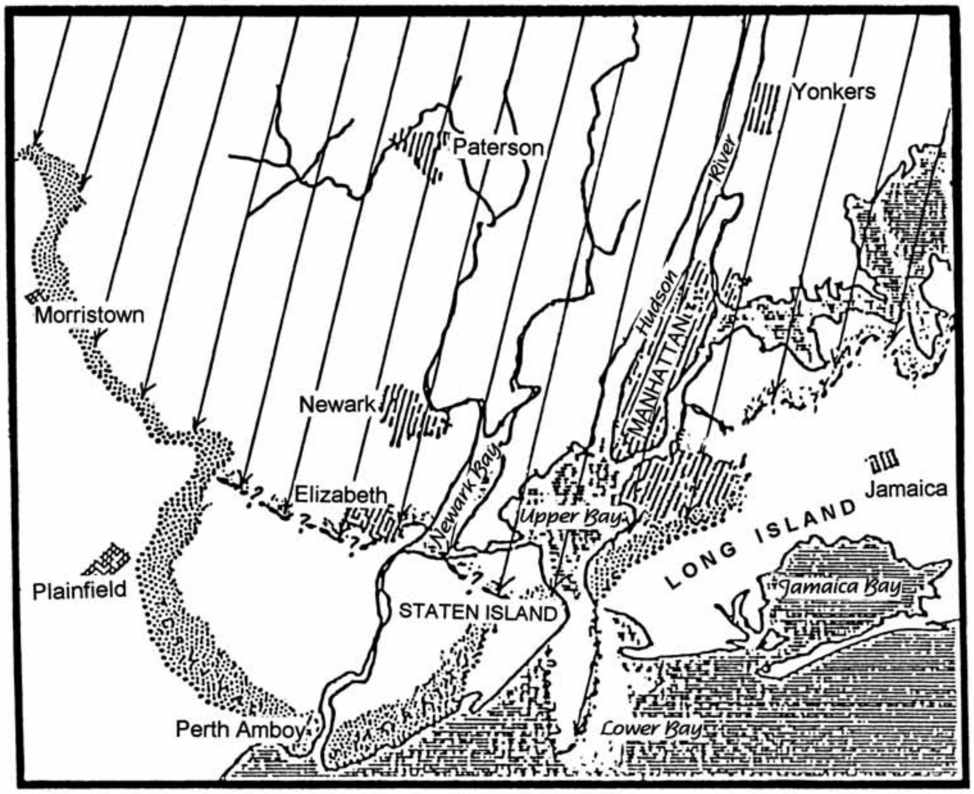


Figure 25 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

Thus, our new view of glaciation is based on evidence for four discrete glacial advances listed from oldest (1) to youngest (4):

1) early advance from NNE to SSW generating gray-brown till (in areas E of the Hudson River).

2) first advance from NNW to SSE generating red-brown till on E side of Hudson River S of Stony Point.

3) a second advance from NNW to SSE generating a second red brown till.

4) most-recent ice advance from NNE to SSW generating yellow-brown till.

Holocene Sediments Deposited by the Flandrian Submergence

The Late Wisconsinan (Woodfordian) ice sheet disappeared from the New York City region very rapidly. The ice front retreated northward, uncovering the lower Hudson Valley, the Mohawk Valley, and the Champlain lowland. It lingered for a time in the upper reaches of the St. Lawrence lowland, thus plugging the outlet now used by all the drainage out of the Great Lakes via Lake Ontario (Figure 26). The weight of the remaining ice continued to depress the surface of the lithosphere so much that even though the level of the sea was still generally low, the sea was able to inundate the St. Lawrence-Champlain lowland, forming the Champlain Sea. At this same time, all the water flowing out of the Great Lakes did so via the Mohawk Valley-Hudson Valley route past New York City. (See Figure 26.) Eventually, vast quantities of water from the melting ice flowed back to the oceans. As a result, the sea rose rapidly. This rapid rise of sea level has been named by European geologists as 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 such as the Newburgh-Beacon Bridge across the Hudson River (Figure 27).

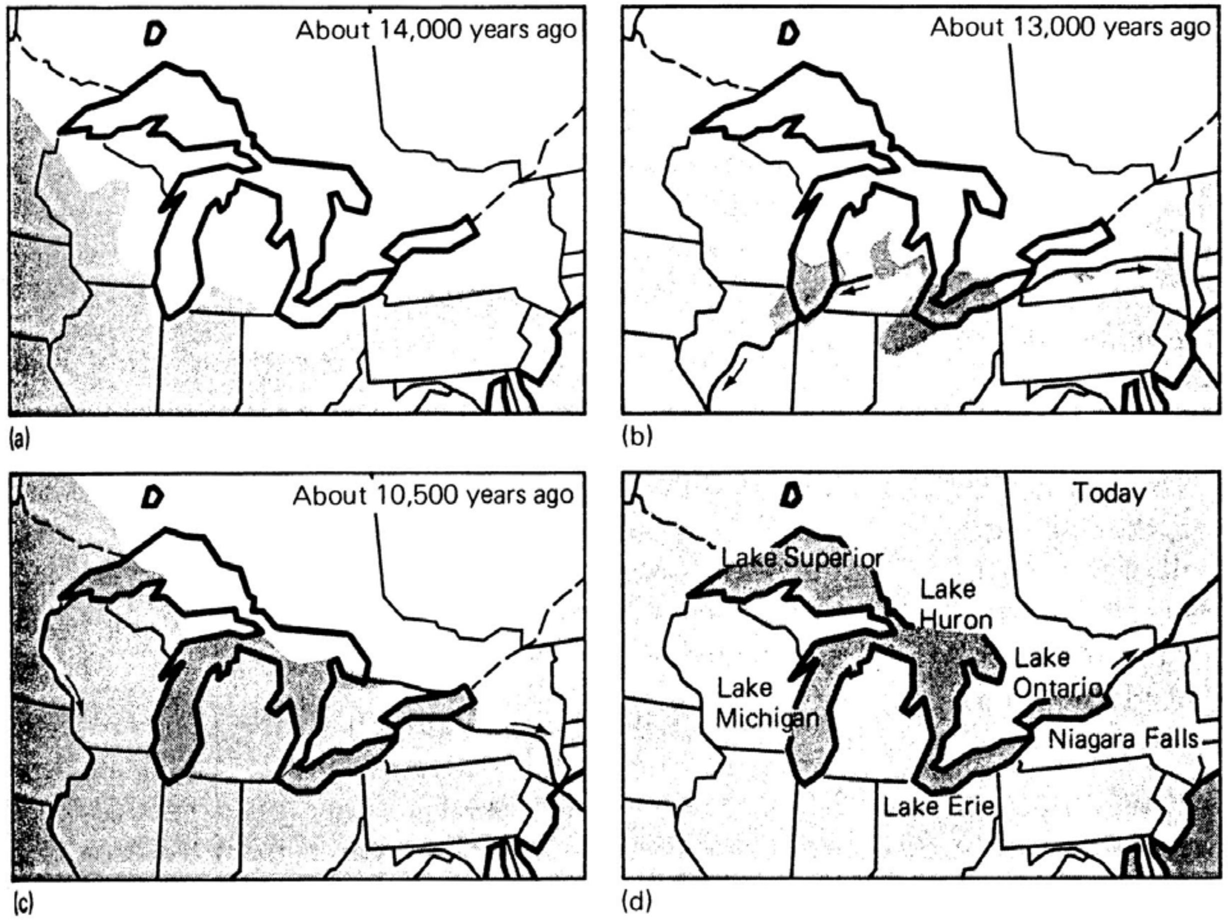


Figure 26 - Sketch maps showing Great Lakes at Wisconsinan glacial maximum, at two stages during deglaciation, and at present. (From F. B. Taylor, in Frank Leverett and F. B. Taylor, 1915, (b), pl. 17 facing p. 392; (c), pl. 19 facing p. 400; redrawn by J. E. Sanders, 1981, fig. 13.34, p. 333.)
(a) Maximum 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).

Once this silt began to be deposited in an area, the pattern did not change. We note a few points about this Holocene silt. First of all, similar to a geologist after a pizza lunch, 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 using ordinary small-boat continuous seismic-reflection profilers, as with sparkers, boomers, and air guns to obtain continuous seismic-reflection profiles of subbottom sediments. Many a hopeful investigator has supposed that it would be possible to obtain such continuous seismic-reflection 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.")

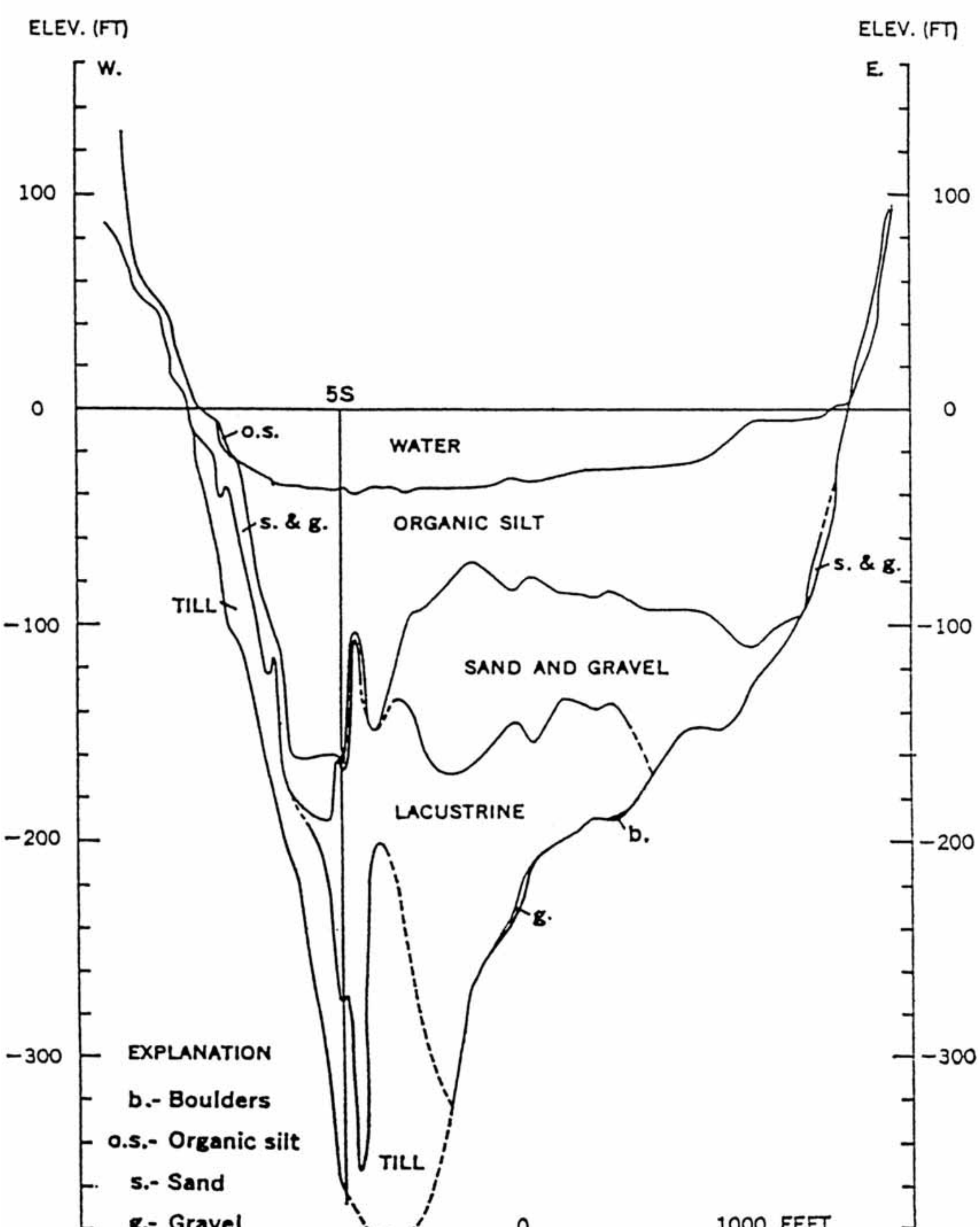


Figure 27 - Profile-section across Hudson River at Newburgh-Beacon bridge on I-84, based on samples from engineering borings, showing thick Holocene organic silt overlying lacustrine clay and -deltaic sand and gravel. Geologic interpretation by Newman, Thurber, Zeiss, Rokach, and Musich (1969); samples from boring 5S studied by Owens, Stefannson, and Sirkin (1974). (J. P. Owens; K. Stefannson; and L. A. Sirkin, 1974, fig. 10, p. 403.)

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, p. 404-405) obtained samples from the I-84 Newburgh-Beacon bridge borings (See Figure 27.) and compared the clay minerals from samples of the Upper Quaternary lake sediments with those of the Holocene estuarine silt and also performed chemical analyses on the silt. They found that illite is the predominant clay mineral; next came about equal amounts of kaolinite and chlorite. Montmorillonite was least abundant (averaging 15%). Illite and montmorillonite are more abundant in the estuarine silt than in the lake sediments. Chemically, in the lake sediments, CaO and CO2 are consistently higher than in the estuarine silts, sulfur is more abundant, and ferrous iron is higher than ferric iron. 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.

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 (137Cs - derived from nuclear-weapons tests in the atmosphere that began in 1954 and reached a peak in 1963--just before the treaty banning such tests took effect--and were 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, most of these sediments were being 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! (It is a splendid analogy to that story of the downcast person who was told by a cheery friend to "Cheer up!

Things could be worse." Thus heartened, the downcast person cheered up and sure enough, things got worse.)

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.

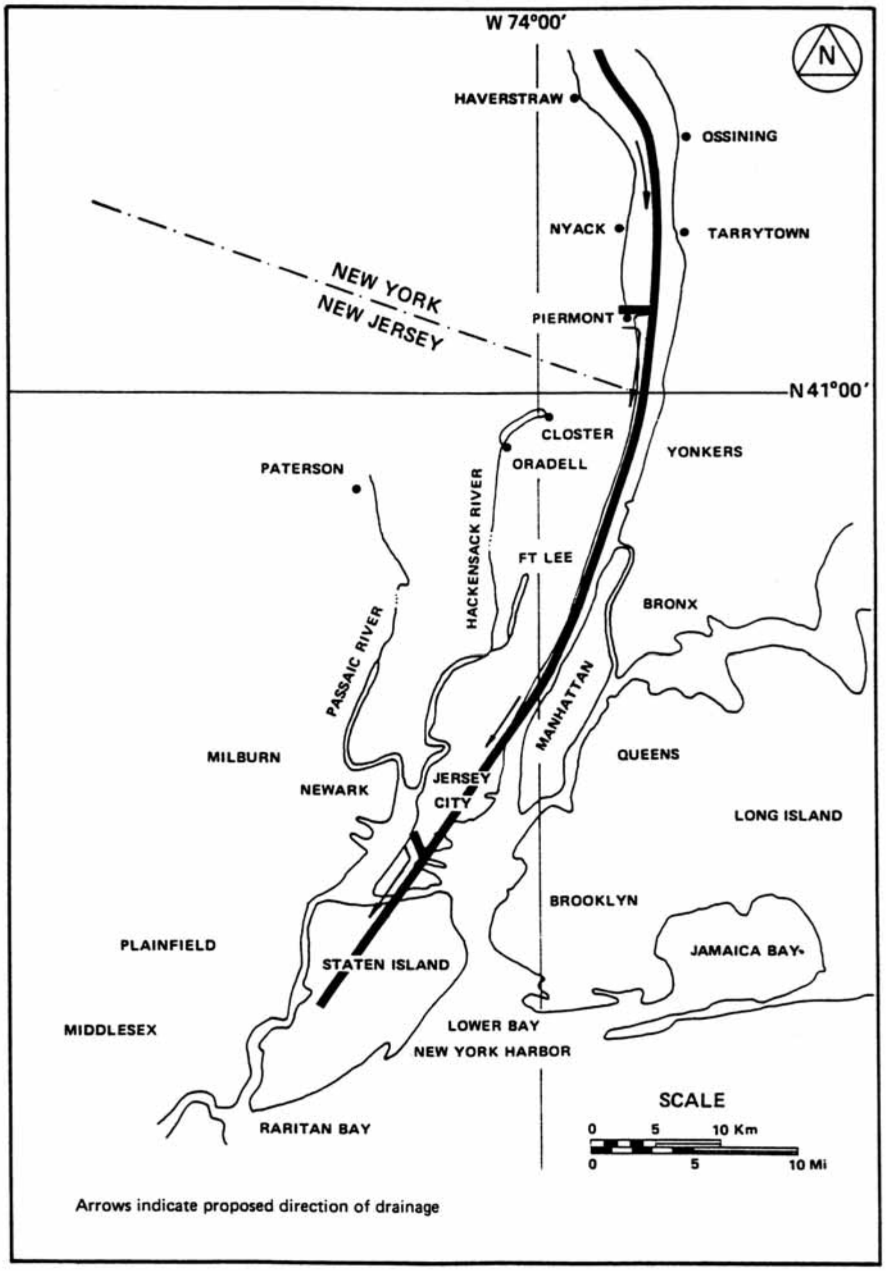
DRAINAGE HISTORY

The key objective of analyzing drainage history is to understand the relationships between rivers and the modern landscape. As a starting point, one pays attention to the relationships between rivers and the valleys in which they are flowing and between rivers that flow across highland areas (which rivers are supposed to avoid). Such rivers form parts of what are known technically as cross-axial drainage (the axis referring to the highland area).

Relationship Between Modern Rivers and Valleys

Modern rivers are flowing in valleys having considerable age spans. Some of these valleys have been in existence for hundreds of millions of years. Others are only a few tens of thousands of years old. The local candidate in the "oldest-valley" category is the strike valley at the base of the Newark Supergroup (Figure 28). (A strike valley is defined as a linear valley, parallel to the strike of dipping strata, that has been eroded where weak strata are enclosed between resistant units. At the base of the Newark Supergroup, the two resistant units are the pre-Newark metamorphic rocks of the Manhattan Prong and the Palisades sheet of igneous rock. The weak strata are the sandstones and shales between the Palisades sheet and the surface of nonconformity at the base of the Newark Supergroup. It is a reasonable geologic inference that this strike valley was established almost immediately after the Newark strata had tilted to the NNW, elevated, and eroded, starting in Mid-Jurassic time. The modern Hudson River enters this basal-Newark strike valley at Stony Point, New York, and follows it to Hoboken, New Jersey. At Hoboken, the Hudson River makes a turn to its left of about 15° (from about N15°E-S15°W to about N-S). It continues on this N-S course past Jersey City and into Upper New York Bay. The strike valley, however, persists on its regional trend toward the SSW and eventually passes beneath the coastal-plain Cretaceous on Staten Island. (See Figure 28.)

Figure 29 shows buried valleys in the New York City area inferred to be of Late Pliocene age. (Drainage changes from Lovegreen, 1974.) The post-Miocene interval was marked by the first of the great swings of sea level and stream erosion of the lowland now occupied by Long Island Sound (and the inner lowland elsewhere along the eroded edge of the coastal-plain strata). After the last glacier melted and receded northward, the damming effects of the Harbor Hill moraine of Long Island westward through Staten Island created a large lake of meltwater (Lake Albany) that stretched from the Narrows northward to Albany, New York. JES reckons that the lake received water from Great Lakes via the Mohawk River when the St. Lawrence Seaway was plugged with ice. The reign of glacial lake Albany ended abruptly when a dam at Narrows broke and water surged out across the shelf, eroding Hudson Shelf Valley. The Croton Point delta was built into this lake and once formed a conspicuous delta lobe into Croton and Haverstraw Bays (Figure 1, cover; further details in a following section). After the dam at the Narrows had broken, and Proglacial Lake Albany (Hudson) had drained catastrophically, the sea still stood near the outer edge of the existing continental shelf. Soon afterward, however, sea level rose rapidly. The rising saline water entered the former lake basin to create the modern Hudson estuary. The timing of the changeover from lacustrine- to estuarine conditions is contrained by a radiocarbon date of 12,000 b.p. on a basal peat deposit found beneath 120 feet of continuous tidal silt on Iona Island, north of Croton Point near the Bear Mountain Bridge (Newman and others, 1969).



Arrows indicate proposed direction of drainage

Figure 28 - 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).

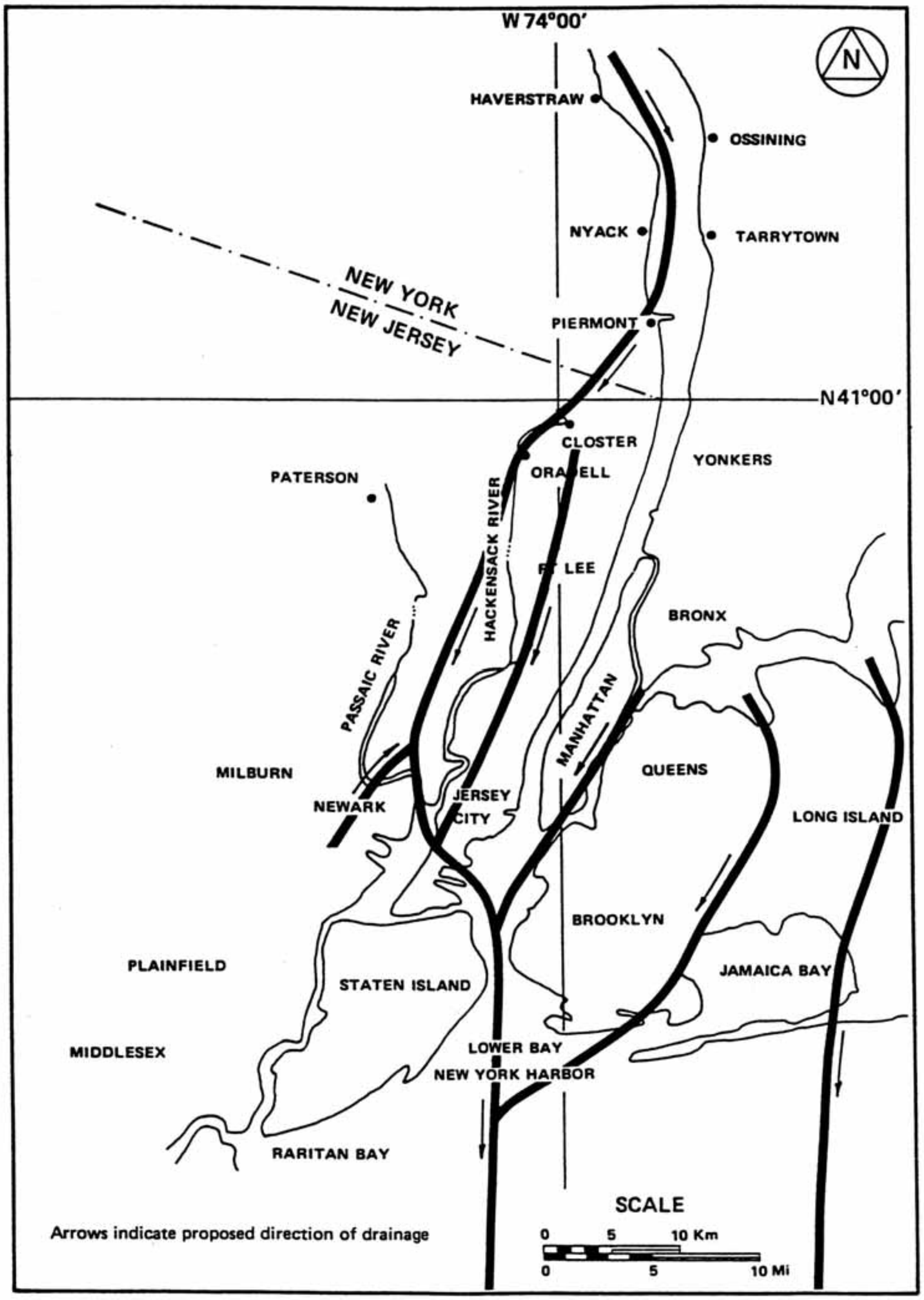


Figure 29 - Inferred drainage channels, Late Pliocene (before first glacier arrived). (J. Lovegreen, 1974 ms., Figure 22, p. 151).

Cross-axial Drainage: Hudson Crossing the Hudson Highlands

Locally, three rivers cross parts or all of the Hudson Highlands and thus might qualify as being cross-axial drainage anomalies. From W to E these are: the Ramapo, Hudson, and Croton rivers. We begin with the Hudson River.

From Hudson Falls to Storm King opposite Cornwall, the Hudson River flows almost due S across the Appalachian Great Valley, a ready-made lowland that trends NNE-SSW. At Storm King, the Hudson enters the Hudson Highlands, the highest territory around. It follows a zig-zag course through the Highlands. H. D. Thompson (1936) showed how the Hudson's zig-zag course through the Highlands follows zones of weakness in the Precambrian bedrock.

From Peekskill south to Hoboken, the Hudson follows another ready-made lowland, the strike valley at the base of the Newark strata. Thompson thought that the Pleistocene glaciers did not significantly influence the course of the Hudson through the Highlands. However, if our interpretation of multiple glaciations from contrasting directions is correct, then at least four continental glaciers buried the highlands. Two of these flowed parallel to the Hudson's zigs, and two parallal to the Hudson's zags.

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 Croton River, whose lower reach lies within the Manhattan Prong, cuts across the Highlands from Carmel into the Harlem Valley.

GEOLOGY OF CROTON POINT PARK

Croton Point Park is situated on the east shore of the Hudson River near Harmon, New York. Warring (1877) first identified the high sandy plains as being erosional remnants of a delta fed by the Croton River into a postglacial lake (Lake Albany). Here, Pleistocene- and Holocene surficial deposits unconformably overlie subvertically oriented Proterozoic and younger rocks (Layers I and II) of the Manhattan Prong. To the west and across the Hudson River (estuary), the trap-rock ridge of the Palisades is clearly visible.

The most-comprehensive modern review article on the geology of Croton Point Park was published by Markl (1971) who gave due credit to the important work of Kindle (1949, 1958). According to Markl, the deposits at Croton Point consist, by order of superposition, of till, clay, and sand. We agree that this is the correct order for the youngest units, but have discovered and will demonstrate today that more than one till is present and that the undulating top of a narrow N-S-trending ridge of till extends from Enoch's Nose to Teller's Point. This ridge of till profoundly influenced the distribution of sediments in the Lake-Albany phase of the park's history.

John Muenzinger, of the Westchester County Department of Planning, prepared a pre-landfill map of the surficial deposits of the Croton Point Park (Figure 30). Muenzinger's map shows not only the general locations of various sedimentary units but includes notations about exposures. His "moraine" is our till. We have not yet seen the exposures on which he based the diagonal-lined area of "glacial outwash containing apparent Triassic source material" on the E side of the knoll at Enoch's Nose (but have seen distinctive red-brown outwash in the cliffs along the W side of this knoll). Likewise, we have not yet seen the patch of eroded till in the intertidal zone W of Enoch's Nose. The "delta remnants" underlie the flat terraces at altitude of 50 to 60 feet; two of these are separated by "organic marsh and estuarine mud".

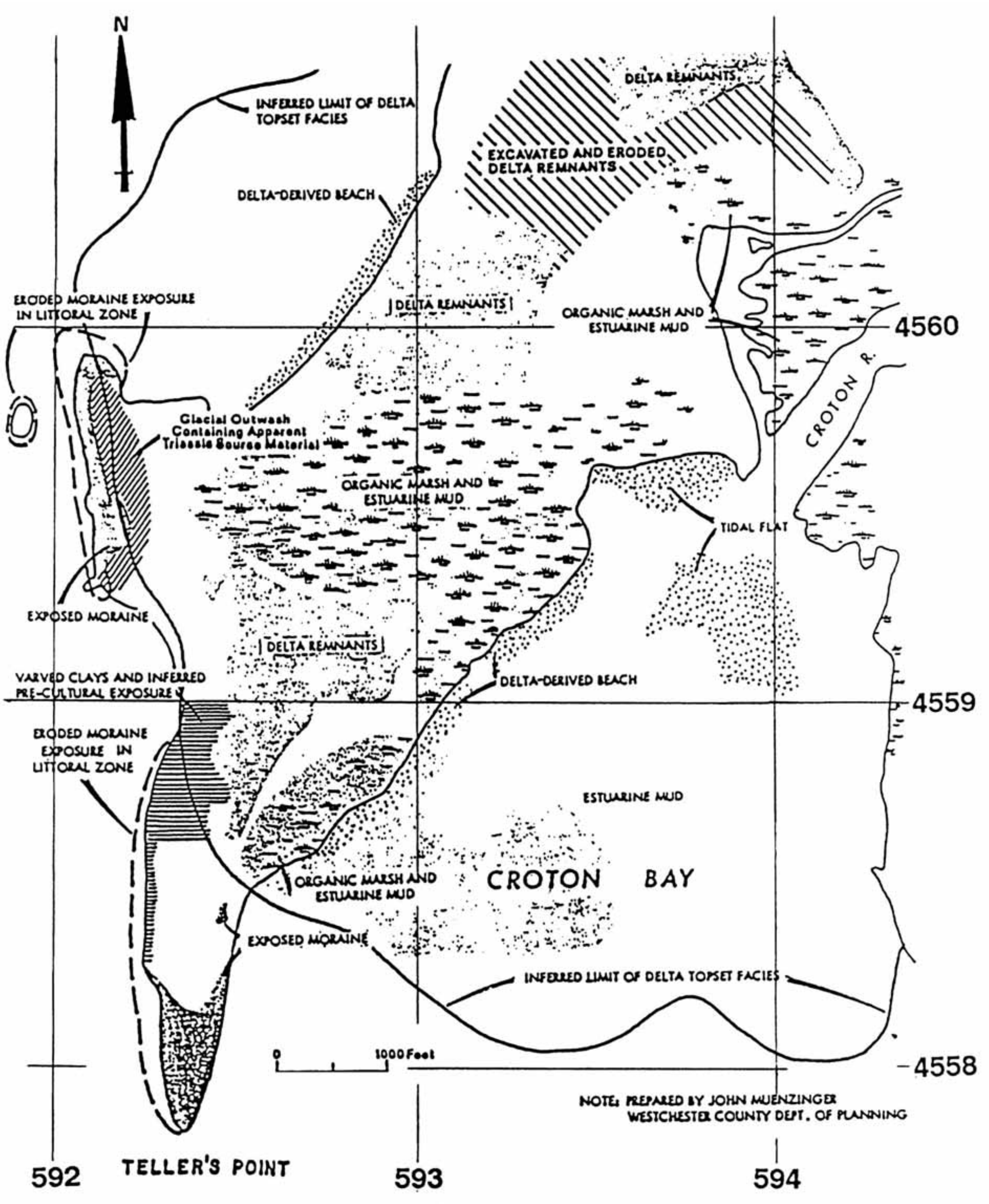


Figure 30 - Surficial deposits of Croton Point Park prior to beginning of major garbage dumping in the mid-1960s, compiled by John Muenzinger. (Slightly modified from Geraghty & Miller, Inc., report on Ground-water investigation at the Croton Point landfill, fig. 2, p. 10.)

The tills are exposed along the west edge of Croton Point Park at and northward from Teller's Point (Stop 2) and near Enoch's Nose (Stop 4). (See Figure 1, cover.) The upper surface of the exposed till(s) is undulatory. Just N of Teller's Point (Stop 2), till extends continuously from river level up to the crest of a knoll at altitude 50 feet (UTM Grid = 592.38E, 4557.95N). In Squaw Cove (Stop 3), the top of the exposed till drops below water level. At Enoch's Nose, till (interrupted by a layer of outwash) extends from river level to the top of the knoll at altitude 60 feet.

Markl noted that boulders from the Palisades, from the Newark Basin, from the Cortlandt Complex, and from the Hudson Highlands are being eroding from the till at these two localities. Markl agreed with Kindle's conclusion that the elongate distribution of till is best explained by supposing that it represents a lateral moraine deposited by glacial ice flowing down the Hudson River channel.

Sirkin, Cadwell, and Connally (1989) described two tills in southeastern New York as follows:

> "Lower Till. In general the drumlin-shaped hills that form the uplands of southeastern New York are capped by a layer of glacial (sic) till up to 10 m thick. This appears to be a basal till deposited during the earlier of two glaciations. This lower till forms the north-south trending (sic) drumlins in Westchester County. It is usually medium (sic) to dark brown, blocky and oxidized on the blocky surfaces. Uplands formed on the resistant ridges of Fordham Gneiss and Cortlandt Complex have (sic) only thin patchy deposits of till. The lower till may be correlative with the 'drumlin till' of southern New England." (p. 232)
>
> "Upper Till. The upper till appears poorly sorted, with occasional crude stratification and is interpreted to be a recessional deposit, such as ablation (sic) or meltout till. This unit is generally 1-3 m thick and may overlie the lower till. It may also occur as a meltout (sic) or flow till in ice-contact deposits. The upper till represents wasting of the Woodfordian glacier.
>
> "Many glacial erratics in the study area were quarried by the glacier from the rectangularly jointed bedrock units. Some erratics retain a rectangular shape and presumably were not transported far. Striations (sic) on bedrock surfaces generally trend north-northwest to south-southeast. Glacier flow from

> the north-northwest would account for Palisades basalt and Brunswick sandstone erratics of Hudson Lobe deposits in southern Westchester and western Long Island." (p. 233)

"LACUSTRINE DEPOSITS"

"...Glacial Lake Hudson developed between the Terminal Moraine and the retreating Woodfordian glacier margin and Lake Flushing formed in the position of the present Long Island Sound behind the end moraines on Long Island.

"The best evidence of Lake Hudson in northern Westchester County is Croton Point, a large delta that juts into Haverstraw Bay (Figure 1.) (sic) This bay, just south of the Hudson Highlands, is a widened and overdeepened part of the Hudson estuary. Some of the glacial deposits can still be seen even though much of the delta has been eroded, mined for the brick-making industry, or covered by a landfill. Stratified drift is exposed locally on the hillslopes adjacent to the railroad. Grain size (sic) analyses of these deposits show fining toward the delta and the sediments may represent the topsets of the delta. The west end of Croton Point is composed of ablation till overlying stratified drift. Here, erosion of these deposits has left a lag of boulders, dominantly composed of Cortlandt, Palisades, Brunswick, and Highlands lithologies as a beach. Lake clays are also exposed in the cliffs along the west side of the Point a few feet above river level and overlying glacial drift. The clays appear to be rhythmites possibly deformed during initial glacial retreat from the Croton Point ice margin..." (p. 235).

Although they did not mention it in their guidebook, Sirkin, Cadwell, and Connally accept the interpretation that the ridge of till, thought by Kindle to be a lateral moraine, is a drumlin. We agree.

Immediately above the till in several places occurs a minimum 3-10 foot thick gray clay deposits (commonly varved) that in the nineteenth century, were used to supply brickyards on Croton Point. Similar clays (up to 200 feet thick) are present near Haverstraw (Reeds, 1928; Schuberth, 1968); thinner deposits are known at Peekskill and Ossining. These clay are lake deposits that formed away from the Croton deltaic sands.

Clean, stratified, fine- to coarse-textured sands are present stratigraphically above the gray-clay unit. They are interbedded with pockets of gravel and lenses of silty clay and extend from below the present level of the Hudson River to thicknesses of 100 feet. (Is this fluffy sand really part of the deltaic complex? or is it wind-reworked delta sediments?)

In total contrast to the narrow ridge of till are two isolated flat-topped areas underlain by well-stratified sands and gravels (at the surface, but giving way downward to silts and clays). One of these flat-topped areas lies just NNE of the Teller's Point ridge (what's left of the former playing field); it tops out at altitude 60 feet. The second is about 1 km ENE of Enoch's Nose (the camping area) whose top reaches an altitude of 70 feet.

The flat-topped areas form the sand terraces of Croton Point Park. (See Figure 1, cover and Figure 30.) Particle-size distribution population studies by Markl (1971) indicate that gravels are more numerous near Harmon Park than regions to the south, that progressively coarser material is present from the bottom up, and that the long axes of current ripples are oriented roughly NE-SW. As such, the sand unit represents a former progradational delta whose source area was the Lower Paleozoic rocks to the north. One or more rivers may have fed this delta. One could have flowed in the valley occupied by the present Croton River. A second could have occupied the valley now followed by Route 129. The position of Route 129 and the inferred channels are shown on Figure 1 (on cover). An extensive intertidal marsh formerly extended along the SE side of the low area between these two flat-topped areas underlain by sand (Figure 31). (See also Figure 30.)

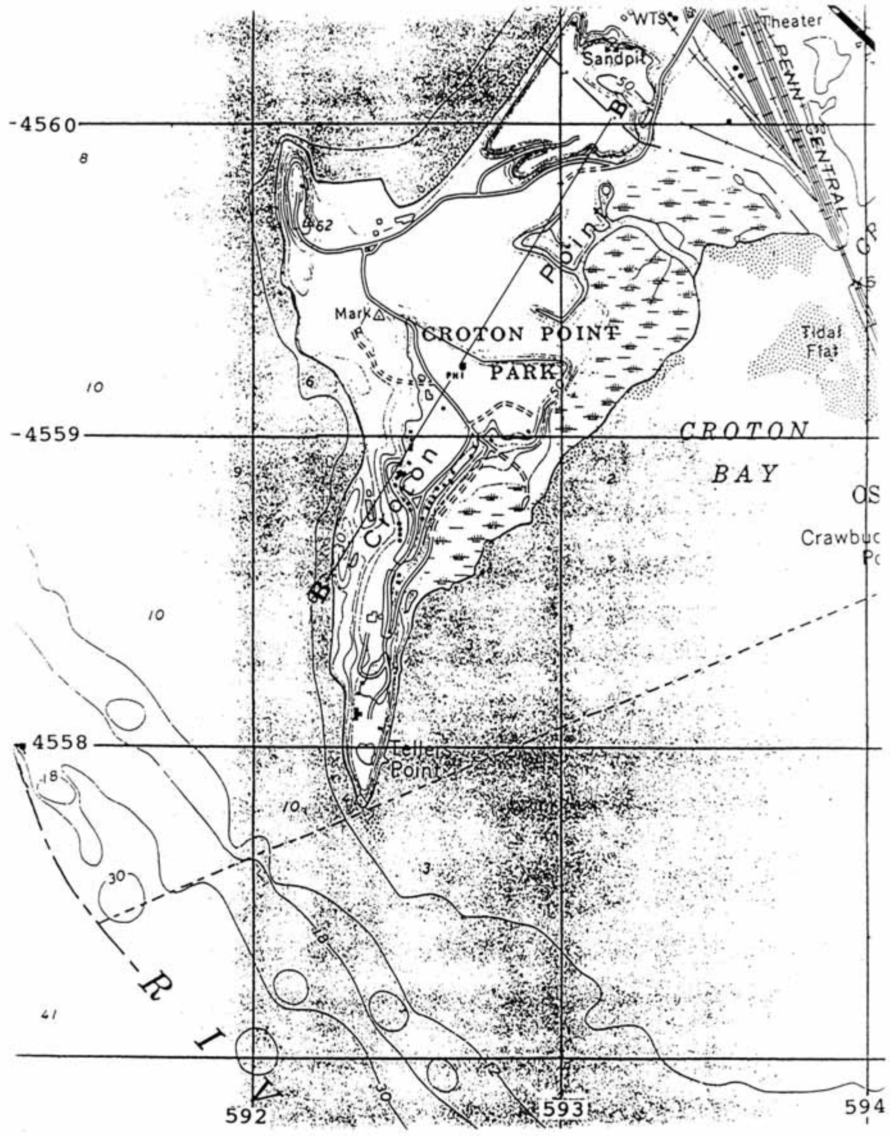


Figure 31 - Topographic map of Croton Point Park before major changes resulting from dumping of garbage. Line B-B' indicates line of profile-section of Figure 34, B. Location of Boring PH1 transferred by JES from Figure 33. (Part of U. S. Geological Survey 7.5-min topographic map of the Haverstraw quadrangle edition of 1967.)

Shell middens (masses of oyster shells) have been discovered at many places along the shores of the Hudson River from New York City to the Bear Mountain Bridge. Shell middens are especially numerous at Croton Point at Enoch's Nose where they overlie the till above river level. Another is exposed at Teller's Point. A radiocarbon date on charcoal associated with the middens at Croton Point yielded 5,863 (+/- 200) B.P. (Markl, 1971). Because oysters of the kind whose shells are in these middens need saline water to exist, the above date marks a modern period of estuarine conditions as discussed earlier.

The former low area underlain by intertidal-marsh sediments is now a high mound of garbage, a local Mt. Trashmore (Figures 32, 33, and 34, A). Westchester County dumped its garbage here from the mid-1960s to 1986. Much of the sand from the delta built by the Croton River into the former high-level lake was dug up and used to bury the trash.

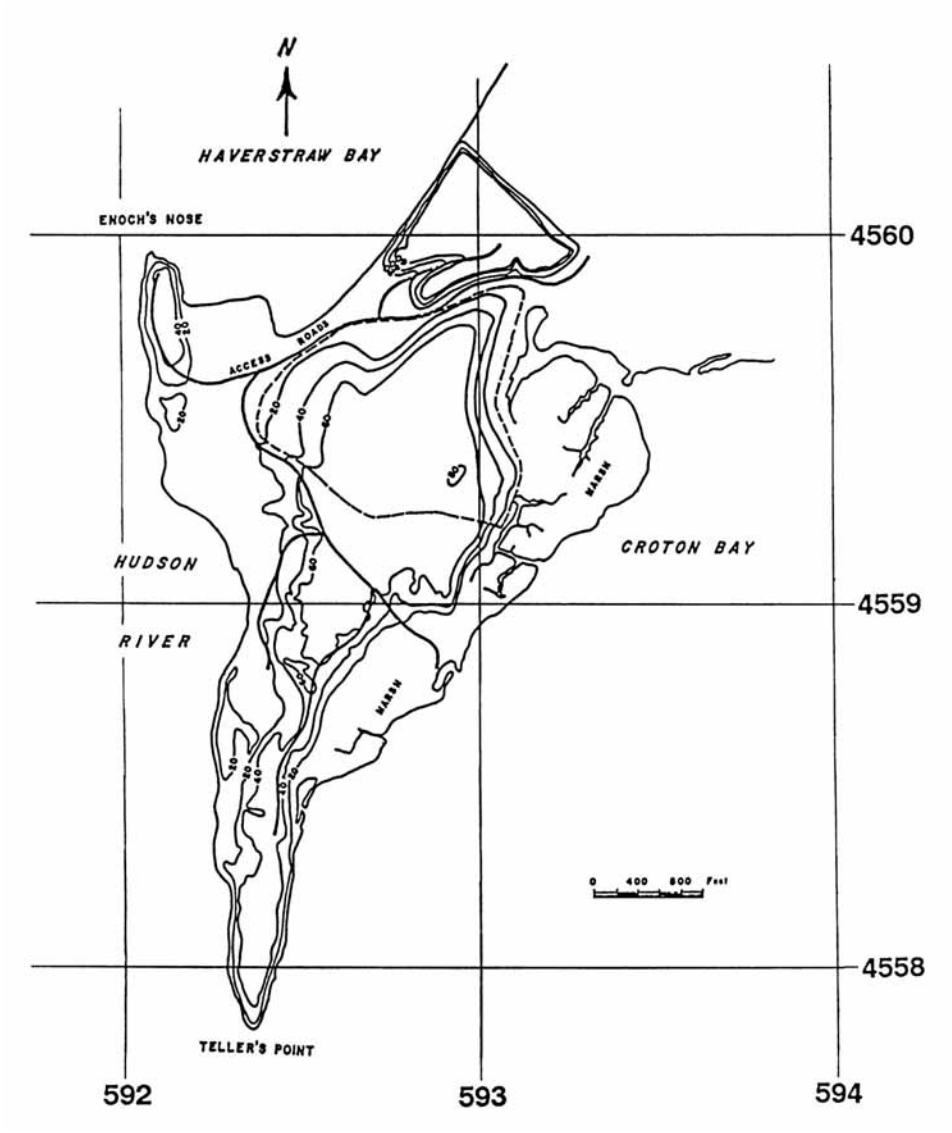


Figure 32 - Topographic map of Croton Point Park in 1974, after top of landfill had reached an altitude of 60 feet. (Modified by JES from map in Geraghty and Miller, 1976, fig. 11, p. 35.)

Figure 33 shows the general outline of the landfill, location of the Geraghty and Miller wells and borings, and the location of the profile section of Figure 34. Figure 33 is a topographic map of the land surface dated June 1974 when the top of the landfill had reached altitude 80 feet and thus had completely filled in the natural depression between the flat-topped remnants of the delta deposits (top at altitude 60 feet on the SW side; altitude 70 feet to the NE).

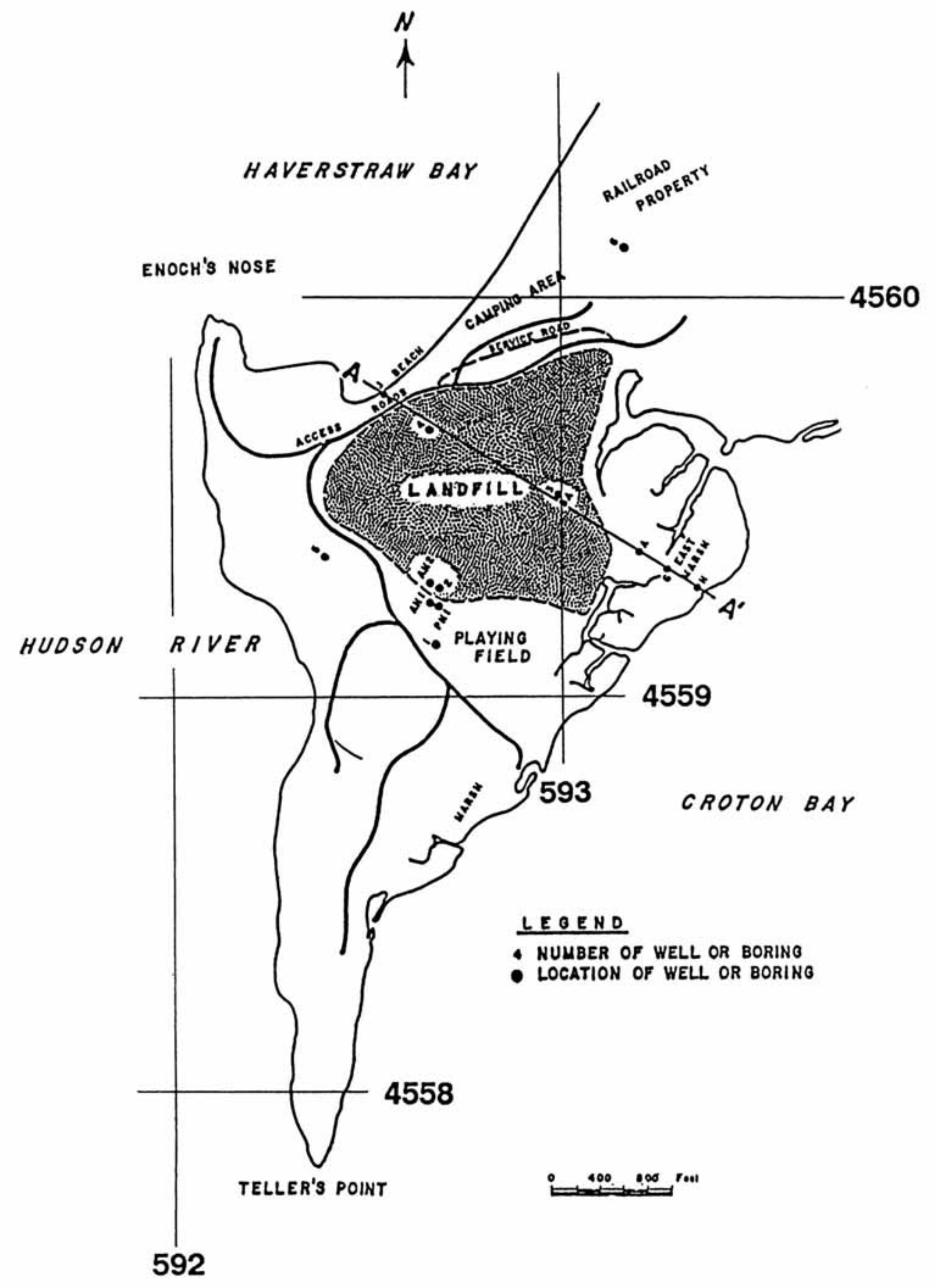


Figure 33 - Map of Croton Point Park showing location of landfill, line of profile-section of Figure 34, A, and locations of borings. (Modified by JES from map in Geraghty and Miller, 1976, fig. 1, p. 4.)

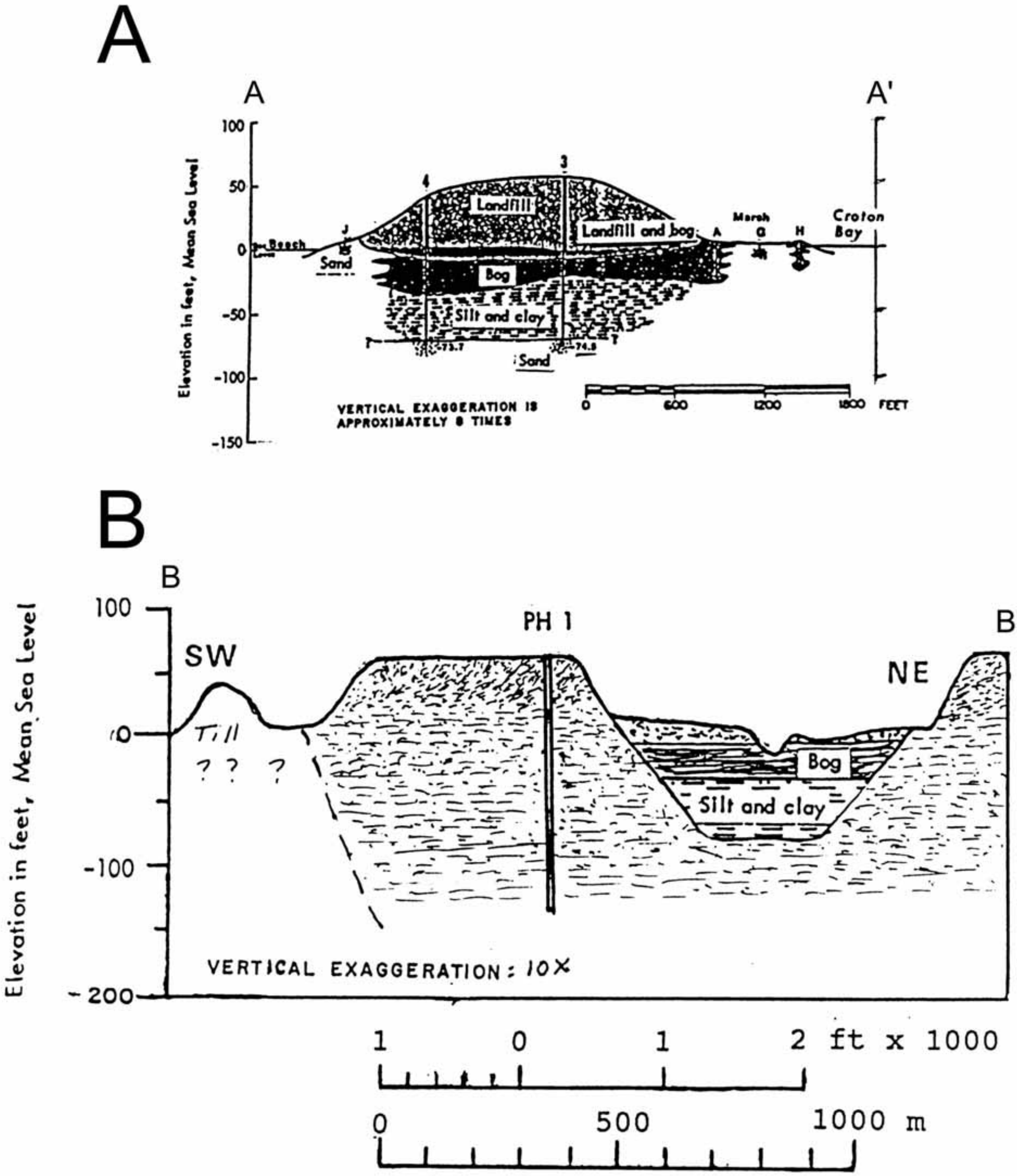


Figure 34 - Profile-sections of Croton Point Park.
A. Along line A-A' of Figure 33; parallel to axis of buried valley. (Geraghty and Miller, 1976, fig. 3, p. 11.)
B. Along line B-B' of Figure 31; perpendicular to axis of buried valley. (JES, using topographic base of Geraghty and Miller, 1976.)

The borings through the landfill prove that the former low, flat area underlain by the intertidal marsh is the top of a sediment fill of a valley that was eroded into the delta when the lake level dropped suddenly. The base of the silt and clay at about -73 feet (sea-level reference) marks the former valley floor (Figure 34, B). The thickness of this silt-clay is about 50 feet. Overlying the silt/clay unit is about 20 feet of "bog," which probably indicates intertidal marsh deposits that became established when relative sea level stood about 20 feet lower than today, and which thickened upward as sea level rose. The depth to bedrock is projected with queries at a subsea elevation of about 160 feet. The only control on this estimate is based on Hole PH 1, located about 1200 feet SW of the midpoint of this profile-section (location on Figures 31 and 33) began at altitude 60 feet on the ballfield adjacent to the landfill (subsequently removed in the Phase-II expansion of the landfill) was drilled 200 feet deep in what JES interprets as deltaic sediments to about 55 feet and lake clays and silts from 55 to total depth of 200 feet. Thus, no bedrock nor till was encountered at the bottom of the hole (-140 feet, MSL reference datum).

In summary, the sediments exposed at Croton Point are products of three contrasting depositional settings: (1) continental glacier; (2) postglacial lake with water level about 70 feet higher than modern river level; and (3) sediments deposited during the Flandrian submergence, including a basal silt/clay and capping "bog" (intertidal marsh formed along the encroaching shores of the Hudson Estuary).

So much for geologic background. We now summarize the litigation over Westchester County's use of Croton Point Park as a landfill.

ENVIRONMENTAL LITIGATION OVER WESTCHESTER COUNTY'S USE OF CROTON POINT PARK AS A LANDFILL

In the early 1960s, Westchester County began to dump garbage on the intertidal marsh at Croton Point Park. (See Figure 31.)

Figure 30 shows the surficial geologic relationships as prepared by John Muenzinger for the Westchester County Department of Planning (in the 1970's?). The site of the future landfill is labeled "organic marsh and estuarine mud."

On 09 May 1972, the U. S. District Attorney filed a complaint in the U. S. District Court, Southern District of New York, seeking injunctive relief for the pollution of the Hudson River by leachate coming from Westchester County's Croton Point landfill. The U. S. Attorney based this case on Sections 10 and 13 of the Rivers and Harbors Act of 1899 (33rd U.S. Congress pars. 403 and 407) and on Section 1 of the New York Harbor Act of 1888 (33rd U. S. Congress, par. 441.)

After several court orders, the first of which was dated 06 June 1972, Westchester County agreed to undertake certain actions with respect to the operation of the County landfill, the parties negotiated a settlement that was formalized as a Final Judgment (On Consent) 72 Civ. 1964, signed on 04 February 1975 by Constance Baker Motley, filed on 11 February 1975, and entered as a Judgment on 18 February 1975.

Several notable consequences resulted from this Judgment. First of all, the then-County Executive was Edward Michaelian, who was a "force" in the Republican Party; his influence extended well beyond Westchester County. The case against Westchester County was the last one ever to be brought under the Rivers and Harbors Act of 1899 (33rd U.S. Congress pars. 403 and 407) and under the New York Harbor Act of 1888 (33rd U. S. Congress, par. 441). A noteworthy feature of these two acts was the bounty provision whereby citizens who instigated successful court actions against a polluter were awarded the fines levied against the convicted polluter. When the U. S. Congress passed PL92-500, the Federal Water Pollution Control Act of 1972 (popularly referred to as the "Clean Water Act" or CWA), it established the U. S. Environmental Protection Agency. At the behest of the Nixon Administration, a special amendment was added to this act. The date the amendment passed was 18 October 1972. This amendment specifically took away the bounty-hunting aspect of the 1888 New York Harbor Act and the 1899 Federal Refuse Act.

Although we have not investigated any documentary proof of the proposition and mention it as pure speculation, we think that not much stretching of the imagination is required to visualize that Ed Michaelian (former Westchester County Executive) got in touch with his pal, the unimpeachable Richard Nixon in the White House, and drew Nixon's attention to the potential havoc that could be wrought by active citizen pollution bounty hunters, such as those who had founded the Hudson River Fishermen's Association and had just laid a Judgment on Westchester County over the Croton Point landfill.

The environmental groups who had brought the matter of the pollution of the Hudson River by leachate from the Croton Point landfill to the attention of the U. S. Attorney felt that this Consent Order represented a great victory for them and that Westchester County had been immediately enjoined from dumping trash at the Croton landfill and had been forced to begin immediately using alternative means of dealing with its ever-growing stream of solid wastes. A careful reading of the Consent Order, however, indicates that what the environmentalists thought they had gained and what was actually agreed to were not the same. In order to show the differences, we quote from the consent order.

III

"The County is permanently enjoined and restrained from depositing or permitting the deposit of refuse of any kind from the Landfill into the waters of Croton Bay or the Hudson River; provided, however, that this paragraph shall not be deemed to apply to the discharge of leachate occurring due to the natural movement of water through, over or under the Landfill so long as the County is in full compliance with the following provisions of this Judgment:

> "A. The County shall continue to operate and maintain the landfill in a manner conforming to the regulations and standards of the New York State Department of Environmental Conservation (hereafter "DEC")."
>
> [JES comment: This is not exactly the

same thing as telling the County to cease immediately the dumping of further trash at Croton Point!]

"B. The County shall within six (6) months of the date of this Judgment decide upon the maximum elevation and final grade and shape of the Landfill, based upon the studies and recommendations of Geraghty & Miller, Inc., and as approved by DEC. The final shape of the Landfill shall be in accordance with such decision."

[JES comment: This subparagraph left the County room to maneuver, and maneuver they did. They kept delaying this decision about the "final grade and shape of the Landfill." They took advantage of a clause in the Geraghty and Miller report about "further studies" by changing consultants, each of whom drilled more holes, and whatever, en route to this nebulous decision. More than 10 years elapsed before the County announced that it was able to decide on the "final shape of the landfill." Meanwhile, they doubled its size!

However, the County did modify its operations of the landfill so as to conform to DEC regulations, and thus it remained within the language of the Judgment.]

“C. Those portions of the Landfill which have reached or hereafter reach final grade from time to time shall promptly be provided with a suitable cover and seeded and maintained in accordance with DEC regulations so as to eliminate the washing of silt and refuse there from into the adjacent marshes, and furthermore shall promptly be capped or otherwise sealed in such a manner as substantially to eliminate infiltration of rainfall water or other source of recharge of the ground water. The proposed method of capping or sealing, including gas venting, shall have been submitted to and approved by the Environmental Protection

Agency of the United States (hereinafter "EPA") and DEC prior to implementation thereof.

"D. The County shall continue until five (5) years after the date of the final closing of the Landfill, to monitor annually the level of the ground water (sic) table under the Landfill and the amount of flow of leachate from the Landfill, to determine whether the capping has lowered the water table and substantially eliminated leachate flow by the end of said five years."

[JES comment: Notice that the date of final closure is not mentioned; only that whenever the closure is fixed, the County is committed to 5 years of "post-closure studies." In the summer of 1986, after the County's resource-recovery plant had been opened at Peekskill in October 1984, the Croton Point landfill was finally closed.]

"E. At the end of the first and fifth and tenth years following the final closing of the Landfill, the County shall monitor, in a manner acceptable to EPA and DEC, the quality of the leachate, if any, still flowing from the Landfill. Monitoring shall include making the chemical analyses at various sampling wells as described in Exhibit 'A' annexed.

"F. The County shall continue to employ the Boyce Thompson Institute For Plant Research, Inc. as necessary to complete its present study of the effect on the adjacent marshes of the discharge of leachate from the Landfill, and the possibility of restoring the marshes.

"G. The County shall submit annually, until five (5) years after the final closing of the Landfill, a written report to EPA and DEC and to the United States Attorney's

> Office for the Southern District of New York, describing the decisions made and steps taken by the County in compliance with subparagraphs B and C, hereof and the results of the monitoring and studies done in compliance with subparagraphs D, E and F, and shall also furnish EPA and DEC with the results of the monitoring done at the end of ten (10) years after the final closing of the Landfill.

"If on the basis of such studies and reports it should at any time appear to EPA, DEC or the County that (a) the flow of leachate will not be substantially eliminated within five (5) years from the final closing of the Landfill and that therefore a different system should be instituted to reduce leachate, or treat the pollutants in the leachate from the Landfill, or (b) that feasible and practicable steps can be taken to restore the adjacent marsh to a healthy condition, the County, EPA and DEC shall consult with regard thereto and shall devise such plans as may be appropriate to achieve said results. In the event that the parties hereto cannot agree as to the said plans, any party hereto may thereupon apply, on notice to all parties, for such modification of this Judgment as may be appropriate.

IV

> "The County's expansion of the Landfill into adjacent areas of Croton Point shall be subject to approval by DEC and EPA of plans for the elimination or collection and treatment of any leachate therefrom."
>
> [JES comment: This paragraph scarcely qualifies as an injunction against continued operation of the Croton Point landfill. Indeed, it specifically mentions "expansion" and "into adjacent areas of Croton Point," provided, of course, that DEC and EPA approve. The County sought and received approval from DEC and EPA of its newly adopted practices of operating the landfill and thus was granted permission to continue dumping trash at Croton Point for about 10 years after the environmental groups thought they had "nailed the County to the wall" and had obtained a court order to shut down the Croton Point landfill.]

Most of the many borings were made through the landfill to determine the physical characteristics of the underlying estuarine/marsh deposits for the purposes of deciding how high the trash could be piled with safety. Geraghty and Miller reckoned a limit of 100 feet. (Figure 35 shows the Geraghty-Miller version of the final shape of the landfill.) By contrast, Dolph

Rotfeld Associates and Wehran Engineering computed a safe upper limit of 120 feet. Naturally, the County opted for the larger number because it enabled them to keep dumping during the difficulties they were experiencing in inaugurating an alternative method of disposing of the solid wastes. These borings make possible a delineating of the shape of the valley eroded through the delta sediments when the lake level dropped. (See Figure 34, B.)

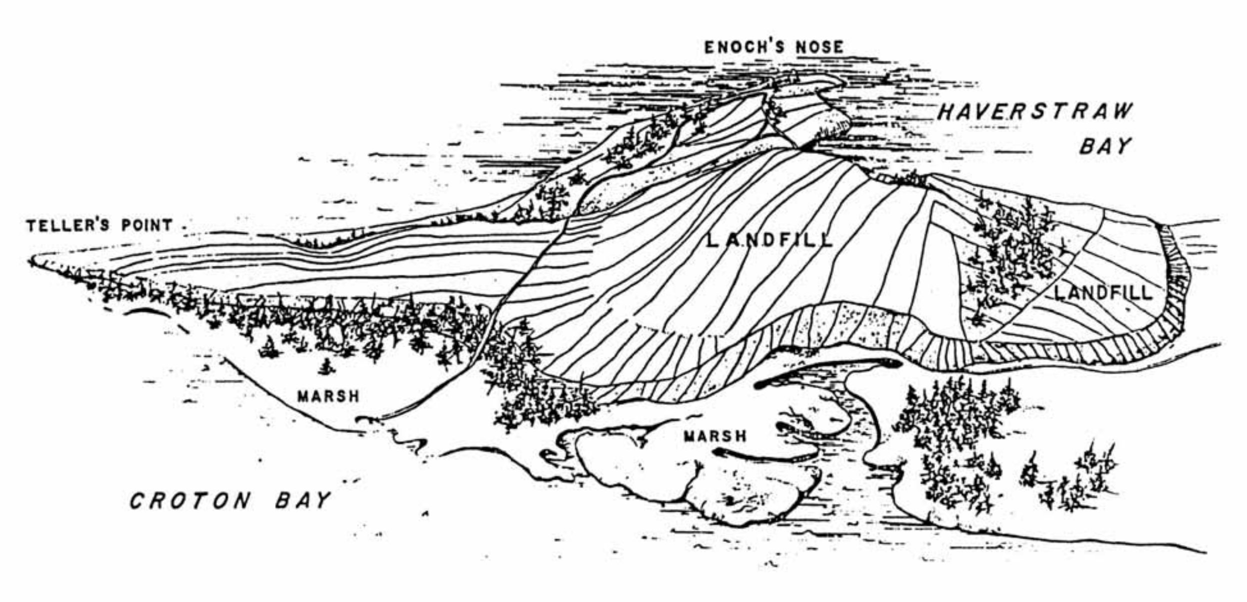


Figure 35 - Artist's conception of final shape of Croton Point landfill with top at 100 feet, the safe upper limit recommended by Geraghty and Miller (1976). (Geraghty and Miller, 1976, fig. 15, p. 39.)

The second cluster of borings was made in the remnant of delta sediments lying southwest of the landfill and on the flat surface of which was situated a ballfield. A significant factor in the so-called Phase-II expansion of the landfill consisted of digging up all the sand from this ballfield area, laying down a plastic liner, and then using the sandy sediments dug up to cover, from time to time, new layers of trash as they were added to the pile. Most of these borings stopped at the base of the sandy parts of the delta foresets. An exception was Geraghty and Miller's boring PH 1, drilled to a depth of 200 feet from a surface elevation of about 60 feet. Figure 36 shows the gamma-ray log and geologic log of this boring. The gamma-ray trace from 190 to about 55 feet shows a zig-zag pattern that begins with high gamma-ray readings (at lower right), indicating clay, and decreases upward (indicating less and less clay. The irregular pattern of increasing again toward the top, starting at about 20 feet, coincides with gravel in the sediments (indicating topset beds of the delta).

One of the important problems with the landfill was the spreading of leachate (rainwater that has seeped through a landfill and reacted with the wastes therein and then flows away from the landfill). JES pointed out in the early 1970s that leachate could be identified by its temperature, which is warmer than non-leachate ground water. This relationship of warm leachate is well shown on Figure 37. The outer limit of the dump is marked by water having a temperature of 75° Fahrenheit. The maximum is 95° F. This contrasts with the temperature of normal ground water, which generally approximates the mean annual air temperature of a region (in this case, about 55° F).

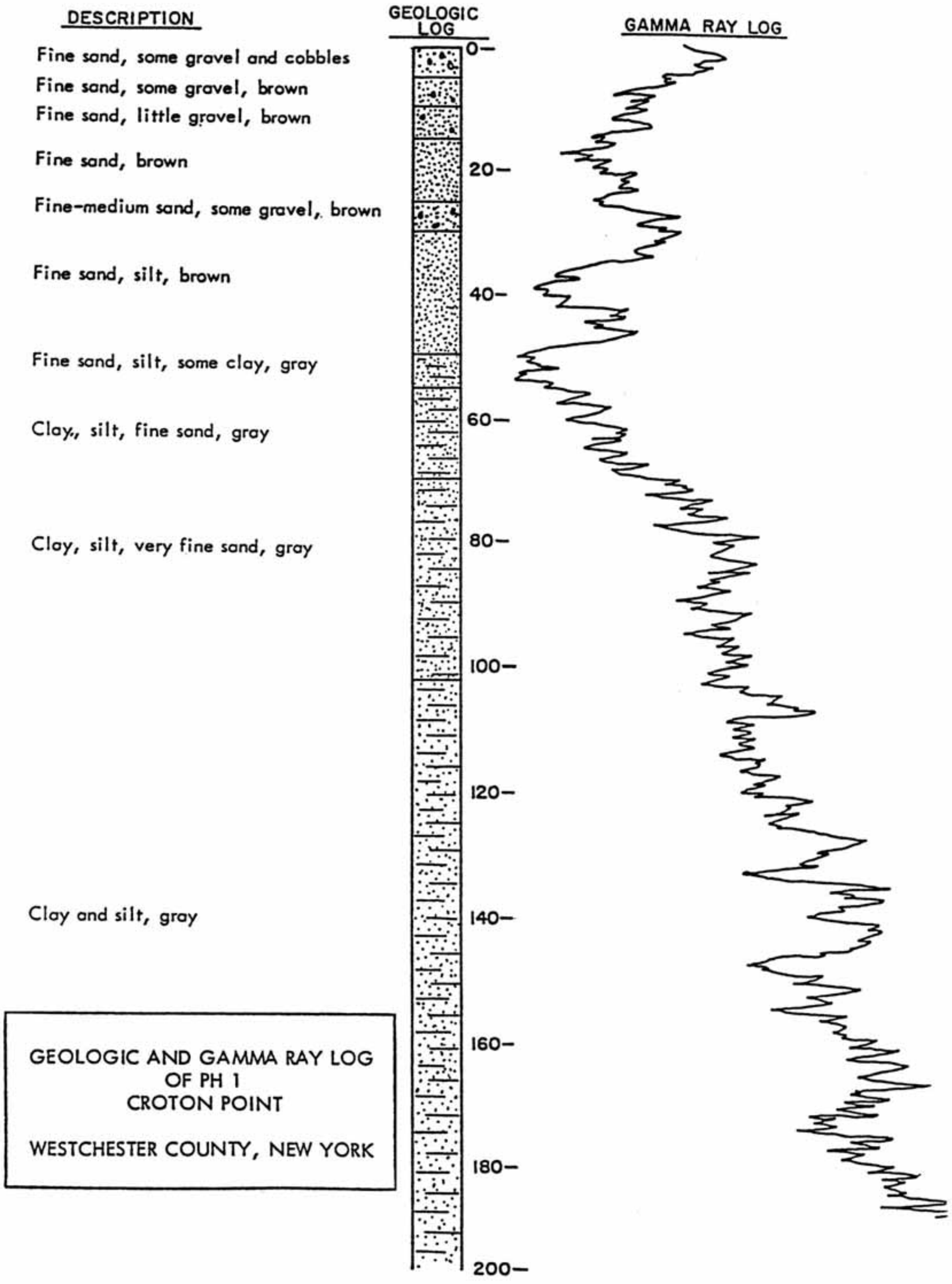


Figure 36 - Gamma-ray log and geologic section of boring PH 1. (location at UTM 592.68E - 4559.23N, on Figure 33) showing upward coarsening from clay to silt to sand and to gravelly sand, a typical succession found in a Gilbert-type delta. (Geraghty and Miller, 1976, fig. 2, following p. 10.)

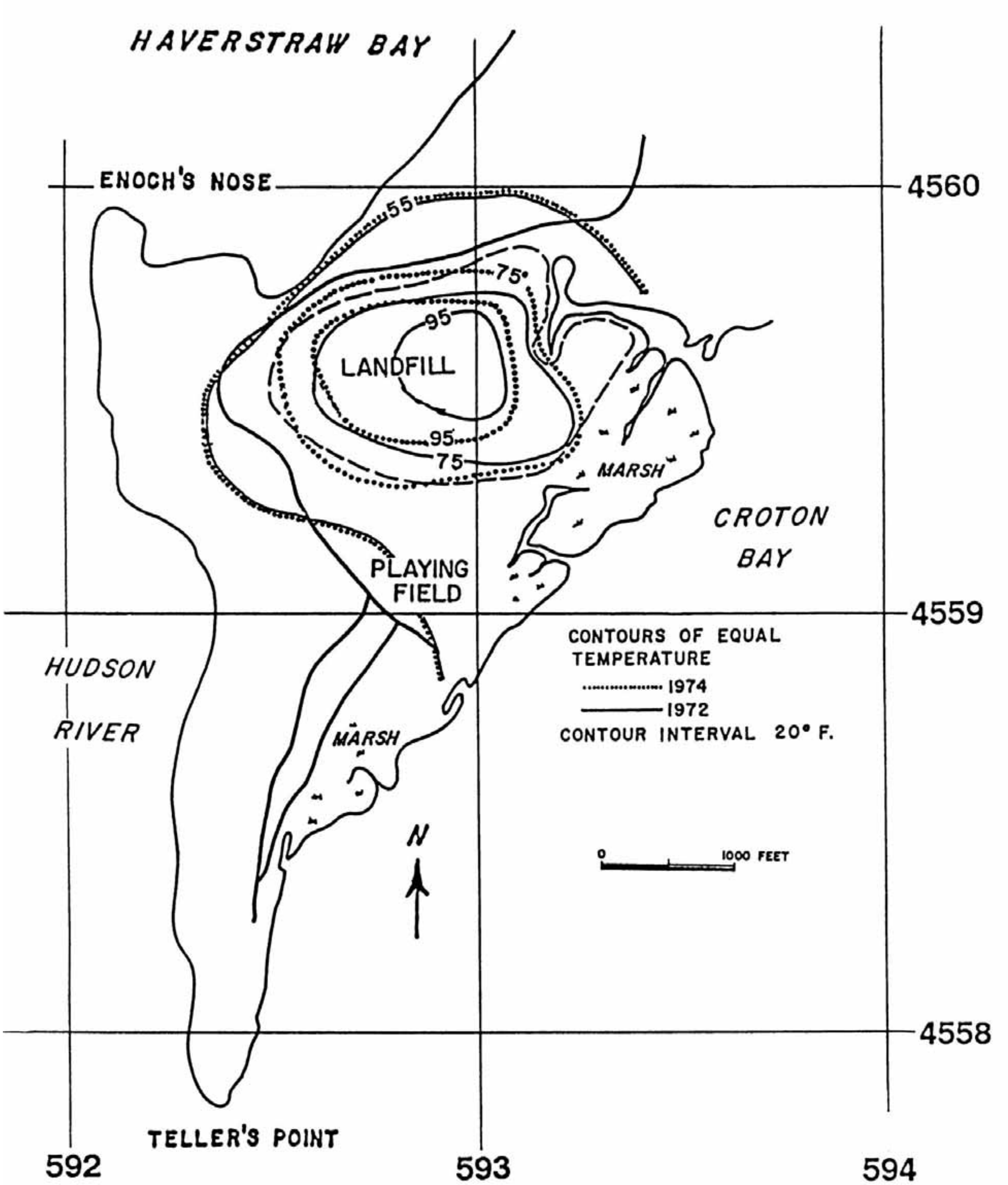


Figure 37 - Map of Croton Point landfill showing distribution of temperature of ground water in test wells. (Modified by JES from map in Geraghty and Miller, 1976, fig. 20.)

Onward! We now get to the specifics of the trip, starting with the objectives.

OBJECTIVES

1) To examine the depositional features in the deltaic sediments at Croton Point Park.

2) To compare and contrast the red-brown tills with those having colors other than red-brown.

3) To study the gray varved clays that were deposited in the same lake into which the delta grew, but that were protected by higher-standing parts of the former lake bottom (underlain by till) from the influx of sand from the east.

4) To relate the modern depositional setting (intertidal marsh, beach, and boulder-strewn flats) to the Pleistocene sediments.

5) To infer a chronology of events that took place during the Pleistocene glacial age(s) and the Holocene.

6) To study the boulders washed out of the till(s) as indicators of provenance. In this respect, we will concentrate on the kinds of mafic rocks derived from the Cortlandt Complex, a pluton near Peekskill, and the surrounding country rocks, and,

7) To examine the bedrock geology in the vicinity of Peekskill Hollow, a source for many of the boulders in the NNE-derived tills exposed to the south.

LIST OF LOCALITIES TO BE VISITED

The localities for today's On-The-Rocks Field Trip are shown on Figure 38.

Stop 1: N side of Camping area, Croton Point Park: Pleistocene deltaic sediments along cliff face and SST in beach sands (UTM 592.8E-4560.0N).

Stop 2: Cliff at Teller's Point: oyster midden; red-brown till overlying gray till containing decayed granite boulders and erratics from Cortlandt Complex; boulder-residue "beach" (592.38E-4557.81N).

Stop 3: Squaw Cove: gray varved clay resting on red-brown till and capped by brownish silty sand; boulder-residue "beach." (592.27E-4558.37N).

Stop 4: Enoch's Nose: Drumlin, red-brown tills, oyster middens, and upper yellow-brown till; boulder-residue "beach" (592.1E-4559.9N).

Stop 5: Buchanan, NY: igneous flow layering in norite, Cortlandt Complex.

Stop 6: Verplanck, NY: glaciated Inwood Marble and Manhattan Schist? (Annsville Phyllite?).

Stop 7: Roadcut on US9 S of Peekskill: poikilitic flow-layered norite (Pluton V) with xenolith of Inwood Marble.

Stop 8: Roadcut at Annsville: type locality of Annsville phyllite.

Stop 9: Annsville, NY: Poughquag Quartzite (optional).

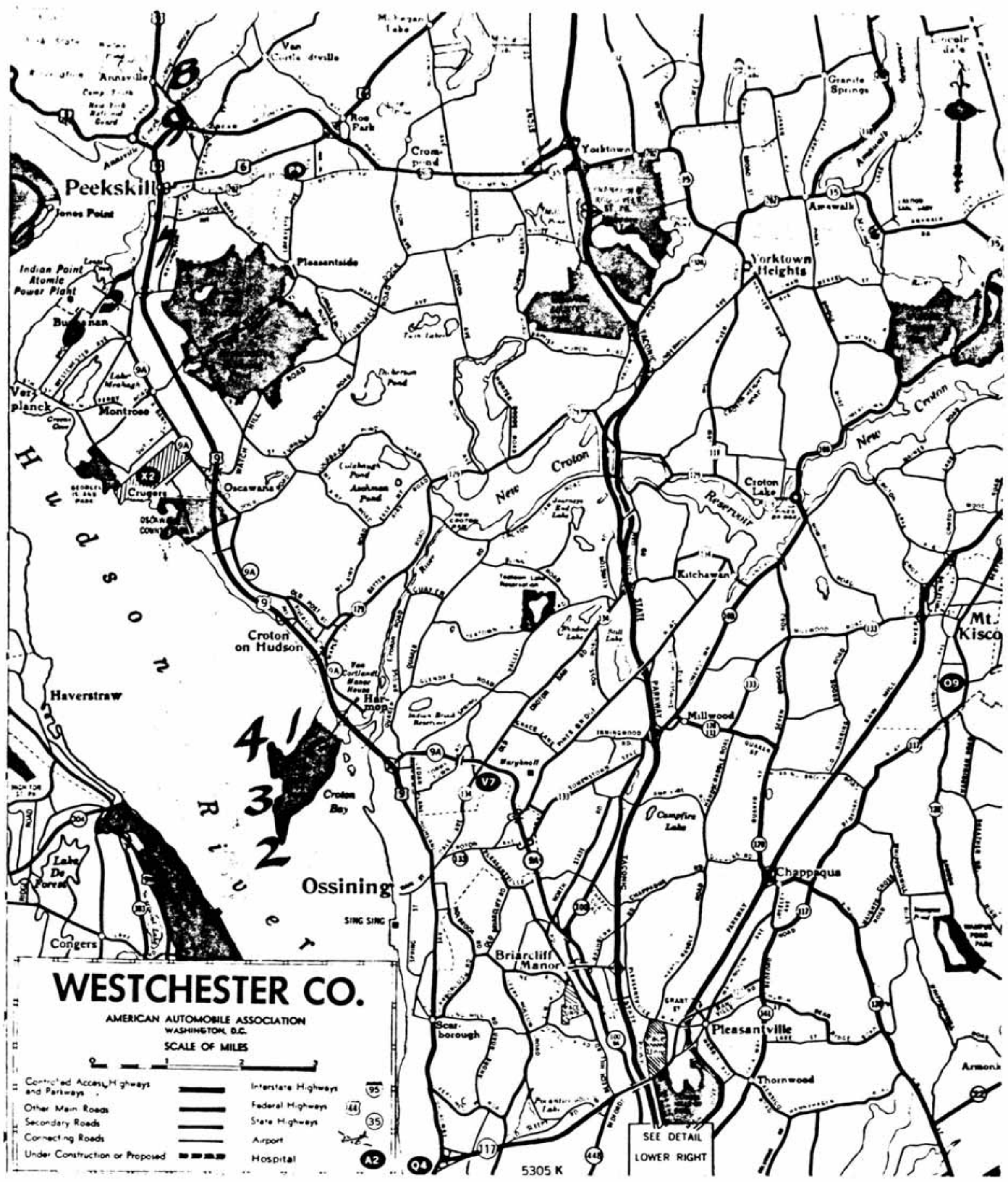


Figure 38 - Road map of Westchester County showing the localities (Stops 1 through 9) planned for today's field trip.

DRIVING DIRECTIONS AND DESCRIPTIONS OF LOCALITIES ("STOPS")

Driving directions from NYAS:

NYAS to FDR Drive Northbound to Major Deegan Expressway (I-84) Northbound to exit for Mosholu Parkway and Saw Mill River Parkway Northbound. Follow Saw Mill River Parkway to Hawthorne Circle area and exit to Taconic Parkway Northbound. Leave Taconic Parkway (at second exit ramp on R) for NY Route 9A North.

Detailed road log starts here:

00.0 Follow Route 9A northbound. You are now located within the United States Geological Survey Ossining quadrangle (UTM Grid 598.8E / 4455.3N).
02.1 Croton Aqueduct crossing underground.
02.2 North State Road traffic light.
03.5 Junction with NY Route 133.
04.9 Junction with NY Route 134.
05.3 Exposure of Manhattan Schist, cuts on R.
05.7 View ahead to Hudson Highlands, Hudson R.
06.6 New enlarged cut of Fordham gneiss (Layer I) and pink pegmatite on R immediately before Croton River.
06.8 On bridge crossing Croton River. Leave Ossining quadrangle and enter Haverstraw quadrangle.
07.1 Exit on R for Croton Point Park.
07.2 At stop sign turn L, cross under NY Routes 9 & 9A.
07.4 Stop light at start of bridge over RR. This is a long light because of the one-lane bridge ahead. If you are the first car, be sure to drive close enough to the traffic light to trip the light-signal sensor in the road (otherwise you might have to wait all day for the light to change!).
07.6 Passing railroad shops on R.
07.7 End of bridge. On the R, closed part of Croton landfill extension. On Hill at R, plastic pipe marks boundary of natural terrace of deltaic sand and cover of landfill. On L, is low marshy area, not yet totally changed by construction.
07.8 Road curves R. There is a natural terrace underlain by sand on R. The hill ahead on L without trees is capped by the main part of the Croton landfill (affectionately known as Mt. Trashmore). Watch for the Leachate Monster (first cousin of the Toxic Avenger) known to lurk here!
08.2 End of deltaic terrace on R. The low area to the R of Park Office leads to beach and Stop 1. Park vans near Park office on R. Mr. Tom Kelly is Park Superintendent/Ranger.

STOP 1 - Pleistocene deltaic sediments along cliff face and SST (Sanders Scientific Trench) in beach sands. [UTM Coordinates: 592.8E / 4560.0N, Haverstraw quadrangle.]

Walk northward beyond the Park Office then turn right along the beach at opening in fence. A couple of hundred yards along the shore look up (to right) to find the preliminary dig site. Our four stops at Croton Point Park are shown on the location map in Figure 39. Note the view to the north of the Hudson Highlands and electric power-generating plants (including Indian Point nuclear reactors). To the west note the north end of the Palisades at High Tor where this sheet of igneous rock swings inland away from the Hudson River. The undulating lowlands to the east and northeast are underlain by metamorphic rocks of the Manhattan Prong that project upward from beneath the water of the Hudson River.

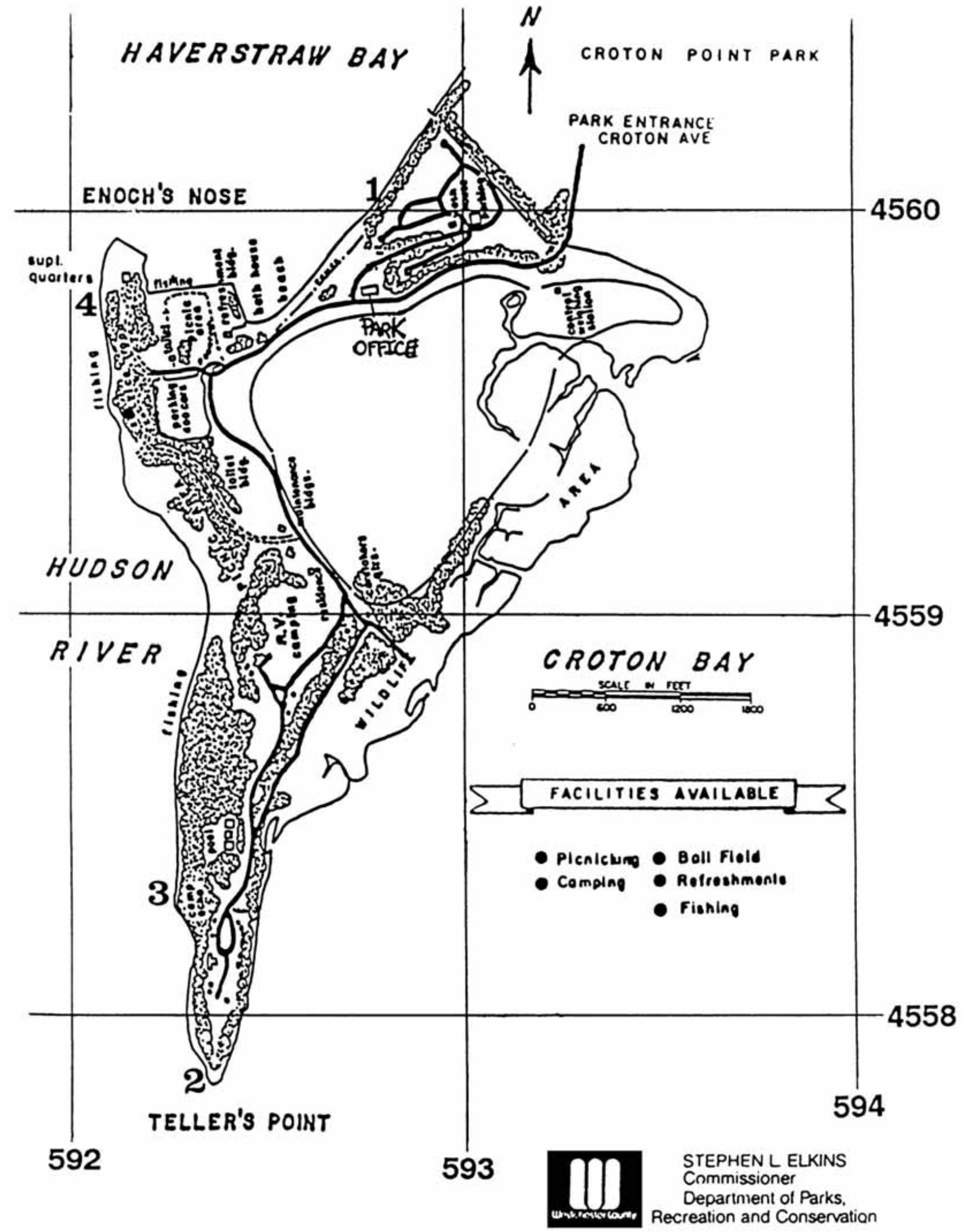


Figure 39 - Map of Croton Point Park showing Stops 1 through 4. (Modified by JES from map drawn by Westchester Department of Parks, Recreation, and Conservation and given to us courtesy Mr. Tom Kelly.)

The dig site will expose the lower part of the deltaic sands of the Croton River delta. (See Figure 36.) The delta was built into Lake Albany that formed when the Woodfordian glacier retreated northward past Croton Point Park. This lake persisted until roughly 12,000 years ago (based on radiocarbon date published by Newman and others, 1969). Glacial Lake Albany drained abruptly when a glacial moraine dam at the Narrows broke and water surged out across the shelf, eroding the Hudson Shelf Valley. Then a very rapid submergence took place, and the Hudson estuary formed and has stayed that way ever since.

The sediments here include fine sands, very fine sands, and clays. The sands show ripple cross laminae and ripple shapes. The sands and clays are interbedded suggesting they may be seasonal. They could be winter layers when the delta was quiet and the lake was frozen over. Along the base of the thickest clay layer seen during our pre-trip investigations, we found a row of "stones", possibly concretions. Two colors of clay are present, light brown and tan. Possibly the tan is the winter deposit and the tan, the finest suspended sediments from the delta. The river mouth was to the south, so the lobe built out and currents on its face here could have been flowing N, NW or NE. Any evidence of what Jopling calls toesets? (Beds deposited at outer base of delta by bottom countercurrent that flows toward the river, even up the slope of the foresets. Not seen in the dig, but typically found in delta foresets, are slump structures.) At the base of a thick fine- to medium-textured sand is a thin clay drape and below that, a very compact, very fine sand. The clay drape has been deformed, possibly while the sand was being deposited. Pockets of coarser sand project down in underlying sand, even beneath the clay drape.

Now what you've all been waiting for--an SST. A Sanders Scientific Trench is to be constructed on the beach below the deltaic sediments at the top of a minibeachface. In our pre-trip investigation in March of 1990 we found a heavy-mineral concentrate full of garnets and black opaque minerals (magnetite and/or ilmenite?). A small trench showed that these dark minerals form a surface capping about 1 cm thick overlying brown sand. Below the brown sand was another, slightly thicker (4 cm?) heavy-mineral layer.

The boulderless beach here is totally different from the beaches we will encounter on Stops 2 through 4 at Croton Point Park. This boulderless business may not seem significant to you now but at the other "beaches," you will see boulders, boulders, and more boulders. Here, driftwood and flotsam are abundant, but the cliff being eroded consists of sand, so the beach consists of sand. Where till is eroded, the beach is littered with boulders, a coarse residue washed out of the till(s). The water body to the north is Haverstraw Bay, the striped-bass nursery of the east coast. The fetch distance for NW winds blowing across the bay is about 5 miles, large enough to enable potent choppy waves to form for eroding the bluff. Other erosion results from water seepage and gravity.

08.2 Reboard vans and leave park office.
08.4 At traffic circle turn L following sign to Family Campground climbing edge of landfill on L.
08.7 Pipes are observation wells.
08.8 Gates L and R to landfill and park buildings.

08.9 Bear R at sign "for authorized vehicles only" (we are authorized) past Ranger Road marked G.F. Smalls.
09.2 Pass gate and "Do Not Enter" sign; we have permission to enter.
09.5 Parking for cabins and pool. Keep R past cliff and cabins.
09.8 Park near small brick shelter and loop at end of dirt road You are now at Stop 2.

STOP 2 - Cliffs at Teller's Point to examine oyster middens, red-brown till overlying gray till containing decayed granite boulders and erratics from Cortlandt Complex and boulder-residue "beach". [UTM Coordinates: 592.38E / 4557.81N, Haverstraw quadrangle.]

The cliffs at Teller's Point are immediately across (about 2 km or 1.2 miles) the Hudson River from the Palisades intrusive just south of Haverstraw, New York. At the left of the path just before the steep descent to the river are some oyster shells from an Indian midden. Walk down the path to the water's edge and begin by scraping off loose sediment from the cliff face. While hacking away at the hard till here in 1990, JES broke his old sidekick army trenching tool. On the day of our previous trip, he showed up with a new one. Will it survive a second onslaught?

Note that two tills are present here. A red-brown till caps the cliff; at a level of about 3 m above the water can be seen the top of a gray-brown till that persists down to water level. We know that the red-brown till is associated with a glacial advance from New Jersey (from NW to SE): it contains boulders and pebbles of various facies of the Palisades trap rock, red-colored sedimentary rocks from the Newark Supergroup, the Green Pond Conglomerate, and chips of anthracitic coal. These unique igneous- and sedimentary indicator stones could have come only from west of the Hudson River. You will find evidence for most of these in the cliff face and strewn along the "beach" where they have been washed out of the till that forms the cliff. The impression we would like to create here is that the two different tills harbor uniquely different suites of boulders, cobbles, and pebbles.

The lower gray-tan till contains rocks not found west of the Hudson River. Rather, the distinctive rocks eroding out of the lower till consist of igneous- and metamorphic lithologies which crop out to the east of the Hudson, mostly from regions due north of us. The feldspars in the dark, smaller stones in the lower part of the cliff face have totally decayed.

These granitic rocks having such totally decayed feldspars are subject to several interpretations. One possibility is that the feldspars decomposed as a result of being weathered after they had been incorporated in the till as reasonably fresh rock fragments. This kind of postdepositional decay of till stones has been extensively studied; it can be used as an indicator of the relative ages of tills: the more the stones have decayed, the older the till.

The second possibility is that the ice picked up stones that had already been decayed in-situ in their bedrock sites. This possibility seems absurd at first thought--how could the ice pick up, transport, and not destroy such "soft" rocks? The strongest argument in favor of the notion of pre-transport decay is the fact that all the stones in this old gray till have not been decomposed to the same degree as the feldspars in the granitic stones. In particular, some of the mafic stones, which normally decompose well before granitic rocks, display only slight effects of decomposition. Borings for the Garrison Tunnel of the Catskill Aqueduct of the New York Water-Supply System have disclosed a zone of deeply decomposed bedrock near in northern Westchester County (Berkey and Fluhr, 1948; Figure 40; location shown on Figure 41). If we can invoke permafrost or something to toughen decayed bedrock, then possibly it is not outrageous to suppose that such soft stones could have been picked up, in a frozen-solid state, by a glacier, survived glacial transport, and have been deposited without coming apart.

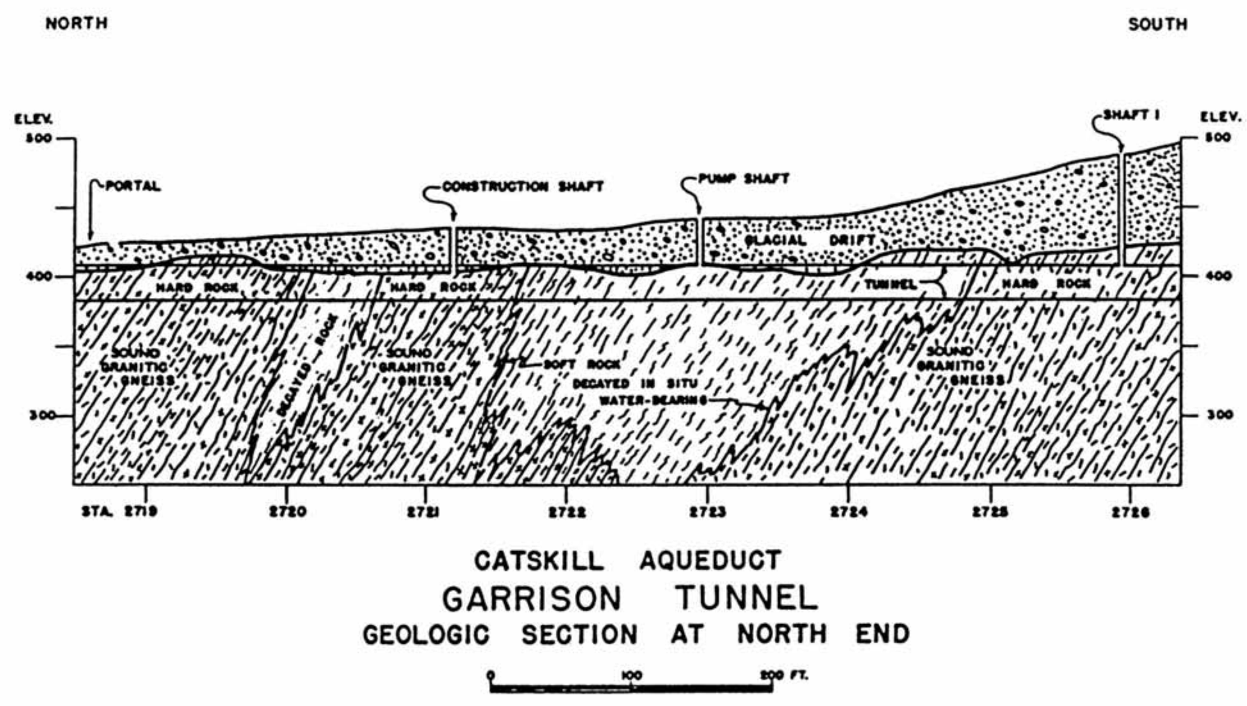


Figure 40 - Geologic profile-section at north end of Garrison Tunnel of Catskill Aqueduct of New York City water-supply system showing two bodies of in-situ decayed granitic gneiss that is present immediately beneath the glacial deposits. The larger body extends for a length of about 250 feet along the line of the tunnel. (Berkey and Fluhr, 1948, fig. 8, p. 132.)

If the pre-transport-decay concept is valid, then granitic stones having decayed feldspars become a specific kind of indicator stone and not badges of the extent of decomposition of the till. In this case, they indicate ice flow from the same direction as the boulders from the Cortlandt Complex.

Whatever is eventually decided about the significance of the granitic stones having decayed feldspars, we are certain from the stratigraphic relationships here and the content of indicator stones from the Cortlandt Complex that the direction of flow of the oldest glacier at Croton Point was from N (or NNE) to S (or SSW; down the Hudson Valley) and not from NW to SE (across the Hudson Valley).

This locality provides the first stratigraphic evidence for an initial glaciation in the New York City area that antdates the accepted advance of glacial from NW to SE across the Hudson. What is more, it corroborates observations made by JES, CM, and itinerant On-The-Rockers at

Inwood Hill Park in Manhattan and in the Bronx Botanical Garden, where NW-SE-trending glacial grooves have been cut into an older NNE-SSW-trending roche moutonnée structure of bedrock knobs. CM and JES were quite happy about discovering this--you should be too!

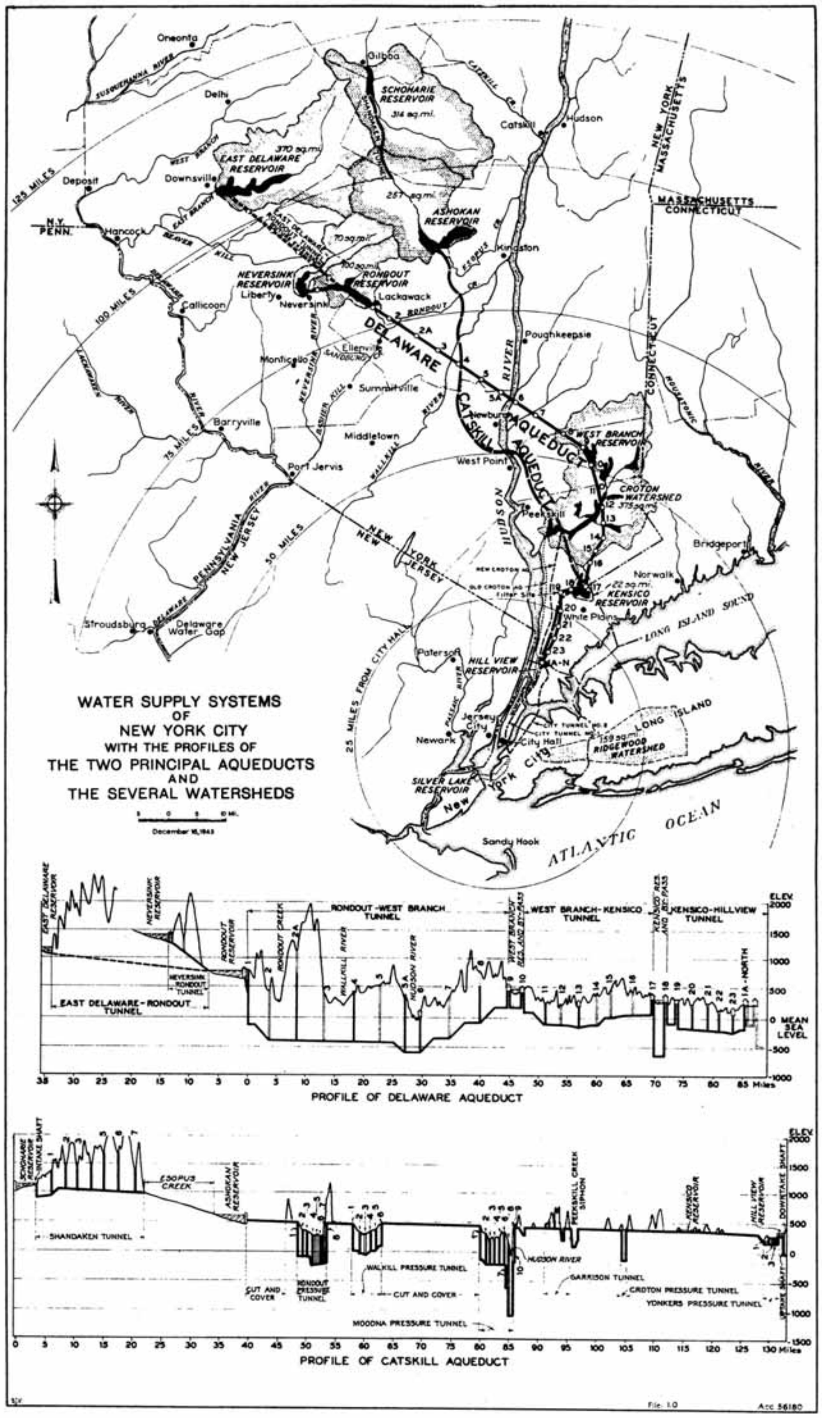


Figure 41 - Index map of Catskill and Delaware Aqueducts of New York City water-supply system, showing location of Garrison Tunnel of Catskill Aqueduct. (Berkey and Fluhr, 1948, fig. 2, p. 124.)

A list of boulders averaging from 2 m to pebbles in size observed at our pre-trip investigation follows. See if you can find these distinctive rock types and perhaps identify some odd lithogies that we've missed. Boulder bashing is an acceptable method of investigation here.

Boulders, boulders everywhere------

IGNEOUS
Diabase showing fine, medium, and coarse textures
Hornblende diorite
Poikilitic pyroxenite
Pyroxenite
Gabbro, norite, and poikilitic norite
Granite and granite pegmatite
Red-orange granite

METAMORPHIC
Granite gneiss +/- garnet, epidote
Hornblende gneiss
Mica schist
Phyllite
Amphibolite
Foliated granite
Hematitic quartzite
Clean quartzite
Greenstone
Folded, foliated rocks
Red jasper

SEDIMENTARY
Limestone
Dolostone
Arkose
Siltstone
Graywacke

09.8 Reboard vans and drive northward a short ways past circle.
10.3 Park at swimming pool parking lot (Pool parking is on flat field by road) and disembark from vans. Backtrack and follow jeep trail that leads downslope toward the river (west) at N end of cabins.

STOP 3 - Squaw Cove beach: Gray varved clay overlying red-brown till overlain by fluffy brownish sand and boulder-residue "beach." [UTM Coordinates: 592.27E / 4558.37N, Haverstraw quadrangle.]

Walk through wooded area to the beach for Stop 3. At the beach, gray varved clay is exposed at the top of a low bluff. A dig a few meters to the N from where the pat ends shows that this same gray clay overlies the red-brown till. We note many more reddish Newark sandstone boulders here plus mafic rocks of the Palisades intrusive sheet (in comparison to Stop 2) and lesser mafic- and ultramafic rocks of the Cortlandt intrusive suite.

Walk northward along the beach for 100 m or so to larger dig face. Divide effort between digging and bashing boulders. Make a list of boulders encountered and compare to the list provided for Stop 2. Note that the land surface undulates. The highest land is at Tellers Point; we think this reflects the abundance of boulders that form a natural armor. In addition, the top of the red-brown till undulates; the gray clay is limited to the low spots. Traced along the bluff toward the north, the whole face is higher and consists entirely of red-brown till. The gray clay is same age as the deltaic sand/clays at Stop 1. It represents a more-distal depositional site that was isolated from the influx of deltaic sand from the east. The N-S-trending ridge of till kept the deltaic sands from spreading this far west. On our pre-trip investigation on 21 October 1992, we found a large dropstone in the clay. (A dropstone is a stone that started its career by being incorporated into a glacier. At the terminus, the glacier calved into the water of a lake, and the ice+stone became an iceberg. The iceberg drifted out into the middle of the lake. When the iceberg melted, the stone to the bottom, coming to rest in a quiet environment where otherwise only clay was being deposited.) On trip day, we plan to clean up a face to show the relationship between this dropstone and the laminae in the clay.

Another 100 m or so to the north is a low bluff that exposes the top of the gray clay. The unit above is a brownish fluffy sand that strikes us as being comparable to coarse loess (windblown sandy silt). The profile-section of Figure 42 illustrates the relationships visible at Stops 2, 3, and 4.

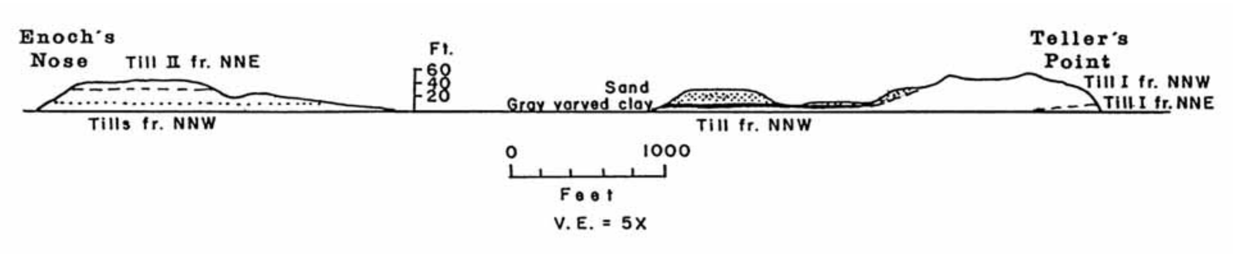


Figure 42 - Profile-section along N-S line from Enoch's Nose to Teller's Point, Croton Point Park, drawn from Geraghty and Miller June 1974 topographic map. (JES.)

10.3 Back to vans and drive northward to Y-intersection.
10.5 Exit on dirt road (lower road) to R.
10.7 Marsh on R is small remnant of a larger area destroyed by the landfill.

10.9 At gate make a L-turn and join main road (high road) at intersection past G.F. Small's residence.
11.0 Junction with main (high) road.
11.5 At traffic circle follow around to L and pause ahead at Stop sign. Follow straight ahead (west) toward large parking lot.
11.6 Park on R near end of blacktop. Walk across grass to trail into woods to N along terrace level for Stop 4.

STOP 4 - Enoch's Nose: Drumlin, red-brown till, red-brown outwash, upper yellow-brown till, oyster middens, and boulder-residue "beach". [UTM Coordinates: 592.1E / 4559.9N, Haverstraw quadrangle.]

Walk along the trail to the large erratic boulder marked by two smaller rocks. The elongate shape of the promontory suggests that it is a drumlin, shaped by the advance of glacial ice. The bluffs here consist of two red-brown tills with local reddish outwash between two units of till. Note that no gray-tan till as observed at Stop 2 is exposed here. However, boulders of the Cortlandt Complex suggest that some gray till or other must have been eroded. Possibly the older such till is present exposed at or below river level. (We will attempt to check this possibility in our diggings). Possibly these boulders came from the upper yellow-brown till that caps the hill.

Walk along the boulder beach. Notice the large erratics from the Cortlandt Complex and a few Newark sandstone boulders. Dig at the NW end of the promontory and, depending on time, we'll look at the large cliff at the north end of the drumlin. Note the oyster middens on the terrace level at the boundary between the youngest yellow-brown till (capping the drumlin) and the older red-brown till(s) exposed in the eroding bluffs.

Kindle's (1949) Croton Point moraine at Enoch's Nose is a drumlin. The capping of this drumlin is composed of yellowish-brown till which is perched above red-brown till. At one place, the sequence is (from the base up): red-brown till, red-brown outwash sand and then red-brown till up to path level where oyster middens occur. Higher up is the yellow-brown till, but such diggings as JES and CM have done previously have not yet exposed the contact between the yellow-brown till and the red-brown till.

Therefore, if the red-brown till here is correlative with those observed at Stops 2 and 3, then the Croton Point till sequence is (from oldest to youngest): gray-tan till, older red-brown till, outwash deposits, newer red-brown till, and yellow-brown till. At the end of this stop, field trip participants will join in to sing a few bars of "Till There Was You".

The sand terraces of Croton Point Park (Figure 1, cover) form broad, flat-topped areas now covered by vegetation. Continuous with the delta sands examined at Stop 1, the terraces mark the topsets of the Croton delta which fed into Lake Albany.

Thus, to summarize the Pleistocene history of Croton Point, we offer the following sequence of events:

(1) Several tills starting with gray-tan, then red-brown, then, after red outwash was deposited, another red-brown till, followed by the yellow-brown till. The red-brown tills contain erratics from the west side of the Hudson River whereas the youngest and oldest tills contain only rocks found on the east side of the Hudson River.

(2) After the youngest of the tills had been deposited and the glacier responsible for it had melted away, the region was flooded. All the drainage from the Great Lakes flowed eastward through the Mohawk Valley and down the Hudson. Proglacial Lake Albany was backed up behind the natural dam of till at the Narrows. Deltaic sediments from the ancestral Croton River and possibly drainages to the north were deposited along the east shore of this lake. The water plane presumably stood at about elevation +70 feet (level of the flat terrace underlain by topset beds of the delta that coincide with the uppermost water level). To the west, the depth of water where the clay was deposited away from influence of the delta was 70 feet. The coarse browner clays probably represent the dark suspended load of the river(s). The light clays are winter deposits when river(s) experienced low- flow conditions and/or were shut down altogether because their waters froze solid.

(3) The dam at the Narrows burst and Lake Albany drained catastrophically out across the shelf, eroding the Hudson Shelf Valey en route to the Hudson Submarine Canyon. The delta was dissected; a valley extending down to at least -73 feet (modern sea-level reference) was cut into it. When the rising sea formed the Hudson Estuary (about 12,000 yr B.P. based on Newman and others' radiocaron date of basal peat recovered from a boring at Iona marsh), this valley was backfilled with 50 feet of fine silty-clay sediments. When the sea reached a position of about -20 feet with respect to its modern level, a marsh became established. The 20 feet of thickness of the marsh peat indicates that the marsh was able to grow upward as sea level rose from -20 to its present level.

Walk back to vans; brief rest at rest rooms. Now that we've examined the glacial geology of Croton Point Park, discussed the development of tills, lacustrine sediments, and deltaic sediments, it is now time to do a little provenance study by heading northward to examine the possible parent areas for many of the boulders seen today eroding from the lowermost (gray-tan) and uppermost (yellow-brown) tills.

11.6 Reboard vans and backtrack toward the Park Office.
12.0 Pass traffic circle leaving park.
12.3 Park office on L (Wave to Mr. Kelly).
12.7 Boundary of landfill.
12.8 Bear L to one-lane bridge.
12.9 Traffic light for one-lane bridge over RR.
13.2 Turn R for ramp to Route 9 Northbound.
13.9 Ramp on R for 9A and NY Route 129. Excellent view of High Tor on L (Palisades Sill) and the Hudson Highlands (including Bear Mountain) in the distance.
14.6 Ramp on R for Sanasqua Rd.
15.5 Cuts on R of sub-vertical Manhattan Schist.
15.8-16.2 More Manhattan Schist.
16.7 Take exit on R (Exit 5) for Route 9A.

16.8 Turn L at bottom of ramp onto Route 9A. At the junction to R is a glaciated knoll of contact metamorphosed Manhattan Schist. On north side of Route 9A occur hornblende diorites and biotite norites of the Cortlandt Complex. (Possible pull-over Stop).
17.2 Continuing on Route 9A. Old Albany Post Road on R.
17.3 Traffic light at Springvale Road. Onward to N.
17.5-17.6 Contact metamorphosed Manhattan Schist on L.
17.7 Cross Amtrak Railroad.
17.9 Mafic rocks of Cortlandt pluton on both sides of road.
18.6 Leave Haverstraw quadrangle. Enter Peekskill quadrangle.
18.8 Traffic signal at Kings Ferry Road to Verplanck.
19.1 Village of Buchanan sign on R opposite Hendrick Hudson High School.
19.3 Buchanan Commons on R.
19.7 Signal at Tate Ave entering from L. As of April 1990 there was construction here exposing highly jointed flow-layered norite of Pluton V. The power lines overhead lead westward to the Indian Point Power Generating Station.
19.8 Turn L onto Bleakley Avenue.
20.0 Park on R. Walk back to exposure for Stop 5.

STOP 5 - Igneous flow layering in norite, Pluton V of Cortlandt Complex. [UTM Coordinates: 588.94E / 4568.78N, Peekskill quadrangle.]

The purpose of this stop is to examine flow layering in igneous rocks of Pluton V (norite) of the Cortlandt Complex. (See Figure 17.) We are situated at the western edge of the Central Basin of Balk (1927). Here notice the well-developed, northeast-dipping coarse- to medium-textured norite with an igneous flow layering. The layers consist 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 mafic rock here. Are you convinced that bedrock such as some of the coarse layers exposed here could have supplied some of boulders we have just examined at Croton Point?

20.0 Continue west on Bleakley Avenue. Note more coarse-textured mafic rocks on R.
20.3 Traffic light at entrance to Indian Point Generating Station (Turn on your geiger counters.) Turn L onto Broadway headed toward Verplanck and note Cortlandt rocks on both sides of road.
20.6 Powerlines by transformer station on L.
20.8 Indian Point 3 entrance on R.
21.1 Manhattan schist on R (phyllite?)
21.5 Turn R onto 11th Street.
21.6 Pull over to side of road for Stop 6.

STOP 6 - Glaciated Inwood Marble and Manhattan Schist? [UTM Coordinates: 587.29E / 4567.44N, Peekskill quadrangle.]

On the north side of 11th Street, note the low, rounded knoll underlain by Inwood Marble. Here, the marble is fine textured and foliated; some calc-silicate minerals typical of contact metamorphism have formed. The vertical foliation in the marble strikes N15°E. Glacial striae on the marble here are oriented S17°W.

On the south side of the street both marble plus schist? (or is it phyllite?) show glacial striae and grooves trending S7°E. According to Ratcliffe and others (1983), the Manhattan Schist member A (of Hall, 1968) is weakly metamorphosed here. In our opinion, the rock is technically a compact, carbonaceous- and pyritiferous phyllite or slate showing none of the coarse mica textures typical of schist. Oxidation of the abundant fine-textured pyrite in the rock has created 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 Annsville Phyllite at its type locality (Stop 8). Of geologic significance, this is one of the few places where the low regional metamorphic grade allows one to examine the contact between the Sauk Sequence (Cambro-Ordovician) carbonates and their overlying Tippecanoe Sequence (Middle Ordovician) pelitic cover rocks. As such, the contact here is overturned and dips toward the southeast. Can anyone remember any till boulders consisting of these lithologies?

21.6 Turn around, retrace route to Broadway.
21.7 Turn L on Broadway headed North.
22.8 Turn R onto Bleakley Avenue at traffic light by Indian Point entrance.
23.1 Note extremely coarse boulder or bedrock(?) consisting of poikilitic ultramafic rock on R by building.
23.3 Turn L on Route 9A, headed N.
23.6 New Bypass Diner on L. Pull over for rest stop.

23.6 After a high-cholesterol snack, pull out of the "Triple Bypass Diner" and turn L (headed N).
23.8 Turn R at light, then move into L lane for immediate L turn onto ramp for US Route 9 northbound.
24.3 New cut on R of typical Cortlandt norite rock.
24.6 Pull-over on Route 9 just before bridge immediately south of sign for South Street and Hudson Avenue for Stop 7.

STOP 7 - Poikilitic flow-layered norite (Pluton V) with xenolith of isoclinally folded, 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 Basin of Balk (1927). Here the norites enclose a contact-metamorphosed xenolith of isoclinally folded Inwood (Wappinger) Marble. Get your cameras ready for a textbook shot. Note also that the igneous layering is dipping more toward the east and southeast in subsequent stops along Route 9. We are seeing the effects of the conical distribution of the flow layering of the igneous funnel. (See

Figures 17, 19.) If the light is right, one can see large plates of alkalic amphibole (kaersutite) forming large poikilitic crystals that enclose the plagioclase and orthopyroxenes.

24.6 Reboard vans and continue past bridge for another pull-over stop.
24.7 Note new cuts on both sides or road. Good cumulate layers visible dipping SE at about 75°. Fewer joints here compared to the Tate Avenue rocks. Layering is great here. Dip down to about 30° near the second bridge.
24.9 Note exit on R exposes a new cut with glacial polish.
25.3 Pass exit for Main Street, NY 35, US 6-US 202 on R. High cuts on R consist of light Proterozoic granitoid gneiss, granite, and amphibolite. Keep to L for US 6 and 202. Do not take Bear Mountain Parkway.
26.0 Turn L at light. Keep R for US 9 Northbound upon crossing bridge over Annsville Creek.
26.2 Bear R for to US 9 North.
26.4 Proterozoic rock on L beneath till.
26.8 Turn R onto Roa Hook Road.
27.0 Turn R at Stop sign onto Albany Post Road (Eastbound).
27.1 Pull over to R before large cut exposed on both sides of Albany Post Road.

STOP 8 - Type locality of Annsville Phyllite, Annsville, NY. [UTM Coordinates: 590.00E / 4573.19N, Peekskill quadrangle.]

This large roadcut exposes the Annsville Phyllite of Medial Ordovician age. We are in the town of Annsville and you are therefore in the type locality of this distinctive, black to dark-gray carbonaceous rock unit. Here, the lithology holds up a ridge bifurcated by Sprout Brook to the west and Peekskill Hollow Creek to the east. The cut exposes a rather monotonous, steeply dipping and highly cleaved sequence of uniform micaceous slate and lustrous, flaggy phyllite that extends northeastward toward Gallows Hill. On the north side of the cut try to identify compositional layering (bedding) in the form of gray siltstone interlayers about 1 cm thick and convince yourself that bedding and slaty (phyllitic) cleavage are subparallel. They strike N50°E and dip 77°SE. CM argues that the presence of a steep down-dip intersection lineation and mineral streaking within the slaty cleavage indicates the presence of non-obvious intrafolial F_1 isoclinal folds that are probably best observed on top of the outcrop. In a few places isoclinal folds (probably F_2 or second generation) of thin quartz veins occur showing SE plunges. There is a sub-horizontal rock cleavage that is axial planar to kink bands and crenulations of the slaty cleavage and late joints that trend N28°E, 32°NW. The overall structure of the ridge is probably that of a synform overturned to the northwest.

On the S side of the cut, at the E end, isoclinal folds of the foliation plunge steeply northward and display a sub-parallel stretching lineation. At the W end, cm-scale siltstone interlayers parallel the slaty cleavage and may represent thin, fine-textured distal graywackes.

The Annsville Phyllite is considered to be equivalent to the upper part (Penn Argyl carbonaceous shale member) of the Martinsburg Formation (Tippecanoe Sequence, Middle Ordovician). Compare these rocks to those sampled at Stop 6 and appreciate the reason why the Annsville Phyllite is regarded as being the lithostratigraphic equivalent of the Middle Ordovician part of the Manhattan Schist. Could these rocks be the potential parents of the dark, carbonaceous boulders and pebbles that have been eroded out of the lower tan-gray till at Teller's Point (Stop 2)? CM and JES think so! How about you?

27.1 Reboard vans and continue ahead (Eastbound) on Albany Post Road for optional Stop 9.
27.4 Turn R into entrance for Peekskill Wastewater Treatment Plant. Authorized vehicles only!
27.7 Disembark from vans, hold noses and examine quartzite exposed to L.

STOP 9 - Poughquag Quartzite. (Optional, time permitting). [UTM Coordinates: 589.82E / 4559.9N, Peekskill quadrangle.]

Here, hopefully up-wind from the sewage treatment plant on the day of our trip, note the gently east-dipping thinly laminated bedding and sub-parallel foliation of the Poughquag Quartzite. The quartzite is of Early Cambrian age; it represents the basal part of the Sauk Sequence (deposits of former Early Paleozoic shelf). The protolith was clean sandstone laid down on the deeply eroded and submerged Proterozoic basement gneiss of the Hudson Highlands (Consult Tables 1 and 2). The Sauk Sequence (Cambro-Ordovician) carbonates are present in an antiform. They underlie the valley to the northwest of us and probably continue beneath the Annsville Phyllite cut of Stop 8. (See Figures 9-11 and discussion of Peekskill Hollow earlier in the text.) Alternatively, the carbonate sequence, which is quite thin here, may be faulted out completely. Northwest of Annsville, no Sauk carbonates are present--only the Lower Cambrian quartzite resting on Proterozoic gneiss.

The Poughquag is a dense, hard, fine- to medium-textured quartzite that ranges in color from white to tan and brown to reddish (Schaffel, 1958). Local conglomeratic facies contain distinctive bluish quartz pebbles. As such, this outcrop belt of the Poughquag (and perhaps its northern correlative--the Cheshire Quartzite) are the probable parents for many of the resistant quartzite (+/- hematite stained) boulders that we found had been eroded from the tills at Croton Point Park.

Driving Directions Back to NYAS from Stop 9.

27.7 Turn around and drive northward away from the smell.
28.0 Turn R onto Albany Post Road (Eastbound).
28.3 Turn R onto Bear Mountain State Parkway (headed south). Link up with Route 9 (Southbound) as far as Croton Point. After crossing bridge over Croton River, move left for upcoming left exit to Route 9A Southbound. After passing exit ramp on R for Saw Mill River Parkway, take next exit on R to NY 100 (Hawthorne) and signs for Sprain Brook Parkway. Continue south on NY 100; at top of hill, make R turn for entrance ramp to Sprain Brook Parkway southbound. Follow Sprain Brook Parkway to its end (merges with Bronx River Parkway). Eventually turn R on Sheridan Expressway, Major Deegan Expressway, local bridges to Manhattan and back to the Academy.

We sincerely hope you've enjoyed today's On-The-Rocks Trip to Croton Point Park and Peekskill Hollow and look forward to seeing you again on future trips. Our Spring 1993 schedule will be sent out as soon as possible.

In the meantime - - - - - - - - - - - - - ->>>Keep On Rockin' :)

ACKNOWLEDGEMENTS

We would like to thank **Mr. Tom Kelly** for assisting us in gaining access to Croton Point Park's unique geological treasures. **Mr. Barry Samuel**, Acting Commissioner of Westchester County Department of Parks, Recreation, and Conservation, kindly granted us permission to conduct today's trip and waived the admission fee. We also thank **Mr. Anthony Colao**, Director of Northern Westchester Parks, for his cooperation. Help from **Matt Katz** and **Marcie Brenner** of the New York Academy of Sciences is, as always, appreciated. Help from the Merguerian storklets keeps the whole show rolling.

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).

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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	**Eastern deep-water zone**
(L. Cambrian - M. Ordovician)	(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.]

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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.
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