DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 23: Geologic Setting of a Cruise from the Mouth of the East River to the George Washington Bridge, New York Harbor

Trip 40: 30 June 1997

Figure 1. Photograph of the five boroughs of New York City and the New York Harbor area including the proposed field trip route (arrowed white line).

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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Trip 40: 30 June 1997

Logistics:
Departure from west side Pier.
Sit back, relax, call waiter.

INTRODUCTION

During a cruise "up the Hudson River" from the mouth of the East River to the George Washington Bridge, observant passengers can see shorelines composed of four of the major components of New York City's geologic record. In order of increasing ages, these are: (1) Pleistocene glacial sediments produced by as many as five separate glacial advances into the New York City area (700,000 to 10,000 years old); (2) the coastal plain (65 to 15 million years old); (3) Newark basin-filling strata and the Palisades intrusive sheet of igneous rock (220 to 170 million years old); and (4) "stumps" of the central part of the much-eroded Appalachian Mountains, a complex of metamorphic rocks deformed several times during plate convergence at a former continental margin (materials 450 to 1350 million years old deformed at 1100, 440, 365, and possibly also at 260 million years ago). A discussion of this four-part geologic framework of the New York City area follows after the introduction. For the interested reader, an Appendix summarizes the important work of Robert Moses in modifying New York's landscape.

Despite the fact that this cruise does not include any stops ashore to look at rocks, nevertheless, the view of the shoreline from out in the water provides interested participants with the opportunity to observe several large-scale morphologic features that are surface expressions of the four major components of the geologic record of the New York City region (Figure 1, cover).

For example, opposite Hoboken, NJ, the Hudson bends sharply to the R from a N-S course to a NNE-SSW-trending course; to the NE it occupies a strike valley at the base of the Newark strata that trends NNE-SSW. Here, a major contrast exists in the materials forming the banks. On the W are the Newark basin-filling strata dipping 10°-15° W, with steep cliffs formed by the eroded edge of the Palisades sheet of tough igneous rock (Figure 2). The columns of rock are bounded by a regular network of subvertical joints that formed when the molten material cooled a few kilometers underground.

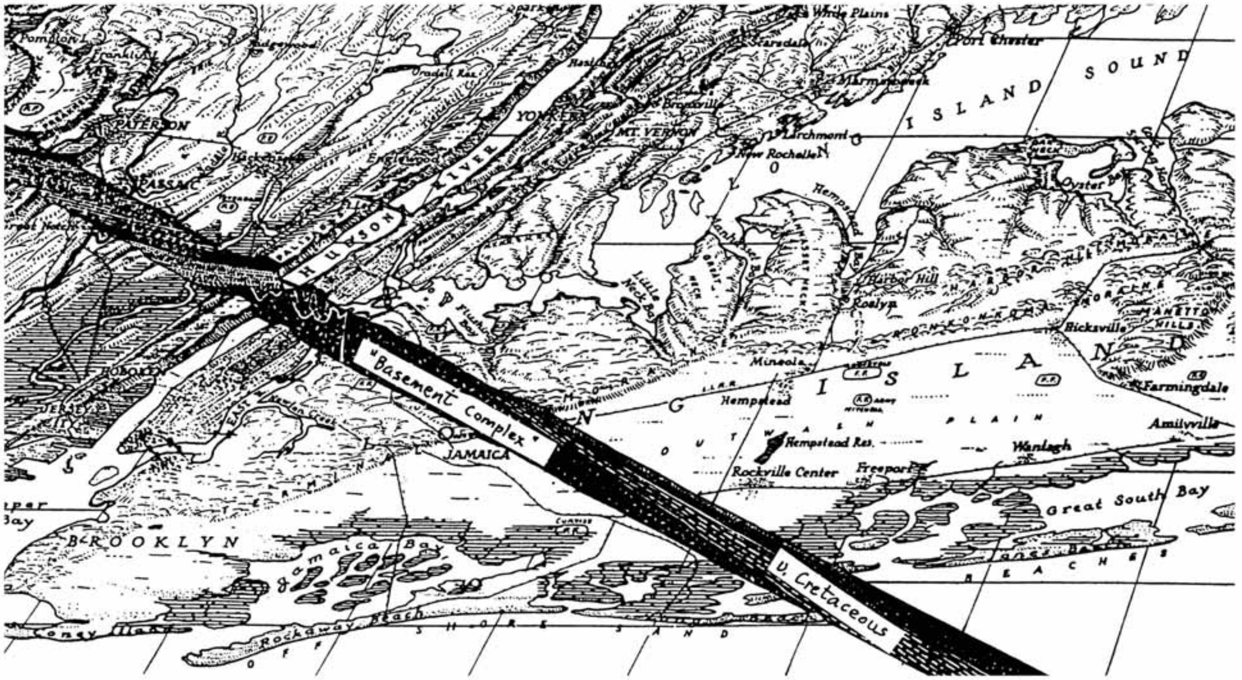


Figure 2. Physiographic block diagram of western Long Island and adjacent areas showing relationship of Upper Cretaceous strata to "Basement complex." (E. Raisz.)

The altitudes on the top of the Palisades ridge decline southward from about 800 feet at High Tor (Haverstraw), to 300 feet at the George Washington Bridge, to sea level on Staten Island, a distance of 40 miles (average gradient is 20 feet/mile). On Staten Island, the eroded, tilted edge of the Palisades sheet passes beneath the coastal-plain strata. Borings also disclose that the depth to bedrock beneath the river ranges from -350 feet at the George Washington Bridge to -950 feet at the Tappan Zee Bridge compared with about -200 feet at the Verrazano-Narrows Bridge.

In the lower Manhattan-Jersey City reach, both sides of the Hudson consist of ancient "basement" metamorphic rocks that form firm foundations for tall buildings. On the E are the "basement rocks" that formed the floor on which the basal Newark sediments (now sedimentary rocks) were deposited. Borings disclose that the basal-Newark strike valley continues to the WSW through Jersey City, Bayonne, and NW Staten Island, where it disappears beneath the coastal-plain strata. The low shore of Brooklyn is underlain by coastal-plain strata covered by Pleistocene sediments.

Thus, our plan for today's cruise in New York Harbor is to point out many of the large-scale geologic features of the New York City region and also to marvel at the numerous engineering structures that have yielded so much information about the subsurface geologic relationships. This guidebook reviews the major components of the local geologic record and relates these to the waterways and shorelines of the cruise route. We start with the general geologic setting of features to be discussed:

1. The scenic Palisades Intrusive Sheet that descends in elevation from north to south. The sheet is lopolithic in form and new research suggests that it is composite, the result of numerous charges of magma. Our joint research indicates that the intrusion took place relatively shallow (~3-4 km) and that magma flowed from SSW to NNE interacting with nonlithified bounding sediments.

2. At the Lincoln Tunnel Manhattan tie-in, near the Circle Line dock, the southwestward flowing Hudson River makes a 15° bend toward the east and heads straight for The Narrows, which separates Upper New York Bay from Lower New York Bay. As a result of this bend, the river flows out of the basal-Newark strike valley, which it follows from Haverstraw to the SW. (See Figure 2.) A big question is why the river leaves a ready-made valley and flows across solid rock. This ready-made valley disappears from the modern landscape, but can be traced in the subsurface. It crosses Jersey City and Bayonne and western Staten Island. As a result, solid bedrock of the kind underpinning Manhattan comes close to the land surface in a strip extending from Hoboken to the SSW. Here, the closeness of the bedrock to the land surface enables tall buildings to be built on the W side of the Hudson. The probable answers to the question as to why the river changes course is related to the sudden disapperance of a large lake that was formerly backed up behind the terminal-moraine ridge and the presence of faults. This formerly continuous dam was breached at The Narrows. The former lake was drained by a colossal flood of water that flowed through the newly breached natural earth-fill dam parallel to weaknesses in the bedrock.

3. On Staten Island, the coastal-plain cuesta and accompanying strike valley at the base of the Upper Cretaceous coastal-plain strata. These strata, which trend NE-SW across central NJ and localities farther to the SW, pass into Todt Hill, where the strike valley disappears and the trend of the cuesta begins to swing around to the ENE-WSW. Following this trend, it crosses Brooklyn, and continues eastward parallel to the long axis of Long Island. Here, the fringing basal strike valley has been submerged as Long Island Sound (Figures 3 and 4).

4. The terminal-moraine ridge and gap at The Narrows where the Verrazano-Narrows bridge was built (completed in 1964). Before the gap at The Narrows was eroded, the moraine ridge served as a natural dam that backed up a large freshwater lake all the way to Albany and beyond; the water from the Great Lakes that now flows into the St. Lawrence River then came eastward in the Mohawk Valley and into the Hudson. When the natural dam burst, the lake drained, the outflowing water eroded a straight channel into what is now the sea floor, and the rising sea entered the former lake to form the Hudson Estuary.

5. Tidal behavior of New York harbor; flushing of salty water from Long Island Sound out through The Narrows. Incredibly detailed studies were carried out in 1908 and 1909 (summarized in the next section).

6. New interpretations concerning the bedrock geology of New York City based on integrated field research. An important feature of regional extent in the local bedrock is a Taconian ductile fault known as Cameron's Line (Figure 5), which extends SW from western CT into the New York City region. Exposures critical to CM's new interpretation of the bedrock schists and visible at the extreme NE end of Manhattan Island, can be seen when the yacht passes

near the Henry Hudson Bridge (one of Robert Moses' first projects in New York City). (See Appendix 1.)

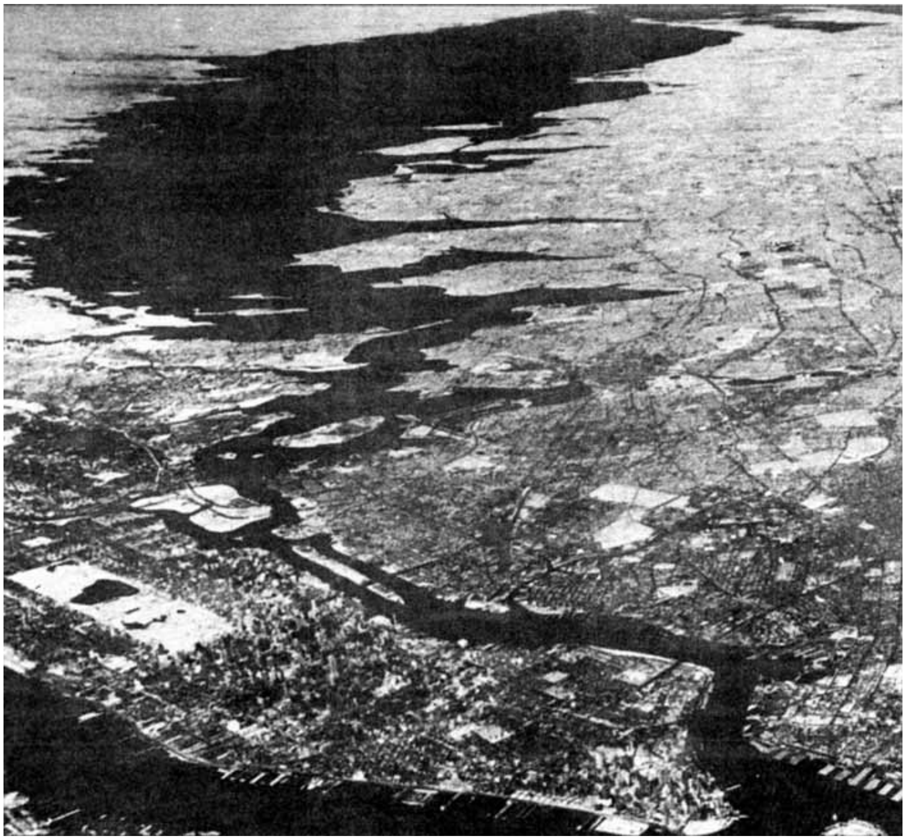


Figure 3. Oblique photograph looking northeastward along the axis of the Long Island Sound. The Sound in a natural boundary (unconformity) between crystalline rocks of the New England Appalachians (to the left; north) and southward dipping sediments of the Coastal Plain and overlying glacial sediments (to the right; south).

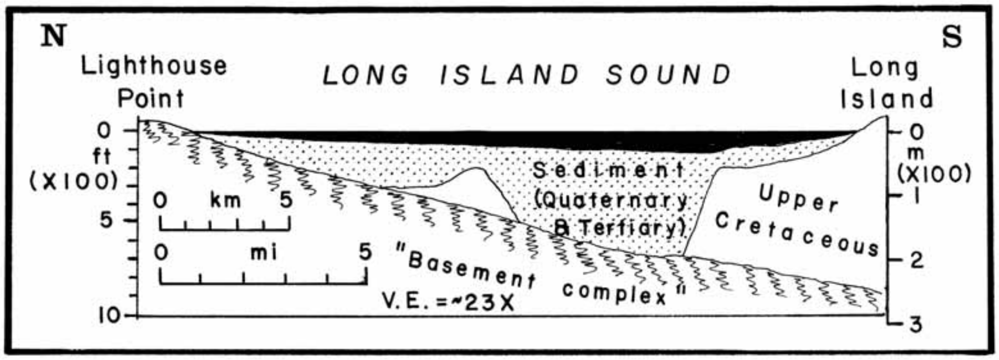


Figure 4. North-south profile-section from Connecticut, across Long Island Sound, to Long Island, along longitude 72° 53' W. Water depths from NOS chart. Subbottom relationships from M. S. Grim, C. R. Drake, and J. R. Heirtzler, 1970, fig. 12, p. 661. Water of Long Island Sound shown in black. (J. E. Sanders.)

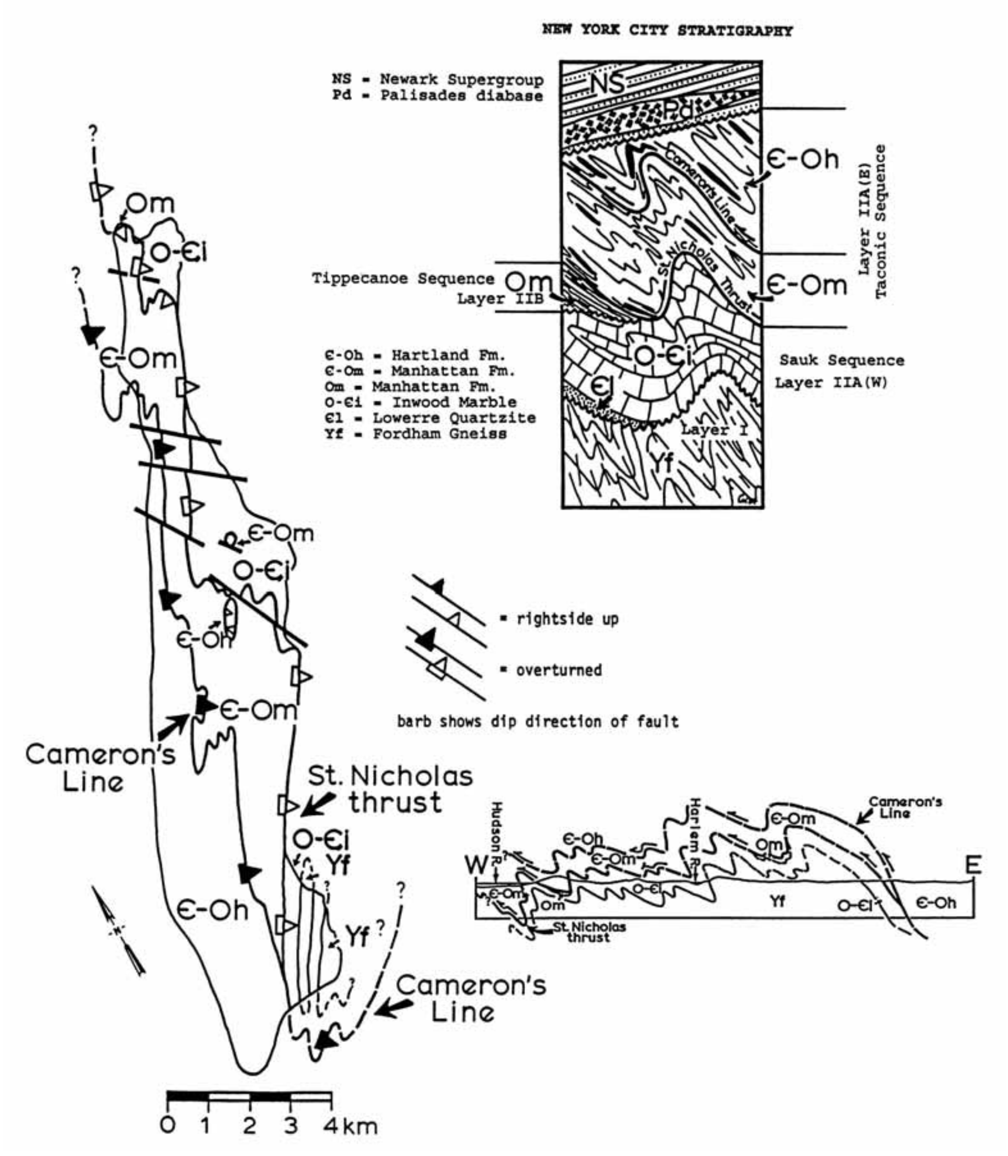


Figure 5. Geologic map of Manhattan Island showing a new interpretation of the stratigraphy- and structure of the rocks formerly included together as a single unit, the "Manhattan Schist. Geologic section (inset) shows folded Taconian ductile thrusts (the St. Nicholas thrust and Cameron's Line) mapped on Manhattan Island and in The Bronx. (Drawn and mapped by C. Merguerian.)

7. Examination of brittle faults and fault valleys in New York City. What is the potential for a damaging earthquake in the New York City area. Our symposium paper (Merguerian and Sanders, 1997) entitled "Bronx River diversion, neotectonic implications" presents evidence for post-glacial (younger than 10,000 years ago) fault-related ground motion.

Parts of this guidebook, written expressly for the International Symposium of Rock Mechanics 1997 meeting, are exerpted from 22 local geologic field guides the authors have written over the last decade while conducting the "On-The-Rocks" field-trip program under the auspices of the New York Academy of Sciences. Our guidebooks are available for a nominal printing fee through Duke Geological Laboratory (see last page of guide).

NEW YORK HARBOR

New York Harbor unquestionably is one of the most-important, -complex, and fascinating seaports in the world. In the early part of this century, the Port of New York was considered to extend east to Port Chester on Long Island Sound, north to Tarrytown on the Hudson, south to New Brunswick on the Raritan River, and including the neighboring New Jersey shore as far as Newark and beyond (Figure 6). Subsequently, the Port has been named the Port of New York and New Jersey.)

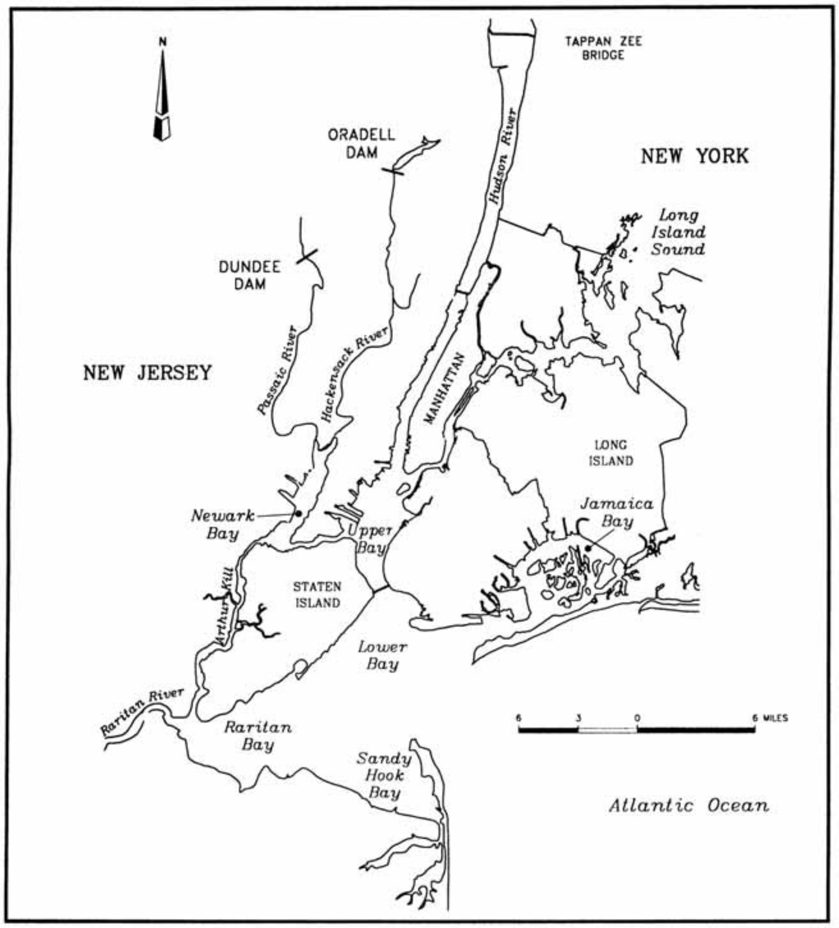


Figure 6. Map of New York Harbor (U.S. Environmental Protection Agency.)

The harbor itself consists of numerous complexly shaped bays, rivers, and estuaries that are intricately connected to the lower Hudson River, which forms the main estuary of the harbor complex. All the bays, estuaries, and rivers interact hydrodynamically to form a system of interactive- and interconnected tidal waterways.

The harbor opens directly to the Atlantic Ocean on the south via New York Bay and indirectly to the Atlantic to the east via the East River, Hell Gate, and Long Island Sound. The whole complex is subject to the influence of the tides and currents sweeping in from the Atlantic Ocean via New York Bight and Long Island Sound and to the river discharges, of which the Hudson is the greatest. In addition, the water levels are subject to being changed by meteorological conditions.

From the Troy dam southward, the Lower Hudson River is a tide-influenced estuary. The Hudson and Mohawk rivers, as well as numerous tributaries, discharge freshwater directly into the Harbor. The distribution of saltwater is influenced by the quantity of freshwater discharged, tide, physical characteristics of the estuary, and meteorological conditions. Depending on interactions among these factors, the estuary may be mixed, partially mixed, or stratified (Pritchard, 1952, 1955). According to Giese and Barr (1967), the channel in the northern half of the lower Hudson tidal system is usually filled exclusively with freshwater. The landward tip of the saltwater wedge ("salt front") typically fluctuates between Mile Points (MP) 20 and 60 north of The Battery, which is approximately between the Tappan Zee bridge and the Newburgh-Beacon bridge (on I-84). Almost every summer during a low-flow water year, it extends north to Chelsea (site of the New York City emergency water-intake pipe at MP 64) and has been found to reach as far north as MP 78, the intake pipe of the Poughkeepsie municipal waterworks (three known times of such northward extension are 20 November 1964, 05-10 November 1982, and in February 1985; Malcolm Pirnie Chelsea report 1986, Section 3). During most of the year, the water in the southern half of the lower Hudson is at least partly saline (salinity >0.1 parts per thousand).

Many efforts have been directed toward understanding the intricate hydrodynamic interactions in New York Harbor. These interactions are fundamental to the water quality in the ecosystem, particularly with respect to disposal of sewage and the dispersion of passive contaminants.

The tidal phenomena in New York harbor have been investigated since the 1860's, initially in connection with requirements for navigation (Henry Mitchell, 1860a, b; 1887a, b, c). The U. S. Coast Survey (later named the Coast and Geodetic Survey) established tide gauges, measured the water levels and currents, and published the results as a series of tables and charts.

Early in the twentieth century, the Metropolitan Sewerage Commission of New York, G. A. Soper, President, carried out an extremely detailed study of all aspects of the flow of water into, out of, and through New York Harbor. The Metropolitan Sewerage Commission published several thick volumes containing the results of all their field surveys. A remarkable- and extremely detailed paper summarizing the work of the Commission's scientific experts was published by H. deB. Parsons (1913). Despite its appearance in a standard engineering journal, this paper seems to have escaped the notice of most later workers. Parsons wrote a treatise on the tides, tidal currents, results of float-tracking experiments, and salinity measurements.

The culmination of the field work for the Sewerage Commission came in 1908 and 1909. They established 11 observation stations throughout the harbor, ranging from Tarrytown on the north to Ambrose Lightship on the south, and from Throgs Neck on the east to Passaic Light in

Newark Bay on the west. (See Figure 6.) From these stations, they made more than 13,000 observations of the surface salinity, plus additional readings at various depths. During the calendar year 1909, they made daily salinity readings at each station; as checks on their field salinometers, they collected three water samples, at 0800, 1200, and 1600, for salinity measurements in the laboratory.

During the summer of 1922, the U. S. Army Corps of Engineers and the U. S. Coast and Geodetic Survey carried out an extensive survey of the currents in the harbor (Marmer, 1923, p. 442). Detailed summaries of other projects related to tides and tidal currents are contained in the U. S. Coast and Geodetic Survey's summary books on the tides and currents in New York Harbor (Marmer, 1925; revised in 1935), in Long Island and Block Island sounds (LeLacheur and Sammons, 1932), and in the Hudson River (Schureman, 1934). Tabular summaries of some of these surveys are presented in Abood (1974). Marmer (1923) also published a non-technical summary of the tides- and currents in the New York Harbor complex. In this article, Marmer emphasized the distinction among the three contrasting situations: (a) the tide as a progressive wave from The Narrows through the Lower and Upper bays and up the Hudson River and also into Newark Bay (Marmer, 1923, p. 425) (but modified by the rivers into an asymmetry typical of river tides); (b) a stationary-wave kind of tide in Long Island Sound (Marmer, 1923, p. 426); and (c) hydraulic flow through straits, such as East River, Harlem River, and the Kill van Kull, in which the currents respond to changing levels of water at either end (Marmer, 1923, p. 433-440). Both Parsons and Marmer showed that the typical situation prevailing in the East River is that the flow oscillates but unequally; a net export of water from Long Island Sound enters Upper New York Bay. Convincing arguments demonstrating this situation came from the extensive network of salinometer measurements (described by Kenneth Allen, 1913, in his written discussion appended to Parson's paper):

"By a series extending from the eastern end of Long Island Sound through the East River to the Upper Bay, for instance, it was shown by the high salinities east of Hell Gate that the waters of the Sound were not those which had come from the Upper Bay, where the Hudson River causes the proportion of sea water to drop to 60 or 70%, but were essentially those of the Atlantic entering from the east, and hence that there exists a definite net discharge to the west and south through the East River--a fact difficult to prove before Col. Black's more recent (sic) gaugings were made."

Despite this "normal" situation, Parsons (1913, p. 2056) mentioned possible deviations:

"It is possible that in the East River the resultant flow on some days may be many times greater than that stated for the normal, and on other days it is possible that it is in the opposite direction, or northerly and easterly. These variations are brought about by various causes, the principal one being the wind inducing abnormal tides in the Upper Bay and in Long Island Sound."

GENERAL GEOLOGIC SETTING: COMPONENTS OF THE GEOLOGIC RECORD

The three components of the geologic record of any area are: (1) the bedrock; (2) the regolith; and (3) the shape of the Earth's surface.

BEDROCK

Under the heading of bedrock, we summarize the general processes, or geotectonic cycles, by which major bedrock units are formed and then relate three of the four major units that compose the local geologic framework to such processes.

Bedrock-forming Machinery: Geotectonic Cycles

Major components of the bedrock result from the operation of lithosphere plates in geotectonic cycles. Two contrasting plate-tectonic settings where geotectonic cycles operate are continental margins and intraplate nonmarine basins.

Continental Margin

A geotectonic cycle at a continental margin typically begins when two plates split apart and a new ocean starts to form. The trailing edges of the moving plates cool and subside. Sediments are deposited in what is known as a passive-margin phase (Figure 7). Eventually the deposited sediments are subjected to a convergent-margin phase in which they are deformed by being folded and duplicated on low-angle thrusts (Figure 8) and in many cases, metamorphosed and some of the rocks partly melted as part of mountain-building processes collectively designated as orogeny. Such cycles accompany the opening- and closing of an ocean basin. Commonly such orogenic cycles are punctuated by periods of uplift and extensive erosion.

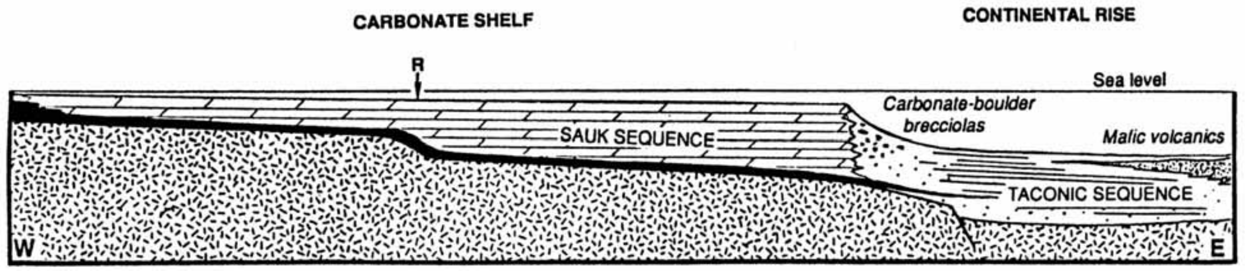


Figure 7. Schematic reconstructed geologic profile-section across Early Paleozoic passive continental margin in what is now eastern New York State. R = Rickard's Line, west of which the thin Sauk Sequence that has not been involved in low-angle overthrusts begins with the Upper Cambrian Potsdam Sandstone and east of which the thicker Sauk Sequence has been duplicated along low-angle thrusts and begins with the Lower Cambrian Poughquag Quartzite. The nature of the change of level at Rickard's Line is not known. Short line segments in random pattern, Proterozoic "basement" rocks not differentiated; black, basal quartzose unit; dolostone pattern for Sauk Sequence includes limestones (now calcite marbles) on seaward part of the former carbonate shelf (modern east, but Early Paleozoic south). (J. E. Sanders, 1995, fig. 1, p. 24, based on Baiying Guo, 1994 ms.)

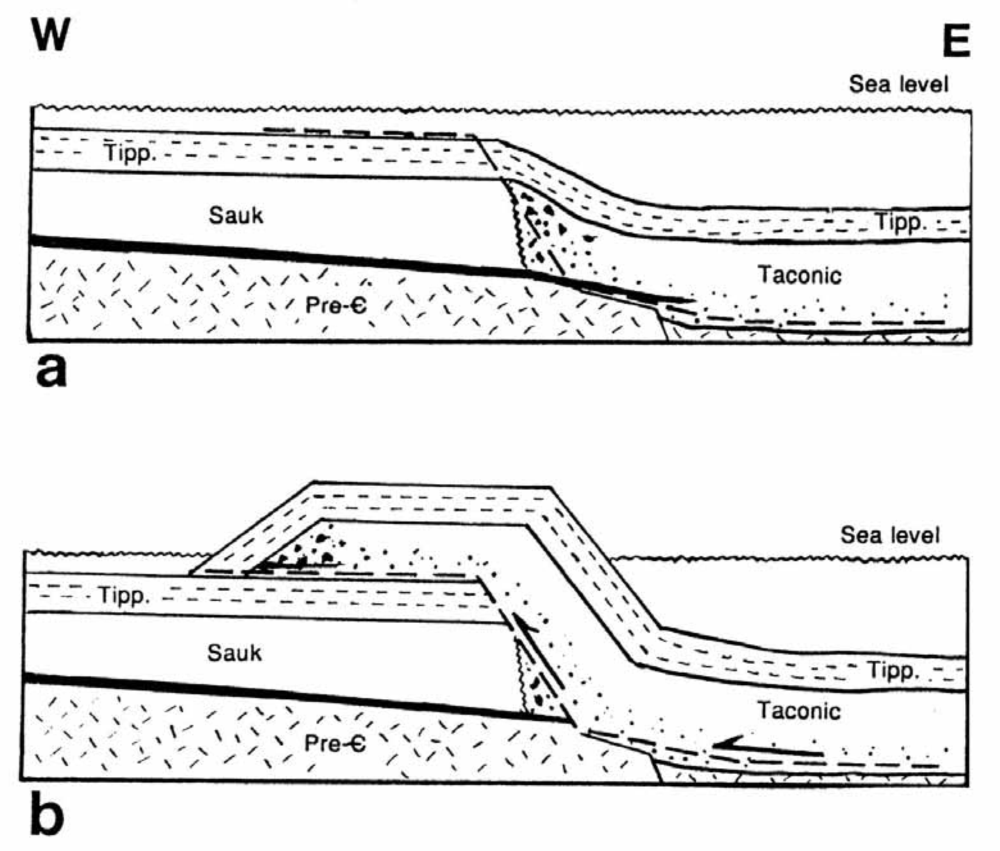


Figure 8. Bedding-type thrust forms after former passive margin becomes a convergent margin, schematic profile-sections. (J. E. Sanders, 1995, fig. 8, p. 37.)
a. Before thrusting; dashed line shows course of future thrust.
b. Early stage of duplication of strata along bedding-type thrust; effects of erosion not shown.

Intraplate Nonmarine Basin

A geotectonic cycle in an intraplate nonmarine basin begins when large parts of a continental lithosphere plate are elevated, some more than others. Deep vertical fractures form. The more-elevated blocks furnish sediments that accumulated on the lagging-behind blocks that become the adjacent lowlands into which the sediments derived from the elevated blocks are deposited.

Three Major Units of New York City's Bedrock

Viewed broadly, New York City's bedrock record can be divided into three major units (Units 2, 3, and 4 as described above) that are products of three continental-margin geotectonic cycles (two completed, one still in progress, perhaps at its half-way mark) and one completed intraplate nonmarine-basin geotectonic cycle (Table 1). The Pleistocene glacial features (listed above as

Unit 1, are discussed in a later section). We list the three bedrock units in order of increasing ages, from top down, but shall discuss them in the reverse order, from the bottom up. These units are: (2) the coastal plain (65 to 15 million years old); (3) the Newark basin-filling strata and Palisades sheet of igneous rock (220 to 170 million years old); and (4) a "basement complex" consisting of the "stumps" of the central part of the much-eroded Appalachian Mountains (1350 to 450 million years old).

Unit (4): "Basement Complex" of Proterozoic- and Paleozoic Age

The basement complex includes metamorphic rocks that were deformed and even recrystallized several times during plate convergence at a former continental margin. Unit (4) bedrock of the "basement complex" is exposed in Manhattan and The Bronx and is known to underlie all other units (3) through (1).

The rocks composing the "basement complex" resulted from the operation of two long-completed continental-margin cycles, the older Grenville and younger Appalachian. The Grenville cycle spanned roughly 700 million years (Ma) and ended with the Grenville Orogeny dated at 1100 Ma. The Appalachian cycle began about 570 ma and before it ended at 260 Ma included three convergent orogenic episodes (Taconian at 450 Ma; Acadian, at 365 Ma; and terminal Appalachian, ~260 Ma).

Rocks of the Grenville Cycle

The rocks of the Grenville cycle are oldest recognized strata in southeastern New York (Layer I of Table 2). They include the Fordham Gneiss in the Manhattan Prong of Westchester County (See Figure 2.) and the New York City area and the Hudson Highlands gneisses (Figure 9). The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss. They constitute a complex whose internal stratigraphic relationships are poorly understood. Taken as a whole, however the ancient Grenville-cycle sequence nonconformably underlies the younger Appalachian-cycle rocks described in the following section.

In the Pound Ridge area (PR in Figure 9), the Fordham gneisses have yielded 1100 Ma 207Pb/206Pb zircon ages (Grauert and Hall, 1973) that fall well within the range of the Grenville orogeny. Rb/Sr data of Mose (1982) suggest that metasedimentary- and metavolcanic protoliths of the Fordham date back to 1350 Ma. Farther south in Westchester County, subunits in the Fordham have been cut by the Pound Ridge Gneiss and correlative Yonkers Gneiss [post-Grenville granitic gneisses] (Z in Figure 9). Using Rb-Sr, Mose and Hayes (1975), have dated the Pound Ridge Gneiss as latest Proterozoic (579+21 Ma). This gneiss body shows an intrusive-, or possibly an nonconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969b) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or -volcanism (Pound Ridge?) in response to rifting of the ancient Gondwanan supercontinent.

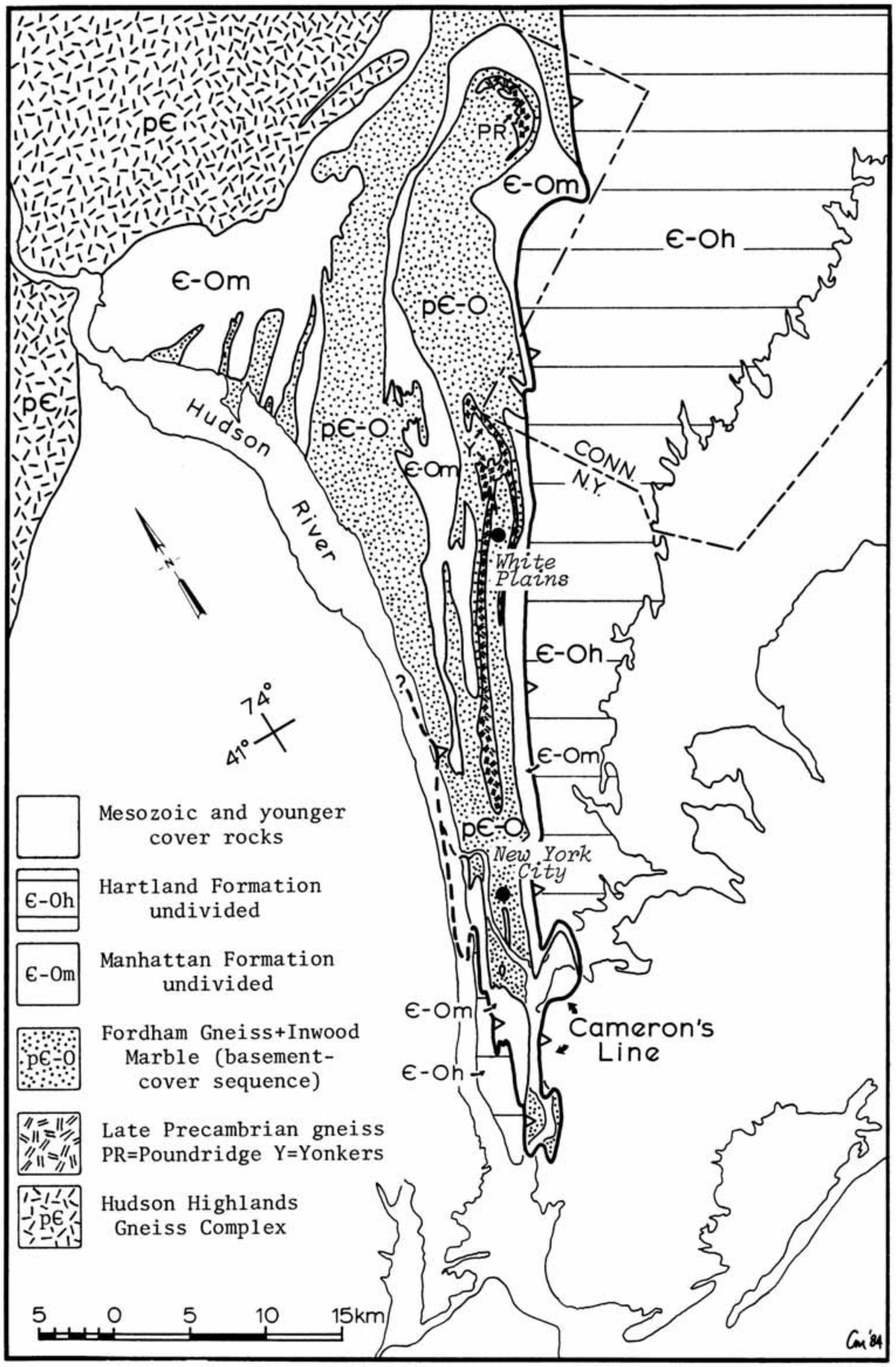


Figure 9. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks from Grenville cycle (Layer I; rocks of Proterozoic Y age) and early phases of Appalachian cycle (Layer II; rocks of Early Paleozoic age). Most faults and intrusive rocks have been omitted. (Douglas G. Mose and Charles Merguerian, 1985, fig. 1, p. 21.)

Recent work by Pamela Brock (1989, 1993 ms., and personal communication) in the vicinity of the Peach Lake quadrangle, New York and Connecticut, shows the presence of a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation) that rest nonconformably on the Fordham basement rocks. As such, Brock may have identified a metamorphosed, easterly volcaniclastic facies of Proterozoic Z intrusive igneous rocks whose probable feeder area is now marked by the Yonkers and Pound Ridge gneisses.

Southeast of the Hudson Highlands, the Grenville rocks consist of the Fordham Gneiss, which has been intricately folded with the Paleozoic-age rocks of the Appalachian cycle that form the bulk of the Manhattan Prong.

Many of the Grenville-cycle units are unconformably overlain by the Lower Cambrian Lowerre quartzite (Hall, 1976; Brock, 1989), the basal unit of the Appalachian-cycle rocks. The Grenville-cycle sequence represents the ancient continental crust of proto-North America that became a trailing edge, passive continental margin early in the Paleozoic Era.

Rocks of the Appalachian Cycle

Nonconformably overlying Layer I of the Grenville cycle in western Connecticut and New York City are the Cambro-Ordovician formations that are products of the early (Taconian) part of the Appalachian cycle (Layer II of Table 2). These sedimentary- and igneous rock units have been highly metamorphosed, folded, and faulted. (See Figure 9.) They began their geologic lives roughly 550-450 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America (Figure 10). For ease of discussion, Layer II can be divided into two sub-layers, IIA and IIB.

The older of these, IIA, represents strata deposited along the ancient passive-margin of North America. The passive-margin deposits of Layer IIA can be subdivided into two facies [IIA(W) and IIA(E)] that differ in their original geographic positions with respect to the shoreline and shelf edge. A nearshore facies [Layer IIA(W)], deposited in shallow water, is collectively designated as the Sauk Sequence. This sequence includes former basal sandy sediment and overlying thick Cambro-Ordovician carbonate sediments, which were predominantly dolomitic in nearshore areas. The Sauk clastics and -carbonates in New York City are the Lowerre Quartzite and Inwood Marble. In western Connecticut and Massachusetts, the basal-Sauk sandy unit is the Cheshire Quartzite and the carbonate rocks, here containing more limestone than in localities closer to the ancient shoreline, are named the Woodville- and Stockbridge Marble. Thus, the Sauk strata began life as sandy- and limey sediments in an environment not significantly different from the present-day Bahama Banks. In fact, during the Appalachian cycle, New York City was situated in the tropical parts of the Southern Hemisphere; what is now east was then south and what is now west, north (Figure 11).

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water Sauk strata (shelf sequence) were deposited in deep water on oceanic crust [Layer IIA(E)]. This deep-water sequence is also of Cambrian- to Ordovician age. In upstate New York, it is known as the Taconic Sequence. Locally, it is represented by units Ꞓ-Ot and Ꞓ-Oh of the Manhattan Schist(s) (See Figure 5.); in western Connecticut, these are the Waramaug and Hartland formations, respectively (Merguerian, 1983a, 1985).

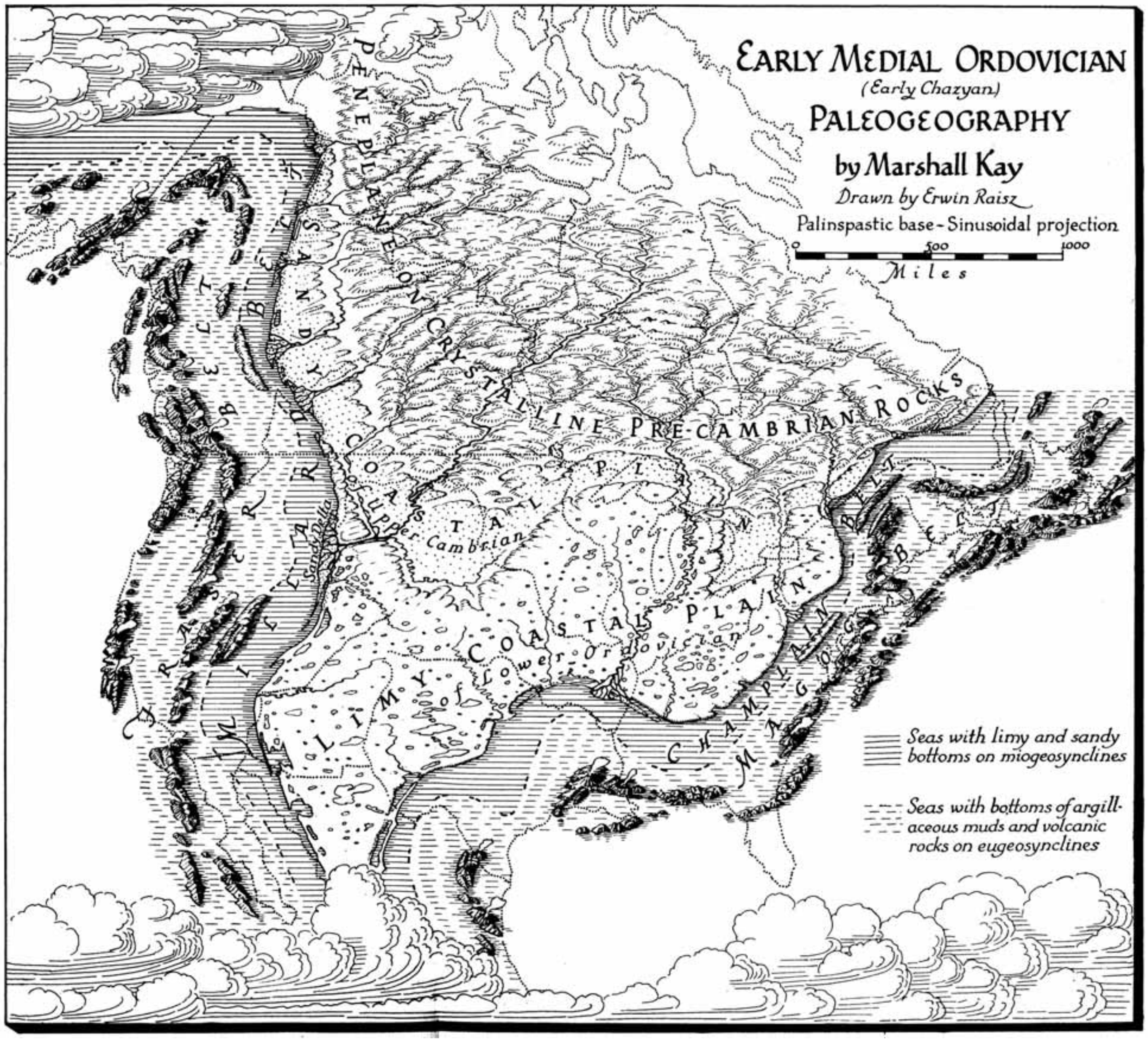


Figure 10. Paleogeographic reconstruction of North America as it is inferred to have existed during the Cambrian Period. Not shown are paleolatitudes and position of the Early Paleozoic Equator, which extended across what is now North America passing through Oklahoma, Kansas, and the Dakotas such that what is now east in the Early Paleozoic was south. (G. M. Kay, 1951, plate 1, facing p. 1.)

Layer IIB consists of younger strata designated collectively as the Tippecanoe Sequence. The Tippecanoe strata overlie the Sauk Sequence [Layer IIA(W)] above a surface of unconformity of regional extent. The change from passive margin to convergent margin took place while the Tippecanoe Sequence was accumulating. The basal unit of the Tippecanoe

Sequence is a limestone (the "Balmville") deposited at the end of the passive-margin phase. Overlying this limestone is a thick body of dark-colored terrigenous strata, the filling of a foreland basin that formed during the earliest part of the convergent-margin regime that supplanted the passive-margine regime in mid-Ordovician time.

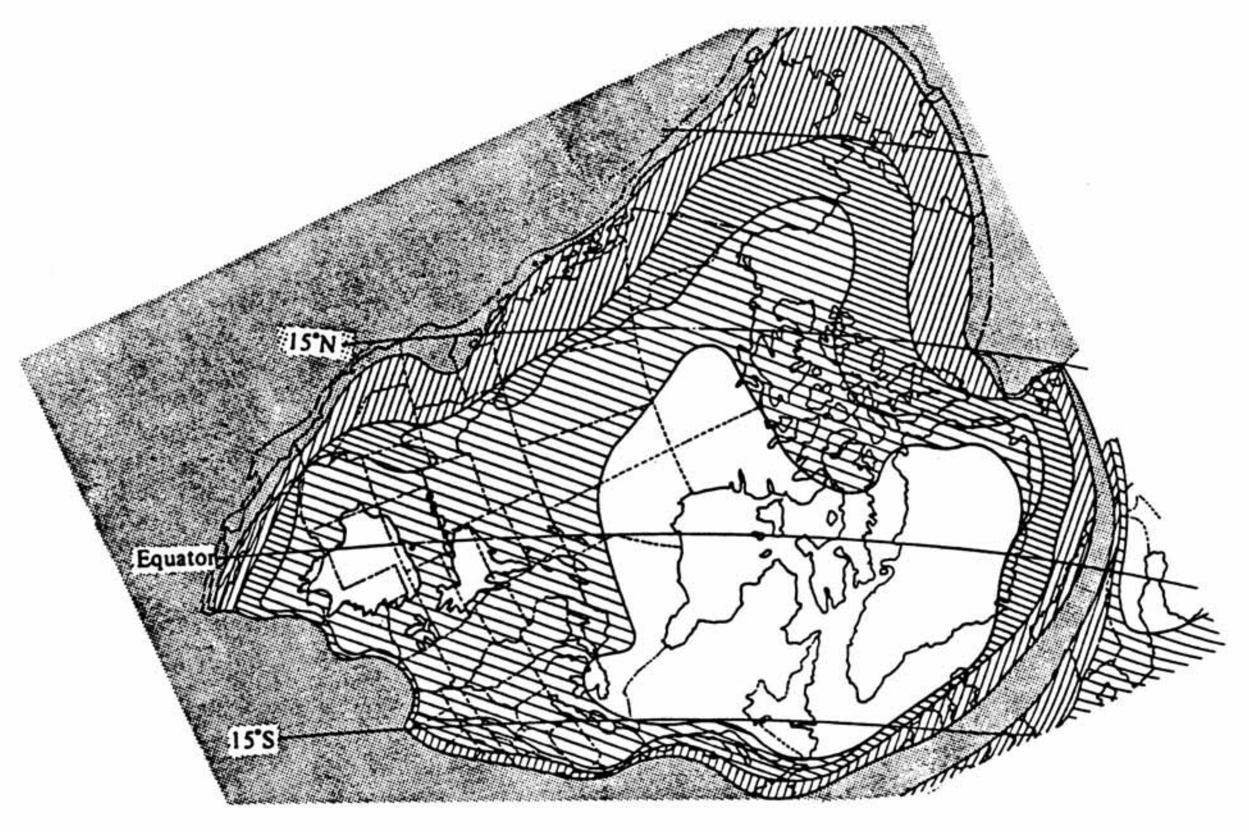


Figure 11. Paleogeographic map showing North America in its Early Paleozoic position astride the Earth's Equator. (Charles Merguerian and J. E. Sanders, 1996, fig. 2, p.118; after C. K. Seyfert and L. A. Sirkin, 1979.)

Bedrock Geology of New York City

The Manhattan Schist Formation

In eastern New York State, the metamorphosed equivalents of the Tippecanoe terrigenous strata are known as the Walloomsac Schist and Manhattan Formation. In New York City, the Tippecanoe Sequence consists of a thin basal limestone (assigned by some to the Inwood Marble) and the overlying Manhattan Schist [Unit Om]. According to Merguerian (1983b, 1994, 1996) Manhattan Schist [Unit Om] is demonstrably interlayered with the basal-Tippecanoe carbonate. At its base at Inwood Hill Park in Manhattan, Manhattan Schist unit Om also contains thin layers of calcite marble (Balmville equivalent) (Merguerian and Sanders 1988, 1991, 1991, 1993, 1993; NYAS On-The-Rocks Trips #3, 16, 21, 26, 28). CM takes this field evidence to indicate that unit Om of the Manhattan Schist is in place where found and therefore belongs to the Tippecanoe Sequence that overlies the Sauk-sequence Inwood Marble, which is the same age as Manhattan units Ꞓ-Ot and Ꞓ-Oh.

Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. Hall's (1968a, b, c) mapping in White Plains established subdivisions of the Manhattan Schist into two basic units. The autochthonous Manhattan A, which was originally deposited as part of the Tippecanoe Sequence overlying the basal Tippecanoe limestone that forms the topmost unit of the Inwood Marble and the allochthonous (transported rocks not found where deposited) Manhattan B and C members. Hall (1976) suggested that the Manhattan C (schist) and B (interlayered amphibolite unit) were Early Cambrian (or possibly older) in age, and thus are parts of the Taconic Sequence (Layer IIA(E) in our scheme) and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 9, Manhattan A is included in the basement-cover sequence (pꞒ-O) and Manhattan B and C are designated Ꞓ-Om. Merguerian (1983a, 1985) interprets the Manhattan B and C as a slope-rise-facies that was formerly deposited continentward of the Hartland Formation and now separated from them by Cameron's Line. Thus, in contrast to Hall's (1976, 1980) views, CM views the Manhattan B and C and the Hartland as essentially coeval tectonostratigraphic units.

Cameron's Line

These metamorphosed, Lower Paleozoic bedrock units are found west of Cameron's Line, a major tectonic boundary in New England (Figure 12). According to Eugene Cameron (of Cameron's Line fame) in a confidential personal communication with CM, the geologic relationship of Cameron's Line was first noted by William Agar who shared them with E. Cameron. According to EC - "I don't know why they called it Cameron's Line, it should have been called Agar's Line!". In any case, Cameron's Line delimits the easternmost exposures of autochthonous Proterozoic Y and Z gneiss and overlying lower Paleozoic quartzite and marble (shallow-water sedimentary strata [Layer IIA(W)] formed originally on continental crust of proto-North America. Together, Layers I and IIA(W) represent deformed North American craton and former overlying shelf deposits.

In western Connecticut and southeastern New York, the Hartland Formation or Complex of Merguerian (1983a) is interpreted as an internally sheared imbricate thrust package that marks the former site of a deep-seated accretionary complex or subduction zone. (See Figure 12.) It consists of a thick sequence of interlayered muscovite schist, micaceous gneiss and granofels, amphibolite, and minor amounts of calc- silicate rock, serpentinite, and manganiferous- to ferruginous garnet-quartz granofels (coticule) (Merguerian, 1981). Hartland rocks (Unit Ꞓ-Oh in New York City) are correlative with metamorphosed eugeosynclinal (deep-water deposits) Cambrian to Ordovician rocks found along strike northward into New England. The allochthonous portion of the Manhattan Schist (Unit Ꞓ-Om) is directly correlative with rocks of western Connecticut and Massachusetts known as the Waramaug and Hoosac formations found along the east flank of the Berkshire and Green Mountains massifs. (See Figure 12.)

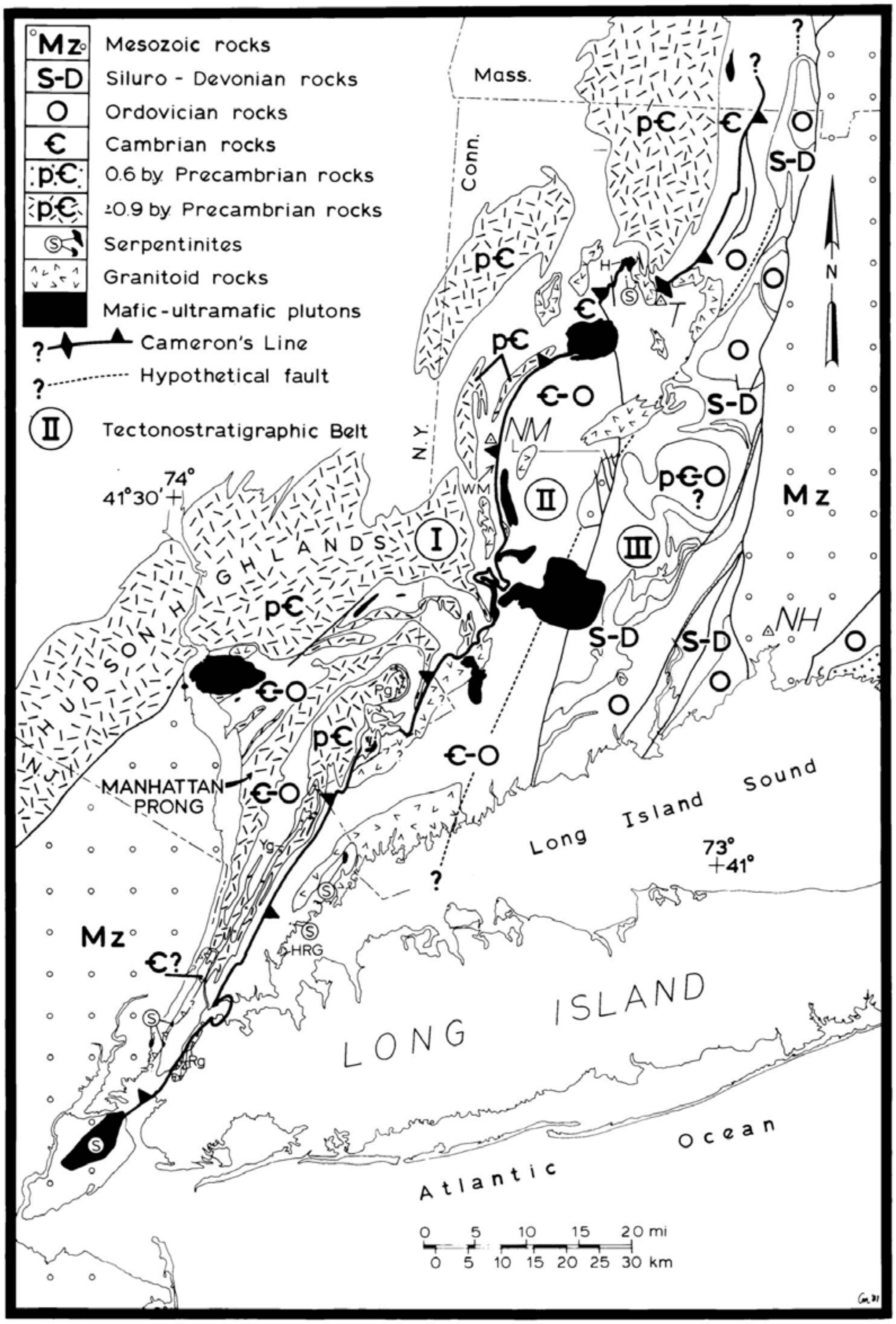


Figure 12. Tectonostratigraphic map of western Connecticut and southeastern New York showing the distribution of Cameron's Line (Belt I - Belt II contact) and adjacent volcanic rocks (Belt III) accreted to North America during the Taconic orogeny. (Merguerian, 1983a, fig. 1, p. 342.)

Numerous lower Paleozoic calc-alkaline plutons occur in southeastern New York and in western Connecticut. Near West Torrington, Connecticut, the Hodges mafic-ultramafic complex and the Tyler Lake Granite were sequentially intruded across Cameron's Line (Merguerian, 1977). Because of their formerly elongate shapes and because the regional metamorphic fabrics related to the development of Cameron's Line in both the bounding Waramaug and Hartland formations display contact metamorphism, these plutons are interpreted as synorogenic. The recognition of significant medial Ordovician plutonism across Cameron's Line (Mose, 1982; Mose and Nagel, 1982; Merguerian and others, 1984; Amenta and Mose, 1985) establishes a Taconian or possibly older age for the formation of Cameron's Line and the syntectonic development of regional metamorphic fabrics in western Connecticut (Merguerian, 1985a).

Structural Geology of New York City

The three schist units of New York City and the underlying rocks have shared a complex structural history which involved three superposed phases of deep-seated deformation (D_1-D_3) followed by three or more episodes of open- to crenulate folding (D_4-D_{6+}). Based upon relationships found in Manhattan, CM concludes that the synmetamorphic juxtaposition of the various schist units occurred very early in their structural history.

The base of the middle schist (Ꞓ-Om) is truncated by a ductile shear zone, here informally named the St. Nicholas thrust (open symbol in Figure 5). The thrust is exposed at Inwood Hill and Isham Parks, at St. Nicholas Park, and at Mount Morris Park. The upper schist (Hartland Formation; unit Ꞓ-Oh) is in ductile fault contact with the middle schist unit along Cameron's Line (I-95 exposure in the Bronx) and in Manhattan. However, this conclusion is based upon regional stratigraphic evidence; in Manhattan, surface exposures of Cameron's Line are rare. CM has mapped the contact in numerous subsurface exposures.

Cameron's Line and the St. Nicholas thrust developed during two progressive stages of Taconian ductile deformation accompanied by isoclinal folding (F_1+F_2). The F_1 folds are inferred from a locally preserved S_1 foliation. An annealed highly laminated mylonitic texture occurs at the thrust zone (Merguerian, 1988). Recrystallized mylonitic layering formed; ribboned and locally polygonized quartz, products of lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 folds. During D_2, a penetrative foliation (S_2) and metamorphic growth of lenses and layers of quartz and kyanite+quartz+magnetite up to 10 cm thick formed axial planar to F_2 folds which deformed the bedrock into a large-scale recumbent structure that strikes N50°W and dips 25°SW.

Although the regional metamorphic grain of the New York City bedrock trends N50°W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25°. S_3 is oriented N30°E and dips 75°SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz- and kyanite lenses and layers into elongate shapes.

At least three phases of crenulate- to open folds and numerous brittle faults and joints have been superimposed on the older ductile fabrics. The effects on map contacts of these late features is negligible but the scatter of older structural elements (Merguerian, 1996) are deemed the result of post-D_3 deformation.

Structure Sections

An inset in Figure 5 presents a simplified W-E structure sections across the New York City area. The W-E sections shows the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer.

In summary, the Fordham+Lowerre+Inwood+Manhattan (Unit Om only) bedrock units of New York City constitute the autochthonous miogeosynclinal basement-cover sequence of the New England Appalachians (pꞒ-O in Figure 9) and are the products of metamorphism of sediments formerly deposited on Proterozoic crust. Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Rodgers and others 1959, Merguerian 1977, 1983b) or Hutchinson River Group (Seyfert and Leveson 1968, 1969; Levesen and Seyfert 1969), or Pelham Bay Member of the Hartland Formation (Baskerville 1982a).

In contrast to the basement-cover sequence, the Hartland Formation consists of a sequence of metamorphosed eugeosynclinal rocks formerly deposited on oceanic crust (Ꞓ-Oh in Figure 5) which became accreted to North America during the mid-Ordovician Taconic orogeny (Hall, 1979; Merguerian 1979, 1983b; Merguerian and others, 1984; Robinson and Hall, 1980). To the west of Cameron's Line, in Manhattan, rocks with lithologic affinities transitional to these extremes (Ꞓ-Om) crop out.

Plate-Tectonic Interpretation

During Early Paleozoic time, the present eastern seaboard of North America formed a broad continental margin with a broad oceanward-facing shelf similar to today. The early Paleozoic shelf received clastic products of the weathering- and erosion of the exposed Proterozoic continental crust and carbonate sediments that accumulated on a shallow sea floor in a near-equatorial warm- water environment. (See Figures 7, 10, 11.) Thus, a continental terrane was formed with a basal layer of Proterozoic granitoid rocks (Fordham protolith) unconformably overlain by discontinuous sand, lime, and clay (Lowerre, Inwood, Manhattan Schist [Unit Om] protoliths). Outboard of the former shelf edge, on quasi-continental "transitional" crust, a succession of poorly bedded silt and turbidites formed (middle unit of the Manhattan Schist - Ꞓ-Om) and in the deeper oceanic environment, deep-water shales, turbidites, and intercalated volcanic rocks accumulated on oceanic crust in the vicinity of a volcanic archipeligo (Hartland Terrane - Ꞓ-Oh).

During the Medial Ordovician Taconic orogeny, as a result of arc-ward subduction, the Taconic volcanic arc collided with, and was accreted to the North American shelf edge, which was a part of the former passive continental margin of ancestral North America (Figure 13). Deformation- and metamorphism of the bedrock units of New York City took place deep within a trench beneath the Taconic arc with internal telescoping of the continental shelf, slope/rise, and oceanic realms along arcward-dipping shear zones within a deep-seated subduction complex. Development of the St. Nicholas and Cameron's Line thrust faults accompanied closure of the marginal ocean basin separating the Taconic arc from the mainland. The bedrock geology of southeastern New York and western Connecticut preserves this collisional boundary (See Figures 12, 13) in a series of subvertical, northeasterly trending, fault-bounded lithotectonic belts. Belt I is bounded on the east by Cameron's Line and marks the Continental Terrane. Locally, within Belt I are allochthonous rocks of the slope/rise sequence. Belt II is the Hartland Terrane of deep-water oceanic deposits and Belt III consists of the roots of the Taconic volcanic arc which also crops out to the east of the Connecticut River valley basin and extend through central Massachusetts into New Hampshire. (See Figure 12.)

Similar to the relationships noted in the Antler orogenic belt of California and Nevada, the deep-seated Taconian folding, metamorphism, and igneous activity occurred shortly before the Taconic allochthon had been emplaced (Merguerian, 1985b). Available age data indicate that the compressive ductile deformation in the igneous- and metamorphic root zone of the Taconic orogen led the supracrustal emplacement of overthrust sheets by a minimum of 20 Ma. The polydeformed internal massifs presumably mark the deep levels of continentward-facing accretionary complexes within which deep subduction and deformation of oceanic deposits preceded the collision of the encroaching volcanic arc terranes. Final docking of the arc resulted in cratonward thrusting of the shallow levels of the subduction complex to form the Taconic allochthon. As such, we see a time gap in deep-seated versus supracrustal deformation, wherein a geometrically predictable vertical pattern of diachroneity within subduction complexes in collisional orogens takes place.

Unit (3): Newark Basin-filling Strata and the Palisades Igneous Sheet

Bedrock unit (3) consists of strata that filled the Newark basin (Layer V of Table 2). The Newark strata overlie the "basement complex" along an ancient erosion surface (Figure 14; Sharp, 1929a). The Newark episode began at about 220 Ma and lasted until 170 Ma. On the basin blocks, nonmarine sedimentary strata, possibly as thick as 10 km, collected; interlayered with the sedimentary strata are widespread flood basalts, products of former lava lakes fed from the deep-seated fractures, and extensive sheets of intrusive igneous rock that formed where the molten igneous material cooled underground. The tilted edges of these sheets of igneous rock are prominent parts of our local landscape: the Palisades along the W bank of the Hudson River (Figure 15) from Haverstraw, NY to Hoboken, NJ (tilted edge of an intrusive sheet; Figure 16) and the Watchung ranges in north-central New Jersey, which are formed by the tilted edges of three flood-basalt complexes that resist erosion more than the shales and sandstones with which they are interstratified. (See Figure 2.)

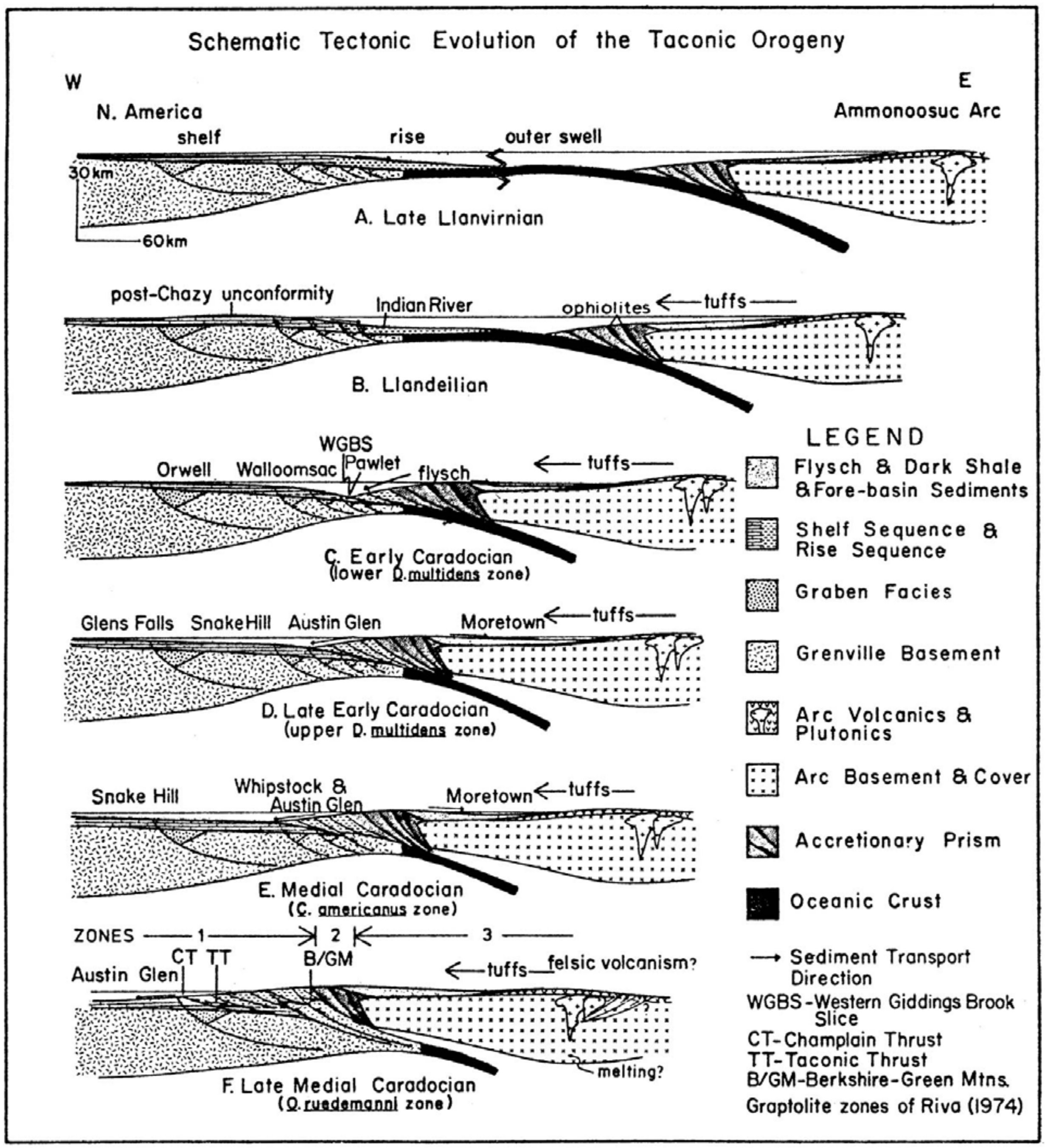


Figure 13. Sequential tectonic cross sections for the Taconic orogeny in New England. (D. B. Rowley and W. S. F. Kidd, 1981, fig. 4, p. 212.)

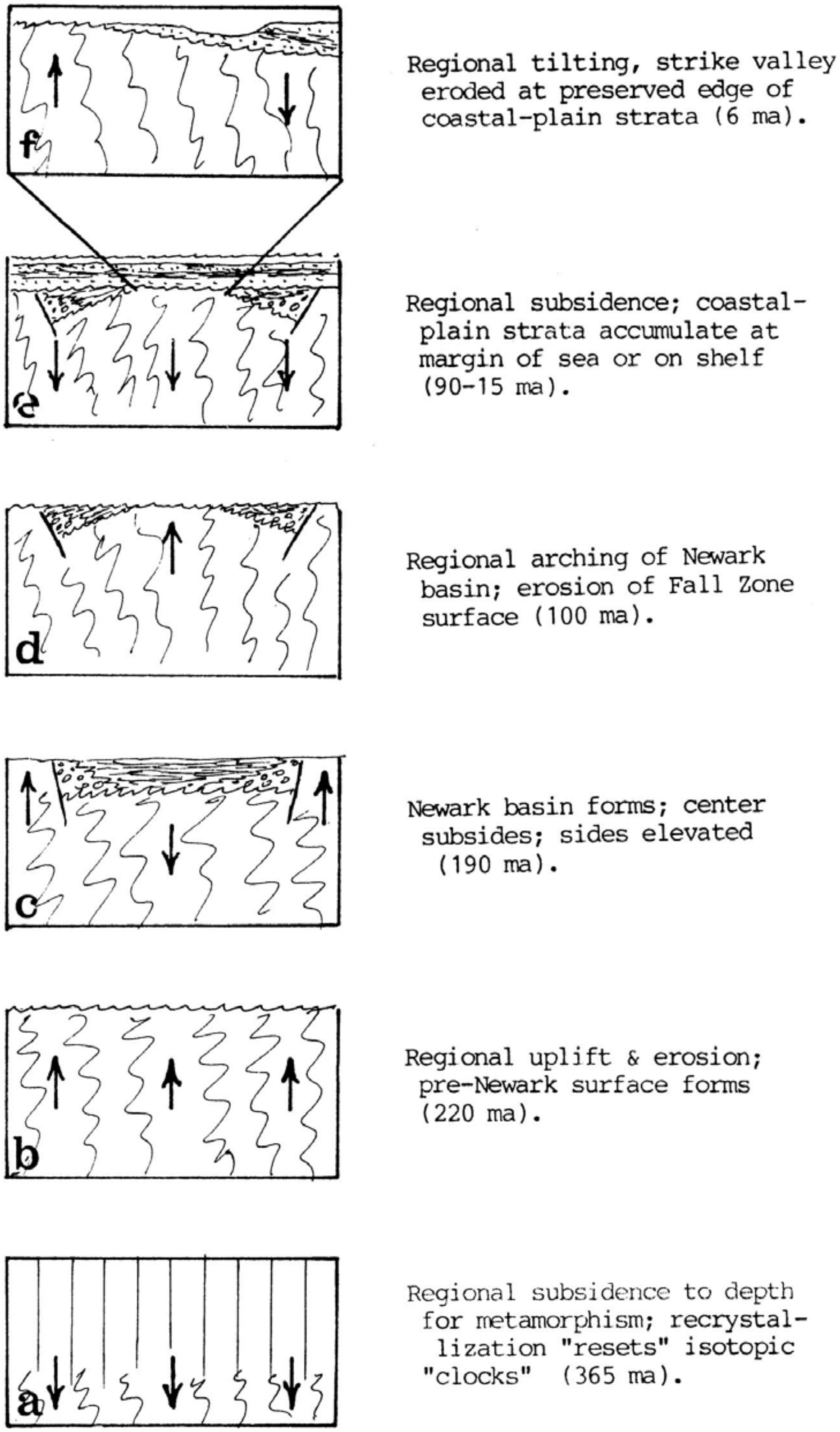


Figure 14. Schematic profile-sections showing stages in post-Devonian development of Long Island and vicinity. (J. E. Sanders.)

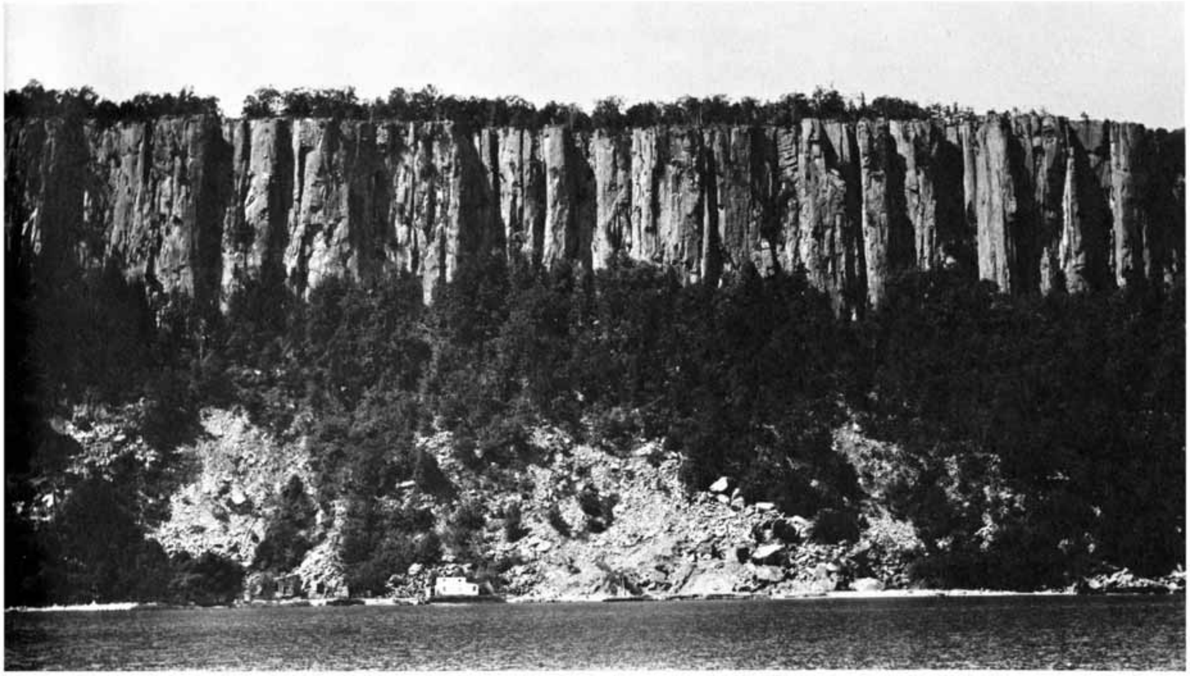


Figure 15. View of Palisades from above the Hudson River looking west. The nearly vertical columns of rock are bounded by steep joints that formed during contraction when the magma solidified to form the mafic igneous rock. (J. E. Sanders, 1981, fig. 6-26a, p. 165.)

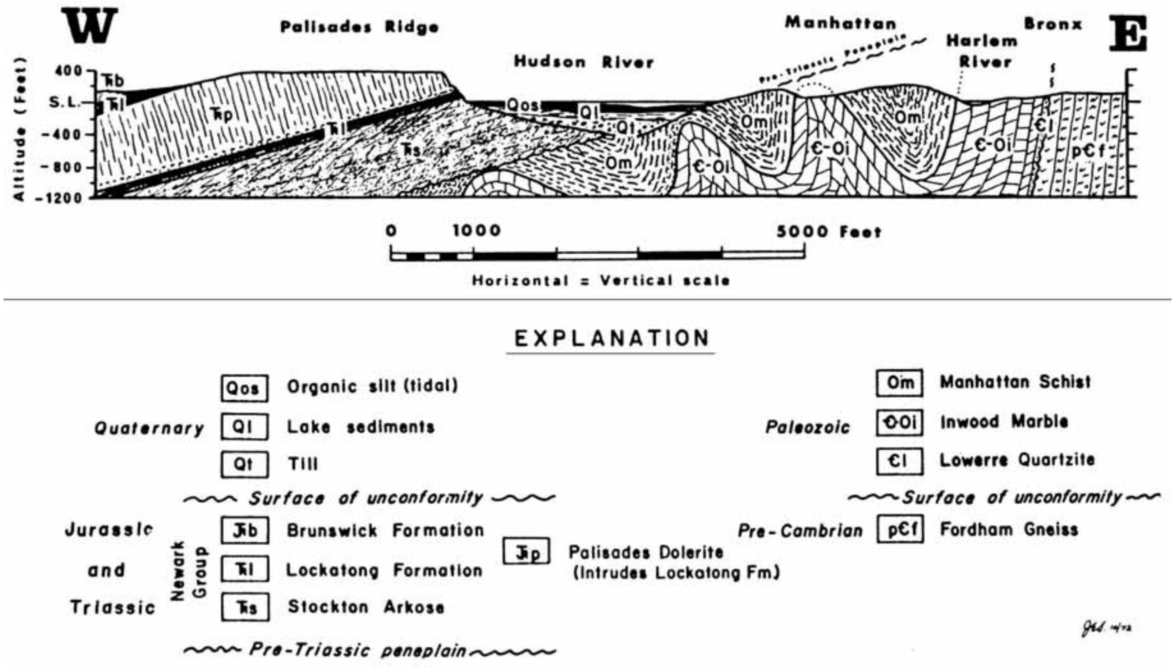


Figure 16. Profile-section across Hudson River at the George Washington Bridge. Topographic relationships from United States Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974a, fig. 3, p. 11.)

The Newark strata of Unit (3) nonconformably overlie the older metamorphic terrane of the Manhattan Prong of Unit (4) and are themselves overlain in angular unconformity by the virtually horizontal Upper Cretaceous sediments of the Atlantic Coastal-Plain succession of Unit (2), the basal unit in the wedge of sediments that has been accumulating along the passive eastern margin of the North American continent for the last 170 million years or so. The area underlain by the Newark strata is shown on the geologic map of the Newark quadrangle (Lyttle and Epstein, 1987).

The name Newark, from Newark, New Jersey, is a venerable one in American stratigraphy; it was proposed by W. C. Redfield in 1856. Today, the term Newark has been accorded the status of a Supergroup (Cornet, 1977 ms.; Olsen, 1980c, Froelich and Olsen, 1985; Luttrell, 1989). The age range geologists have assigned to the Newark Supergroup has oscillated back and forth like a geological pendulum. During the 19th century, based on studies of their fossil fish, Redfield (1856, 1857), assigned them to the Jurassic. By contrast, the dinosaurs suggested Late Triassic. Given this situation, the Newark strata were referred to as the Jura-Trias (for instance, Darton, 1902 in the New York City Folio 83 of the U. S. Geological Survey).

Many geologists, however, took the Newark strata to be synonymous with Triassic (Cook, 1868, 1879, 1882, 1887, 1888, 1889). By contrast, Kümmel (1897, 1898, 1899a, 1899b) initially used only "Newark." When he became associated with the U. S. Geological Survey Folio projects, however, he used "Triassic" (Kümmel, 1914).

But geologists who were inclined toward tidiness in classification were uncomfortable with the notion that a well-behaved formation should span the boundary between two geologic periods. Accordingly, when Pirsson and Schuchert (in their Textbook of Geology published in 1915) proposed the name "Palisades Disturbance" for the episode of crustal unrest that was supposed to mark the end of the Triassic Period, they decided that all the Newark strata were of Late Triassic age. Thus, they started a line of thought that lasted for 60 years. In addition, they also started a tradition that might be expressed by the title of a modern book: "We learned it all in kindergarten." In our analogy, "we" is all geologists trained in the United States, "kindergarten" is the first-year course in geology, and "learned it all" refers to knowledge about the Newark strata. Based on the Pirsson-Schuchert scheme of things, Widmer (1964, p. 85) wrote: "There are no known Jurassic sediments in eastern North America."

Modern students (Cornet and Traverse, 1975; McDonald, 1975 ms., 1982, 1992; Cornet, 1977 ms.; Olsen, 1978, 1980a, 1980b, 1984 ms.; Olsen, McCune, and Thomson, 1982; Olsen and McCune, 1991; Fowell and Olsen, 1993) have re-established what the real old-timers knew all along: the age range of the Newark strata is Late Triassic and Early Jurassic. (For a general summary of the geologic literature on the Newark Group up to 1984, see Margolis, Robinson, and Schafer, 1986.)

The names of the formations of the Newark Supergroup (with thicknesses in the Watchung syncline) are (Olsen, 1980b):

Formation Name	**Thickness (m)**
Boonton (sedimentary strata; top eroded)	500+
Hook Mountain Basalt (two flow units)	110
Towaco Formation (sedimentary strata)	340
Preakness Basalt (2, poss. 3 flow units)	300
Feltville Formation (sedimentary strata)	170
Orange Mountain Basalt (at least 2 flow units, one of them pillowed)	150
Passaic Formation	6,000
Lockatong Formation	150
Stockton Formation	350
Total (Watchung syncline)	**8,070+**

Where the three well-known sheets of extrusive basalt (First-, Second-, and Third Watchung basalts; named by Paul Olsen, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a Newark-type reddish-brown sandstone, -siltstone, or -shale, or even a coarse conglomerate with reddish-brown sandstone matrix, the problem of assigning the correct formation verges on hopeless. Ultimately, some mineral- or lithologic criteria may prove to be helpful for stratigraphic assignment. As such, an important attribute of the Newark strata is the red-brown color of most of them. This color has left its imprint on most of the Pleistocene sediments.

On Staten Island, only the basal formation, the Stockton Arkose, and its overlying Lockatong Formation are present. The parts of the Stockton that are not red are light gray. They can be distinguished from the overlying gray Cretaceous sands by the large content (25 to 33% or more) of feldspar. The Lockatong is typically a dark gray, tough rock named argillite. Toward the SW, the thickness of these two formations is much greater than in the Watchung syncline. In the Delaware Valley, for example, the thickness of the Stockton is 1650 m and that of the Lockatong, 1200 m (McLaughlin, 1959, p. 85). The Lockatong Formation is the unit into which the tabular, generally concordant Palisades sheet has been intruded.

Paul Olsen (1986) has given the name Van Houten cycles to lake deposits made during a change from deep water to shallow water (or even no water) and back to deep water again. Such changes characterize lakes in closed drainage basins. The water-level fluctuations are controlled by climatic changes.

Studies of the cyclicity by Van Houten (1962, 1964) and Olsen (1984, 1986, and continuing from the Newark-basin cored borings) have indicated cycles having periods coinciding with the climatic cycles computed by Milankovitch based on variations in the Earth's orbital elements. The finding of such Milankovitch-type cycles in rocks as old as Late Triassic-Early Jurassic demonstrates that the computer-modelling gurus who claimed that the

Milankovitch periodicities break down within a few million years have got their mathematics all wrong.

Associated with the Newark sedimentary strata are sheets of mafic igneous rocks including both intrusives (the Palisades sheet) and extrusives (the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere).

A subject of recurrent interest among geologists has been about possible identity of times of extrusion and extrusion of the mafic materials of the Newark Basin. Initially, the Palisades sheet was viewed as a product of a single charge of magma. More recently, however, evidence has been found that this sheet is composite and formed as a result of several discrete injections of magma. The major questions have centered on whether the Palisades sheet was intruded at the same time as one or more of the extrusive basalts.

The Palisades Intrusive Sheet

The world-renowned mafic Palisades intrusive sheet is continuously exposed along the east edge of the Newark Basin from west of Haverstraw, New York southwestward to Staten Island, New York City where it passes beneath an intertidal salt marsh (Figure 17). The sheet continues southward, although with limited exposure, into New Jersey and Pennsylvania within the Delaware Subbasin. We discuss this sheet by first debating the use of the term sill for it. Then we take up its mode of intrusion and our new data on its paleoflow direction with possible feeder on Staten Island. Then follows contact relationshps, chilled-margin facies, discordant contacts, and clastic dikes. These raise the issue of the state of lithification of the sediments at time of intrusion and provide another way of estimating the depth of intrusion.

"To be or not to be (a sill)" - only your local geologists know for sure. Prior use of the word "sill" to describe the Palisades intrusive sheet implies that the contacts of this sheet are everywhere concordant with the bedding of the country rock. In many places such concordance prevails. But on an individual- outcrop basis and near its ends, discordance has been demonstrated (Merguerian and Sanders, 1995a, b).

We think that all the alongstrike diagrams that have been drawn in which show the Palisades sheet climbing from low in the Newark toward the top of the Newark, starting at Nyack, New York, do nothing more than display the prevailing ignorance of the effects on the Newark strata (including the Palisades sheet) of the transverse Danbury anticline (Sanders, 1960; Merguerian and Sanders, 1994a, b). JES (both privately and at cocktail parties) has always contended that the curvature of the Palisades sheet from Nyack to a point west of Haverstraw (near the Palisades Interstate Parkway) is not (repeat NOT) the result of a change from a concordant- to a discordant sheet and thus that it climbs in the stratigraphic succession from near the bottom to up near the top, but rather merely reflects the effects of the transverse Danbury anticline. The Newark strata have been folded, folks. And by not one but by two anticlines whose axes are disposed at right angles. Thus, the attitudes of the sedimentary strata swing around from a NNE strike and WNW dip (a result of being on the NW limb of the regional anticline whose axis trends NNE-SSW) to a NW strike and a SW dip (a result of being on the

SW limb of the regional Danbury anticline whose axis trends NW-SE). Only locally near its NW termination does the sheet become discordant; the amount of this discordance is not more than a few hundred meters. How this profoundly important point of regional structural geology can continue to elude otherwise-rational individuals is a complete mystery to us. Look on a regional map. Does the curvature of the outcrop belt of Palisades sheet differ significantly from those of the Watchung extrusives?

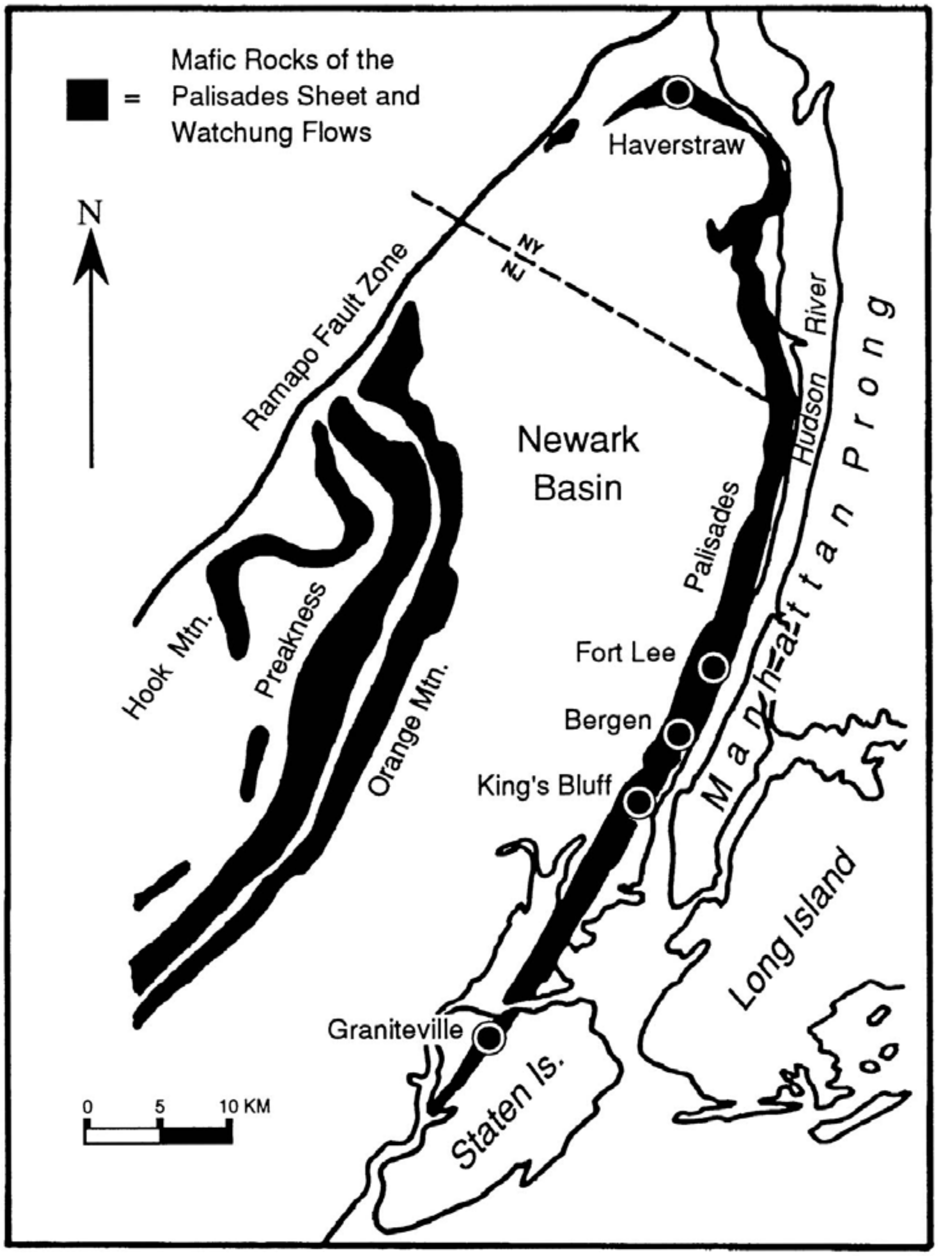


Figure 17. Index map showing the northern half of the Newark-Delaware Basin, the Palisades intrusive sheet, Watchung basalts, and place-names mentioned in the text. (After K. R. Walker, 1969, fig. 1, p. 6.)

Because this sheet of mafic igneous rocks is not concordant along its strike length (Figure 18), we have abandoned the formerly used term Palisades "sill." Rather, from Staten Island northward to Haverstraw, the sheet climbs discordantly upward through the strata from the Lockatong formation (New York City area) to the Passaic Formation (Haverstraw area). Extensions of the Palisades to the SW, (the Lambertville Sill and Rocky Hill intrusive of the Delaware Subbasin) mirror the climbing stratigraphic discordance displayed in the Newark Basin. (See Figure 18.) As such, the longitudinal profile of the Palisades indicates a lopolithic intrusive [following the definition of Grout (1918)]. However, at the NE end, post-intrusive deformation along the transverse Danbury anticline has created much of the hook-like map pattern (Merguerian and Sanders, 1994c, d; See Figure 17.)

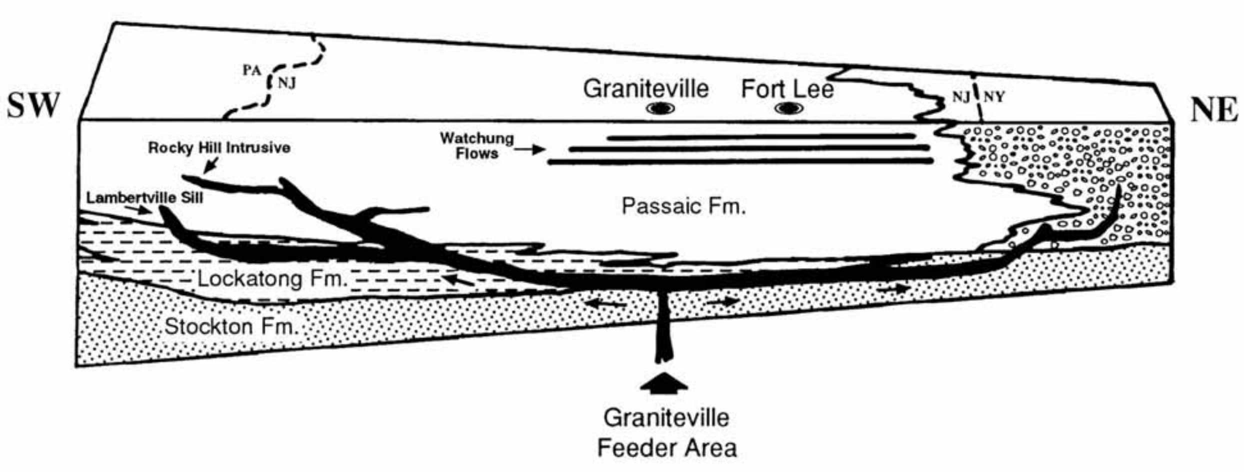


Figure 18. Block diagram showing SW- to NE-trending longitudinal profile (not to scale) of the Palisades intrusive sheet of the Newark Basin and its extension southward into the Delaware Subbasin showing, with arrows, our interpreted paleoflow patterns. Note the overall lopolithic form to the intrusive sheet as viewed in this orientation and the low stratigraphic position of the central part of the sheet including our conjectured feeder area at Graniteville, Staten Island. The positions of Fort Lee, NJ and Graniteville, NY are shown on the top (map view) of the block diagram. (After F. B. Van Houten, 1969, fig. 1, p. 315).

Mode of Intrusion

Historically, the Palisades has been viewed as a concordant sill-like body, the product of a single charge of magma that differentiated in situ by gravity settling [Darton (1889, 1890), Kümmel (1899a, b), Lewis (1908a, b), Walker (1940), Hess (1956), Lowe (1959), and Thompson (1959)]. More recently, however, evidence has mounted that the Palisades sheet is composite. It is inferred to have formed as a result of several injections of already differentiated magma [Walker (1969), Puffer, Geiger, and Camanno (1982), Shirley (1987), Puffer (1987, 1988), Husch (1990), Puffer, Husch, and Benimoff (1992)]. Today, the major unanswered questions center on the consanguinity of the intrusive pulses of the Palisades magma charges and their possible synchroneity with extrusion of one or more of the "Watchung" (Orange Mountain, Preakness, and Hook Mountain) basalt flows.

Our efforts have sidestepped this continuing inquiry into the possibilities of comagmatic ancestry. In search of a better understanding of the environmental conditions that prevailed during injection of the Palisades magma(s), we have focused on the basal contact relationships (Merguerian and Sanders, 1992, 1995b, 1995c). Thus far, these studies have placed constraints on the paleoflow direction of the magma and on the state of lithification of the bounding sediments, and have enabled us to estimate that the depth of intrusion of the Palisades magma(s) lay in the range of ~3 to 4 km.

Contact Relationships

The lower contact of the Palisades intrusive sheet with presumably in-situ sedimentary rocks of the Lockatong Formation is spectacularly exposed on the Palisades Interstate Park access road beneath the George Washington Bridge. The rocks at this locality have been studied by many geologists, including Van Houten (1969), Olsen (1980b), and Puffer (1987). The fact that the olivine zone lurks above the roadbed allows us to infer that most of the Lockatong here has not been detached although some Lockatong screens and xenoliths are present. Within the larger xenoliths, it is possible to see the cyclic successions of strata (Van Houten cycles) that are inferred to have been deposited as the ancient lake level fluctuated (Olsen, 1980a).

These sedimentary strata have been contact metamorphosed; the contact with the Palisades intrusive locally is discordant. Present also are folds as well as numerous nondeformed clastic "dikes", which crosscut the primary igneous-sedimentary contact. Contact-zone breccias include those with angular pieces of basalt in a "matrix" of light-colored feldspathic sand.

The columnar-jointed basal part of the Palisades intrusive in New Jersey is interrupted at the level where olivine has been concentrated. The olivine zone lies above a chilled zone of aphanitic- to glassy basalt (Figure 19). The sizes of the crystals in the igneous rock here change profoundly with distance above the contact. At the contact, the texture is aphanitic to glassy. With increasing distance from the contact, the texture becomes gradually coarser. As a result, many gradations and discrete mixtures can be found, from microvesiculated- to hypocrystalline basalt to aphanitic basalt (near the contact), to dolerite (a few meters above the contact), to gabbro (a few tens of meters above the contact). Local microvesicles in glassy basalt and a pipe amygdale in the base of the Palisades sheet, together imply that the mafic magma was chilled extremely rapidly and that Newarkian pore water, formerly present in the sediment, was transformed into a vapor phase, thus enabling the sediments to become fluidized.

The contact zone displays excellent products of contact metamorphism and disrupted Lockatong bedding. As noted previously by Van Houten (1969), the layers of original argillite have been converted into a black hornfels consisting of biotite and albite with minor analcime, diopside, and calcite, or to green hornfels consisting of diopside, grossularite, chlorite, and calcite, with subordinate biotite, feldspar, amphibole, and prehnite. Miller and Puffer (1972) and Puffer (1987) have noted pinite after cordierite and tourmaline as porphyroblasts in the hornfels. Our studies indicate that although contact metamorphism has changed them to a lesser degree than the argillites, near the contact, the sandy Lockatong interlayers, are chaotic. As described below, they have been "intruded" upward into the chilled zone where they form irregular "sedimentary apophyses" more than 20 cm long.

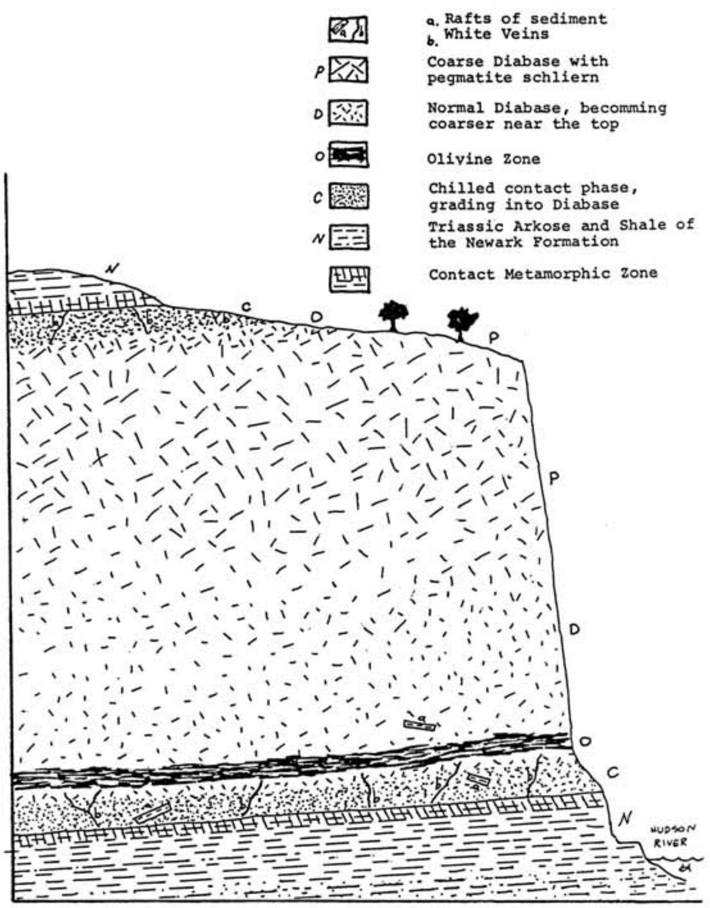


Figure 19. Schematic profile-section through Palisades intrusive sheet, New Jersey. (M. J. Sichko.)

Palisades Chilled-margin Facies; Aphanitic Basaltic Sills and Dikes

Two kinds of products that formed by rapid chilling in the contact zone are present; (1) the chilled border of the main sheet, and (2) aphanitic basalt as small dikes and sills that cut various units in the contact zone.

As mentioned, close above the basal chilled-margin contact of the Palisades intrusive in Fort Lee, olivine has been concentrated. The basal igneous rocks display gradations and mixtures among micro-vesiculated to hypocrystalline basalt to aphanitic basalt (near the contact) to dolerite (a few meters above the contact). The microvesicles and a 15-cm-long pipe amygdale extending upward from the Lockatong into glassy basalt imply that the mafic magma was chilled extremely rapidly and that Newarkian pore water, formerly present in the sediment, was transformed into a vapor phase, thus enabling the sediments to become fluidized.

Locally, the main sheet has been invaded from below by clastic dikes (discussed in a following section). In some places, clastic dikes have intruded across a minor offset (~1 cm) of a basalt-Lockatong contact but in this instance, the basalt is a 0.5-m sill found intruding the Lockatong. Although a rare feature, commingled within the zone of clastic dikes, a 40-cm-thick basaltic offshoot has been found to intrude a xenolith of partly fused Lockatong. We are not sure whether this offshoot, which can be traced back into the chilled zone, is a primary Palisades chilled-margin phase or the result of a younger Palisades intrusive phase. Thus, in the contact zone, late-stage basaltic dikes have crosscut some clastic dikes; therefore some igneous activity postdates the clastic dikes which themselves were mobilized by magmatic heat.

Discordant Contacts and Deformation

When one focuses on the contact patterns of the igneous- and sedimentary rocks (Figure 20), one cannot help being struck by the discordance exhibited by the top-to-the-north ramp-like contact. In almost every case [including exposures near Bergen [Central Park quadrangle; UTM Coordinates: 584.78E - 4516.75N] and at King's Bluff [Weehauken quadrangle; UTM Coordinates: 582.65E -4513.00N], the basal contact of the Palisades ramps upsection toward the NE. (See Figure 17.) The Palisades contact typically migrates gently upsection toward the N; it truncates the bedding in the bounding sedimentary rocks at low angles for distances of a few meters to tens of meters. At the northern end of a ramp, the igneous contact drops abruptly. It truncates the bedding at a high angle, thus creating a broad, saw-tooth contact pattern. Locally, at the leading edges of the Palisades northward-directed ramps, the Lockatong shows broad E-W-trending folds (Merguerian and Sanders, 1995a).

Figure 20. Outcrop view of the megascopic saw-tooth pattern produced by north-directed low-angle ramping of the basal contact of the Palisades intrusive sheet along its contact with sedimentary rocks of the Lockatong Formation in Fort Lee, New Jersey. Hammer handle is 40 cm in length and rests immediately below chilled Palisades basalt. (CM photograph).

The megascopic discordance of the ramp-like contact is obvious, as are localized folds in the bounding sedimentary strata. In one case, about 200 m north of the GWB, a chevron fold with a wavelength of 30 cm, lies immediately below a northward-ramped contact between the base of the Palisades and the Lockatong. The chevron fold plunges ~10° into N75°W with an axial surface oriented N75°W, 90°. After the regional-dip component of the Newark Supergroup has been removed, this structure reorients into a subhorizontally plunging fold. Argillites below the intrusive contact exhibit asymmetric intrafolial Z-folds plunging gently toward the west and with axial surfaces parallel to the intrusive contact, thus indicating top-to-the-right, NE-vergent shear. Elsewhere, folded NE-vergent xenoliths exhibit subhorizontal plunges and steep SW-dipping axial surfaces. The pronounced northward-ramping effect of the basal Palisades contact and the structural evidence together suggest that within the contact zone, top-to-the-northeast shearing prevailed. We can best explain the orientations- and vergences of folds and the discordant northward ramping of the basal Palisades contact by a ductile boundary response to subhorizontal intrusion of a cooling, perhaps gelatinous, high-density mafic magma whose paleoflow pattern was from the SW toward the NE.

Paleoflow Direction of the Palisades Magma

For the Newark Basin segment, many investigators have suggested that the Palisades magma flowed outward from buried fractures paralleling the NE-SW-trending Ramapo fault zone. To reach Fort Lee, New Jersey and vicinity, magma from such fractures would have to have flowed from NW to SE. In Fort Lee, beneath the George Washington Bridge, xenoliths, screens, and in-situ laminated lacustrine Lockatong sedimentary strata (black argillite and interlayered buff-colored feldspathic sandstone) have been contact metamorphosed and deformed. Here, the basal contact of the Palisades sheet cuts across the bedding in a ramp-like fashion toward the north. Similar contact relationships for the Palisades are exposed near Bergen and at King's Bluff, both farther south in New Jersey. (See Figure 17.) Folded xenoliths and folds of Lockatong sedimentary strata at the igneous contacts are products of subhorizontal shear. Their steep- to overturned axial surfaces trend E-W and are vertical or dip southward. Together, these marginal relationships suggest the general paleoflow of the magma was from SW to NE.

A Possible Feeder Area, Graniteville Quarry, Staten Island, New York

Examination of the orientations- and marginal relationships of xenoliths in the Palisades of New York and New Jersey has helped us identify a possible feeder area for the intrusive sheet. At Graniteville, Staten Island [Elizabeth quadrangle boundary; UTM coordinates: 571.60E - 4497.72N], a curved, partially fused, Lockatong xenolith is vertical and largely surrounded by concentrically oriented annular joints. Studies here by Benimoff and Sclar (1984, 1988), offer proof that a xenolith of the Lockatong Formation (formerly considered to be a small dike intruding the dolerite) was not only internally altered by the heat from the surrounding mafic magma, but that some of the Lockatong actually melted in situ to produce a trondhjemitic magma. We have suggested (Merguerian and Sanders, 1992, 1994b, 1995a, 1995b) that such intense melting may have been caused by a continuous heat source, perhaps emanating from an area of active magmatic flow. Furthermore, we have suggested that the annular joint pattern may mimic paleoisothermal cooling surfaces.

By contrast, most xenoliths reported from the New York City area dip gently and are oriented parallel to the contacts of the Palisades intrusive sheet. At Graniteville, a fused vertical xenolith and the annular cooling(?) joints imply that the magma here flowed upward and thus is close to a steeply inclined feeder channel. Geological relationships described above from Fort Lee, Bergen, and King's Bluff, New Jersey suggest that internal flow of the magma in those areas (See Figure 17.) was directed northeastward, perhaps away from Graniteville. If this is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from SW to NE. In support of this model we note that the Palisades intrusive is thickest and at its lowest stratigraphic position in the vicinity of New York City and that the body progressively thins as it migrates up section to the northeast (toward Haverstraw) and to the southwest (into the Delaware Subbasin). (See Figure 18.) Thus, our proposal for magmatic paleoflow toward the NE is consistent with evidence from the quarry at Graniteville, Staten Island.

"Sedimentary Apophyses" and Syn-intrusive Clastic Dikes

In Fort Lee, the Lockatong contains many sandy interbeds of light-colored feldspathic sandstones of typical "Stockton"-type lithology. Although the sandy layers have been less obviously affected by contact metamorphism than have the argillites, near the contact the sands are chaotic. They contain small, angular xenoliths of thermally altered argillite and have been locally "intruded" upward to crosscut baked Lockatong as wispy irregular "sedimentary apophyses" up to 20 cm long. Elsewhere, an irregular "stock-like" mass of feldspathic sediment more than 0.5 m thick, which encloses angular-, brecciated chunks of chilled basalt, exhibits several elongated drusy cavities that resemble miarolitic cavities of igneous rocks.

More commonly, thin light-colored clastic dikes with sharp contacts project into the Palisades chilled zone. We have found more than a dozen examples of the thin, continuous light-colored "dikes" of clastic sandy sedimentary material crosscutting the chilled contact rocks. In marked contrast to their parent sedimentary sources, they are totally nondeformed. Their thicknesses vary from 0.5 cm to a few cms, and their lengths, vary from a few cm to more than a meter. Bifurcating dikes have been observed. These field relationships suggest that the clastic dikes, consisting of formerly fluidized bodies of sand, were intruded upward after the marginal magma had experienced an initial phase of chilling during diminished magmatic flow. The drusy cavities, together with the basalt microvesicles and pipe amygdales noted earlier, support the view that the clastic-dike materials included a vapor phase. We surmise that the bounding sediments still contained pore water before the cooling Palisades magma heated them. Thus, we envision that the sandy injections and dikes represent tongues of hot, fluidized cohesionless sand that were driven by pore waters in the Lockatong and its sandy interlayers that had been vaporized by magmatic heat. In the following, we outline the field- and petrographic data on which our inference that the Palisades sheet was intruded at a shallow depth of burial is based.

Petrography of the Clastic Dikes

Microscopic study of thin sections of representative samples indicates that the light-colored dikes are composed of thermally altered detrital sediments consisting predominantly of subangular feldspathic sand-size particles. Use of the microscope discloses [Sample PAL-5] altered, contact-metamorphosed remnant clastic textures within the "clastic dikes" with subrounded K-feldspar, plagioclase, and quartz exhibiting pronounced monomineralic overgrowths. The feldspars are clouded and show dominantly granoblastic boundaries, which together with the overall felsic mineral components, may have convinced Walker (1969) to suggest that the light-colored dikes ["rheomorphic veins" of his usage] were of igneous origin. Microscopically, the feldspar particles are clastic; some contain subrounded cores and others preserve rounded boundary edges. As such, we suggest that the granoblastic textures are the result of contact-metamorphic- induced recrystallization. Additional detrital components in the clastic dikes include basalt fragments and other lithic fragments including argillite and chert(?).

Another thin section of a clastic dike [Sample PAL-2] shows that near the contact with basalt, sizes of detrital particles increase and also that elongate quartz, K-feldspar, plagioclase, and lithic fragments have been aligned parallel to the margin. In the interior of the dike, many well-rounded quartz- and relatively fresh feldpar particles are present. We interpret that the aligned fabric of elongate particles parallel to the dike margins resulted from a dynamic flow orientation similar to that found in clastic dikes in the sedimentary realm. At the dike contact, the basalt displays a bleached zone. We interpret the coarser texture at the dike contact with basalt as being the result of localized recrystallization and metasomatism; the chilled basalt margin may have still been hot.

Lithification State of the Bounding Sediments at Time of Intrusion

Our efforts, which have focused on the basal contact relationships of the Palisades intrusive, place constraints not only on the paleoflow direction of the magma but also upon the state of lithification of the bounding sediments when the magma appeard. Using evidence about the latter, we have made a new estimate (discussion below) on the depth of intrusion of the Palisades magma(s). In the following we focus on the field evidence that at the time of intrusion, the Newarkian sediments had not yet become lithified. We describe late syn-tectonic clastic dikes, and suggest an approximate depth of intrusion.

Cooling-depth Model

The presence of clastic dikes and vesiculated features in the base of the Palisades suggests that, in the vicinity of New York City, Palisades magma was intruded into Lockatong sediments that had not been buried deep enough so that they had become totally dewatering and lithified. Rather, we suspect that upon being heated by the magma in the chilled margin of the Palisades sheet, the water-bearing sediments became vapor-charged-, fluidized bodies of cohesionless sand. The fact that columnar joints penetrate the Palisades intrusive, the clastic dikes, and Lockatong xenoliths, indicates that the clastic dikes were injected quite early in the solidification history of the Palisades igneous rock.

An analogous situation, from a quarry in West Rock in New Haven, CT, in the Hartford Basin, was reported by Walton and O'Sullivan (1950). There, a layer of conglomeratic arkose produced a branching, irregular clastic dike exhibiting sharp contacts which was intruded upward more than 10 m into the dolerite sill. The dike consists of detrital material derived from the underlying conglomerate including several large pebbles, one of which was transported 0.6 m above the base of the sill. According to Walton and O'Sullivan, the clastic dikes were intruded at a temperature of roughly 400°C and a pressure of 0.4 Kb. We suggest similar conditions for our observed features and would argue, based on a simple stratigraphic calculation (below), that the depth of intrusion for the Palisades was in the range of 3 to 4 km.

As noted above, the Newark mafic igneous rocks include both intrusives (the Palisades mafic intrusive sheet) and extrusives (forming the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere). A recurrent subject of interest among igneous geologists has been proof of consanguinity between the Watchung extrusives and phases of the Palisades intrusive. The Palisades mafic sheet was intruded into the base of the Newark Supergroup during the Sinemurian age of the Early Jurassic (roughly 201 ñ1 Ma) according to recent U/Pb data on Palisades zircon and baddeleyite by Dunning and Hodych (1990). These data conform with Sutter's (1988) 40Ar/39Ar dating, which has yielded a 202.2 ñ1.3 Ma age for a fused xenolith of Stockton arkose within the Palisades.

An important point to be established about the Palisades intrusive is the timing of the intrusion relative to extrusion of one or more of the Watchung extrusive sheets. According to petrographic studies and modal calculations of Sichko (1970 ms.) and geochemical studies of Puffer (1988) and Husch (1990), a likely correlation is between the high-Ti magma that solidified to form the Palisades and the various lavas that cooled to form the multiple flows of the Orange Mountain Formation (First Watchung Basalt). Husch (1990) also correlated a low-Ti magma component of the Palisades with the upper low-Ti flow unit of the Preakness Formation (Second Watchung Basalt).

Based on their interpretation of the duration of deposition under the influence of climate cycles in the associated sedimentary strata, Olsen and Fedosh (1988) calculated that approximately 2.5 Ma elapsed between the time of extrusion of the Orange Mountain Formation and that of the Preakness Formation. This means that if igneous activity within the Palisades took place at the same time as that of the extrusion of these two ancient lava flows, then more than 2.5 Ma were available for the composite Palisades intrusive sheet to cool. The general absence of chilled zones within the main mass of the Palisades intrusive implies that all pulses of magmatic activity took place in a short time interval, before the mafic intrusive had cooled.

The synchroneity of intrusion of the Palisades with one or more of the Watchung flows also settles a further point, the depth of intrusion. Depth of intrusion then is the stratigraphic thickness of Newark strata between the base of the oldest Watchung flow and the base of the Palisades sheet. Using an outcrop-belt map distance of 18 km between the base of the Palisades and the base of the Orange Mountain Basalt and an average dip of 12.5°, the stratigraphic thickness would equate to [Sine 12.5° (0.2164) X 18 km = 3.89 km]. A 10°-dip assumption would decrease the estimate to 3.12 km. A 15°-dip assumption would increase the estimate to 4.65 km.

Tectonic History of the Newark Basin

The topic of formulating a geologic history of the Newark strata is colored by one's interpretation of the strata in the first place. Views on the postdepositional geologic history have ranged all the way from nothing of significance to a long and complex series of tectonic activities. (For a review of the intellectual history of the Newark rocks, see Merguerian and Sanders, 1989, 1991, 1993a, and 1993b.) Most modern geologists are concentrating on the relationships between the Newark strata and the basin in which they were deposited (Olsen, 1984 ms., 1988a, 1988b; Olsen, Froelich, Daniels, Smoot, and Gore, 1991; Olsen, Schlische, and Gore, 1989; Klitgord and Hutchinson, 1985; Manspeizer, 1988; Schlische and Olsen, 1988; 1990).

If one accepts the premise that the Newark strata were deposited in horizontal positions, then one needs to infer tectonic movement to explain the observed dips of the Newark strata. Some argue that the floor of the basin was being rotated toward the basin-marginal fault during deposition, so that by the time the uppermost strata were deposited as horizontal layers, the older layers had acquired their modern-day dips. Because of the relationships between strata and ancient lava flows, however, we prefer the position that most of the tilting took place after the strata had been deposited. (We have not been privileged to look at any continuous seismic profiles across the Newark Basin, so our position on this matter may be totally disproved by what such profiles disclose.)

No matter. It is clear that whatever happened to the Newark strata of Unit (3) took place prior to Late Cretaceous time, when the Upper Cretaceous coastal-plain strata of Unit (2) started to be deposited. At Sand Hill, NJ, in an outlier, Upper Cretaceous strata rest on the exposed edge of the Rocky Hill-Palisades sill, a relationship that gives a vague limit for the date of deformation of the Newark rocks (Widmer, 1964).

In the middle of the Jurassic Period, because of tectonic deformation that included folding and faulting (but not large-scale low-angle thrusting nor regional-scale metamorphism), strata ceased accumulating in the Newark basin. This Newark-basin-ending tectonic activity formed no mountain chain; thus, it has not been accorded the status of an "orogeny."

We think the geotectonic cycle that formed the Newark strata does not belong in the continental-margin category. We classify the Newark episode as being a kind of switchover setting between the preceding completed Appalachian continental-margin episode and the following Atlantic continental-margin episode, still in progress (Sanders, Friedman, and Sternbach, 1981; Merguerian and Sanders, 1994b).

After all the post-Newark elevation and great erosion, an erosion surface having low relief (= a peneplain) formed. The surface that formed early in the Cretaceous Period is the Fall Zone surface (Sharp, 1929b). Evidence from borings indicates that this surface, formerly horizontal, now dips SE about 80 feet per mile (Figure 21). Many water wells deep enough to reach the basement rocks have been drilled since Fuller's time (DeLaguna and Brashears, 1948; Suter, DeLaguna, and Perlmutter, 1949). In general, the newer maps show that relief on this surface is small. A possible exception is a deep valley that extends SW from New Haven

Harbor, Connecticut. The age of this valley has not been determined definitively; JES thinks that the most-likely possibility is pre-Cretaceous (Sanders, 1965, 1989 ms., 1994b). Flint (1963b) described upland remnants of the Fall Zone surface in Connecticut.

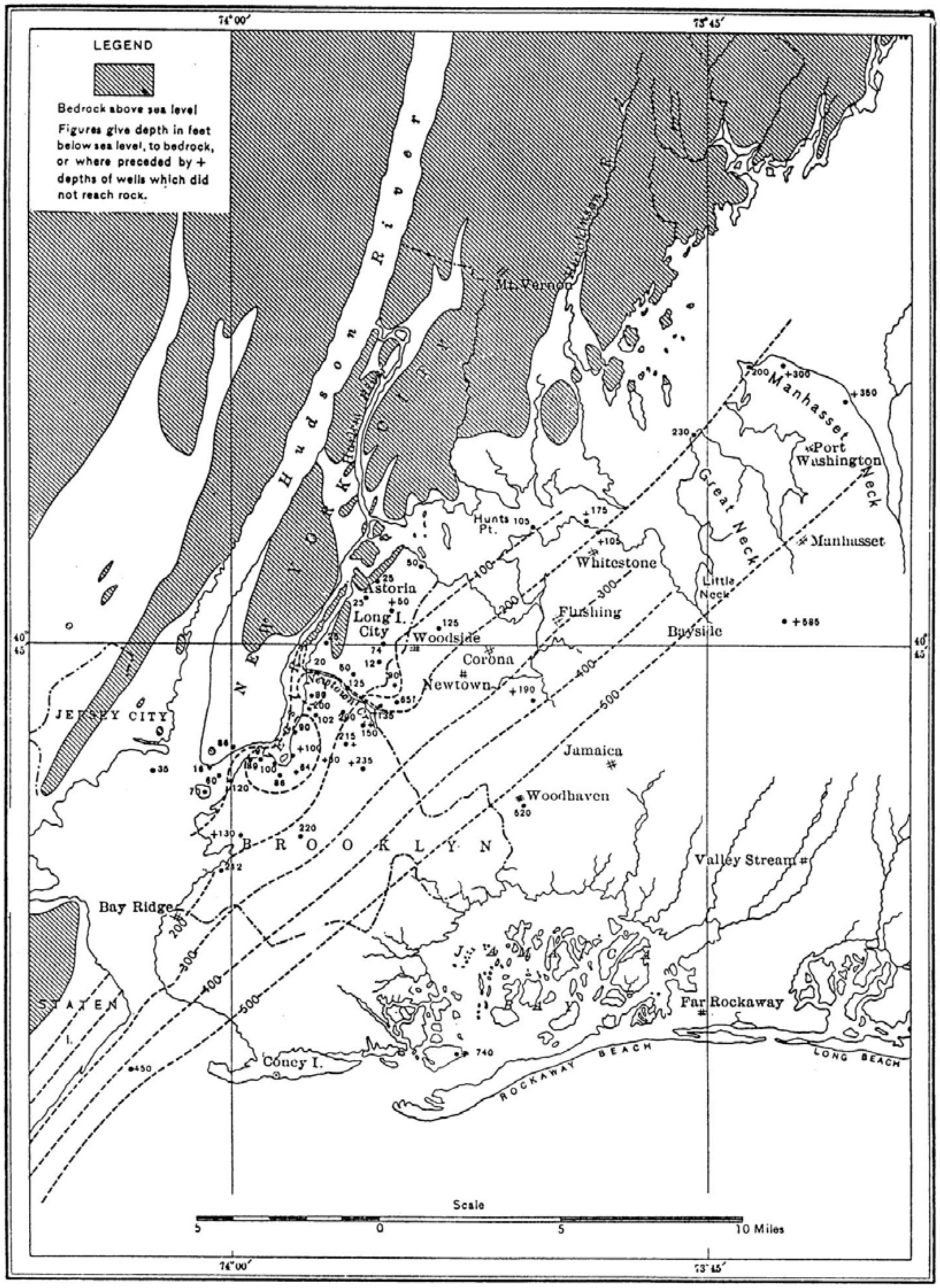


Figure 21. Map of NW Long Island showing contours on top of basement surface sloping 80 feet per mile to the SE. (A. C. Veatch, Pl. XV in M. L. Fuller, 1914, between p. 66 and 67.)

Unit (2): Atlantic Coastal-plain Strata

Unit (2) includes the coastal-plain strata that underlie Long Island, parts of Staten Island, and eastern New Jersey. In these localities can be seen the eroded edges of a vast body of sediment that thickens toward the ocean (Figure 22). This body of sedimentary strata is analogous to the one that accumulated during the passive-margin phase of the Appalachian geotectonic cycle of the Early Paleozoic. (See Figure 7.)

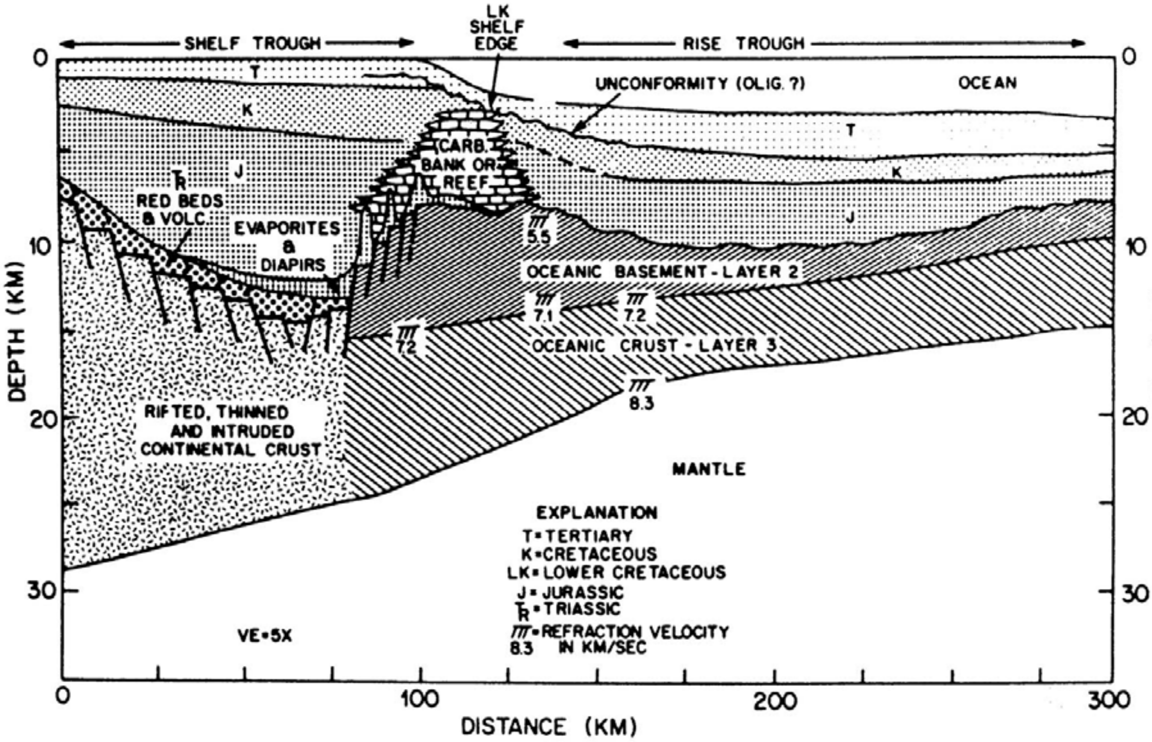


Figure 22. Diagrammatic profile-section across continental terrace off Cape May, New Jersey, based on U. S. Geological Survey miltichannel-seismic Line 06. (Robert E. Sheridan, 1981, fig. 5, p. 44.)

The coastal-plain strata are products of the Atlantic continental-margin geotectonic cycle that began at about 150 Ma. We are still in the passive-margin, sediment-accumulation stage of this cycle; thus we seem to be at about the half-way point.

Along the northern margin of the New York Bight, the Atlantic Ocean has overstepped the elevated- and truncated edge of the coastal-plain strata (Figure 23). Although the Upper Cretaceous strata are exposed in a few places on Long Island, for the most part, from New York Harbor to the E and NE, the top of the depositional terrace is submerged. This arrangement implies two tectonic events: (1) an earlier elevation of New England; and (2) a later subsidence, in some places greater in amount than the earlier elevation. During the first event, the elevation of New England changed the strike of the coastal-plain strata from N45°E (in eastern New

Jersey) to about N75°E (on Long Island), and thus formed the framework of the New York Bight. During the second event, the formerly elevated area subsided to enable the sea to overstep the eroded edges of the Upper Cretaceous strata. This subsidence is still going on. Our coasts are being submerged not because the sky is falling, but because the ground is sinking. This sinking is in the opposite sense and is overriding any isostatic rebound associated with the melting of the last Pleistocene glacier.

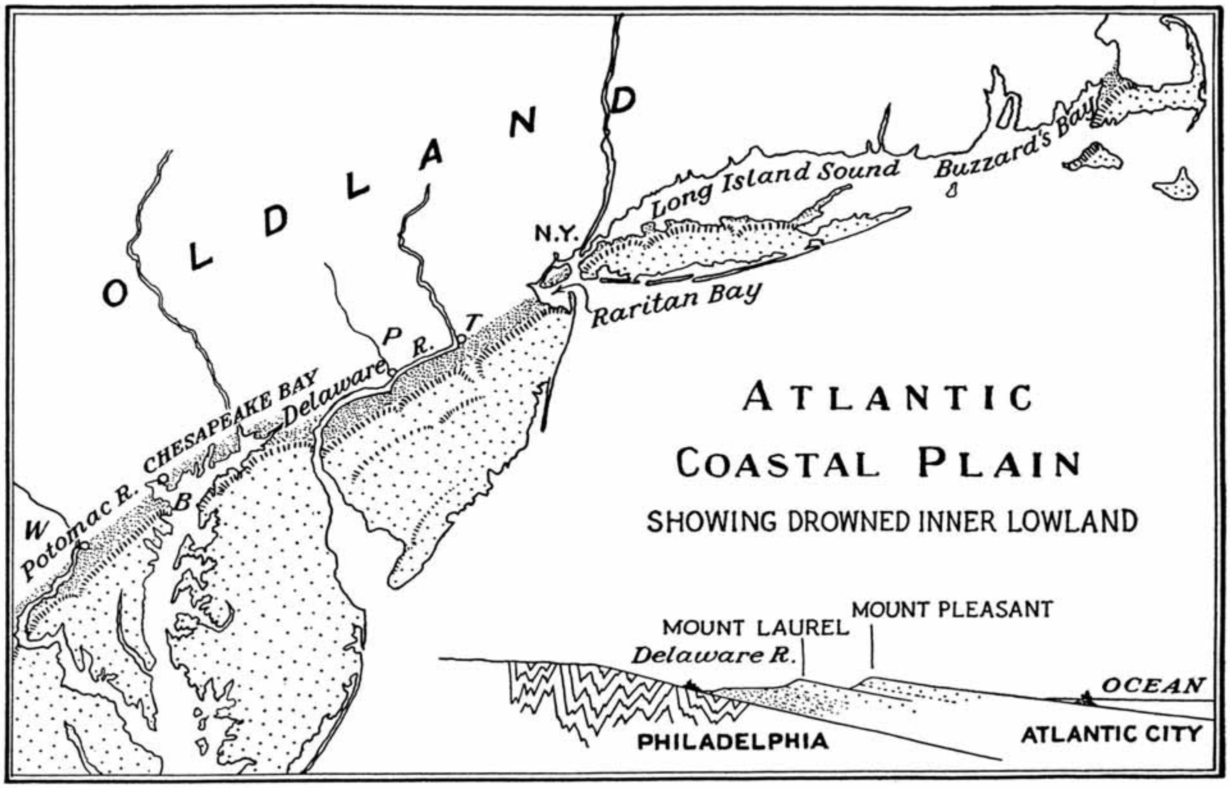


Figure 23. Diagrammatic map of part of Atlantic Coastal Plain (open stipple) from Washington, D. C. (W at lower L) to Cape Cod, Massachusetts showing how the inner lowland (close stipple) at the preserved edge of the coastal-plain strata has been submerged northeast of New York City (N.Y.). Inset schematic profile-section (large vertical exaggeration) extends SE from Philadelphia, PA (P) to Atlantic Ocean off Atlantic City, NJ (not shown on map). (A. K. Lobeck, 1939, p. 456.)

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

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

The coastal-plain strata belong to the large category of basin-margin sediment fillings whose interpretations have been revolutionized as a result of new concepts of seismic stratigraphy. These new concepts have grown out of detailed analyses of the new generation of continuous seismic-reflection- profile records collected from moving research ships. Instead of confining the analysis of the seismic records to evidence of buried geologic structures, the chief goal of seismic surveys and the only point of interest by most geophysicists, a group of geologists at the Exxon Research Laboratories in Houston, TX, under the leadership of Peter Vail, have shown how these new seismic records contain evidence of the profound influence exerted by changes of sea level on the sedimentary strata that accumulate at the margins of the oceanic basins. Analysis of data from passive continental margins collected worldwide has enabled Vail and his co-workers to compile a sea-level curve. The notion that the stratigraphic record exposed on the continents records numerous changes of sea level had been proposed early in the 20th century, by the American geologist A. W. Grabau among others and various European geologists such as the Termier's or Umbgrove. Subsequently, the pendulum of geologic fashion in interpreting strata swung in the opposite direction and the effects of sea-level changes were not much emphasized. But, now it's back to Grabau and then some, but with one difference: the new "young Turks" think that they invented (not re-invented) the great wheel. They do not mention Grabau (1936a, b; 1940), T. C. Chamberlin (1909), Charles Schuchert (1916), E. O. Ulrich (1911, 1913, 1916), or Stuart Weller , to name a few of the notable early American proponents of the interpretation that the continental stratigraphic record had accumulated in response to numerous, extensive changes of sea level. To be sure, the main emphasis of many of these early American studies was to use the gaps in the stratigraphic record as boundaries between systems, for example. In contrast, armed with the new regional look made possible by the seismic-profile records, the seismic stratigraphers are able to show how sea-level changes are expressed--not only in the areas where formerly the breaks resulting from an episode of emergence were emphasized but also in the basins, where deposition was continuous. The seismic expression of strata deposited at a high stand of the sea differs from that of strata deposited at a low stand. Therein lies the secret of success of the new interpretations.

Given such a powerful stimulus, nearly all stratigraphers are now reevaluating their data in terms of sea-level changes. An example is R. K. Olsson's (1988) use of benthic Foraminifera from the Upper Cretaceous in the coastal plain of New Jersey for making estimates of paleodepths of the Cretaceous sea. Combining the information from all sources, Olsson has prepared the stratigraphic chart of the formations of the New Jersey coastal plain (Figure 24).

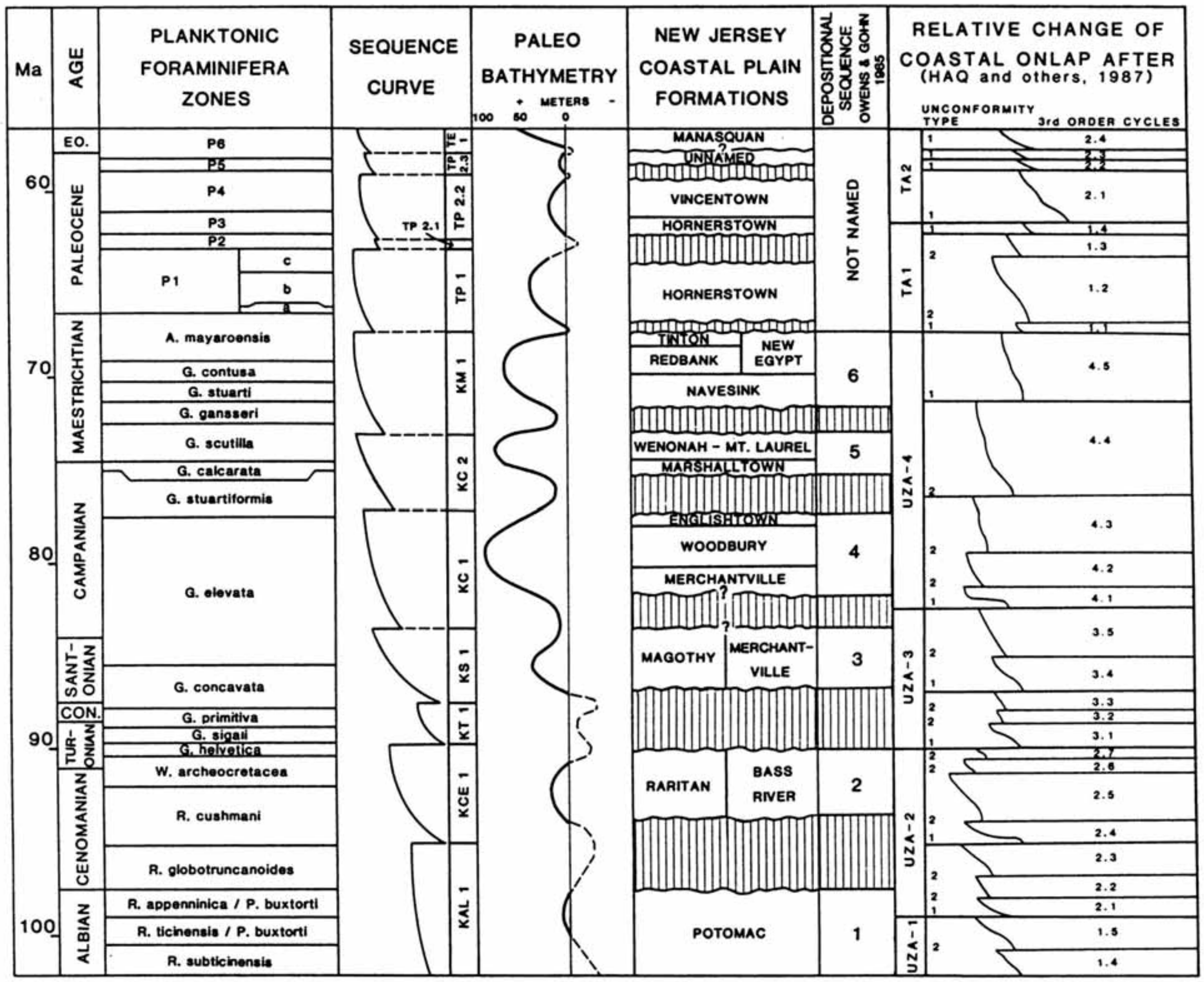


Figure 24. Chart of Upper Cretaceous formations of New Jersey Coastal Plain (column to right of center) showing inferred ages, zones based on planktonic foraminifera, newly recognized sequences (and sequence curve), paleobathymetry curve, and inferred sea-level curve based on coastal onlap inferred from continuous seismic-reflection profiles (right-hand column). (R. K. Olsson, 1988, fig. 7, p. 293.)

Near New York City, the local representative of the Upper Cretaceous is the Raritan Formation, which was named by G. H. Cook (1888):

"Raritan clays.--Include (descending): sand, clay, and lignite, 50 ft.; clay and sand, 40 ft; stoneware clay bed, 30 ft.; sand and clay 50 ft.; South Amboy fire-clay bed, 20 ft.; kaolin, 13 ft.; feldspar, 5 ft.; micaceous sand bed, 20 ft.; laminated clay and sand, 30 ft.; pipe clay, 15 ft.; Woodbridge fire-clay bed, 20 ft.; fire-sand bed, 15 ft.; Raritan fire-clay bed, 15 ft.; Raritan potter's clay bed, 25 ft. Underlies Clay Marls [Matawan group] and rests on Archean." [As thus defined Cook's Raritan clays are 347 ft. thick and include Magothy fm. of present nomenclature.]

From that beginning, various changes were proposed by Clark (1893, 1904); Kümmel (1911); Kümmel and Knapp (1904); and Berry (1906). Modern usage is contained in Owens, Minard, and Sohl (1969) and Owens and Sohl (1969). For up-to-date information, consult Olsson (1980, 1987, 1991).

The Upper Cretaceous coastal-plain strata are exposed in only a few places on Long Island (Figure 25). In some places, such as the Mannetto Hills (E of Hicksville, N of Farmingdale), the strata are in situ. In some of the northern coastal exposures (e.g. - Port Washington sand pits), ice-thrust deformation has involved the Cretaceous sediments.

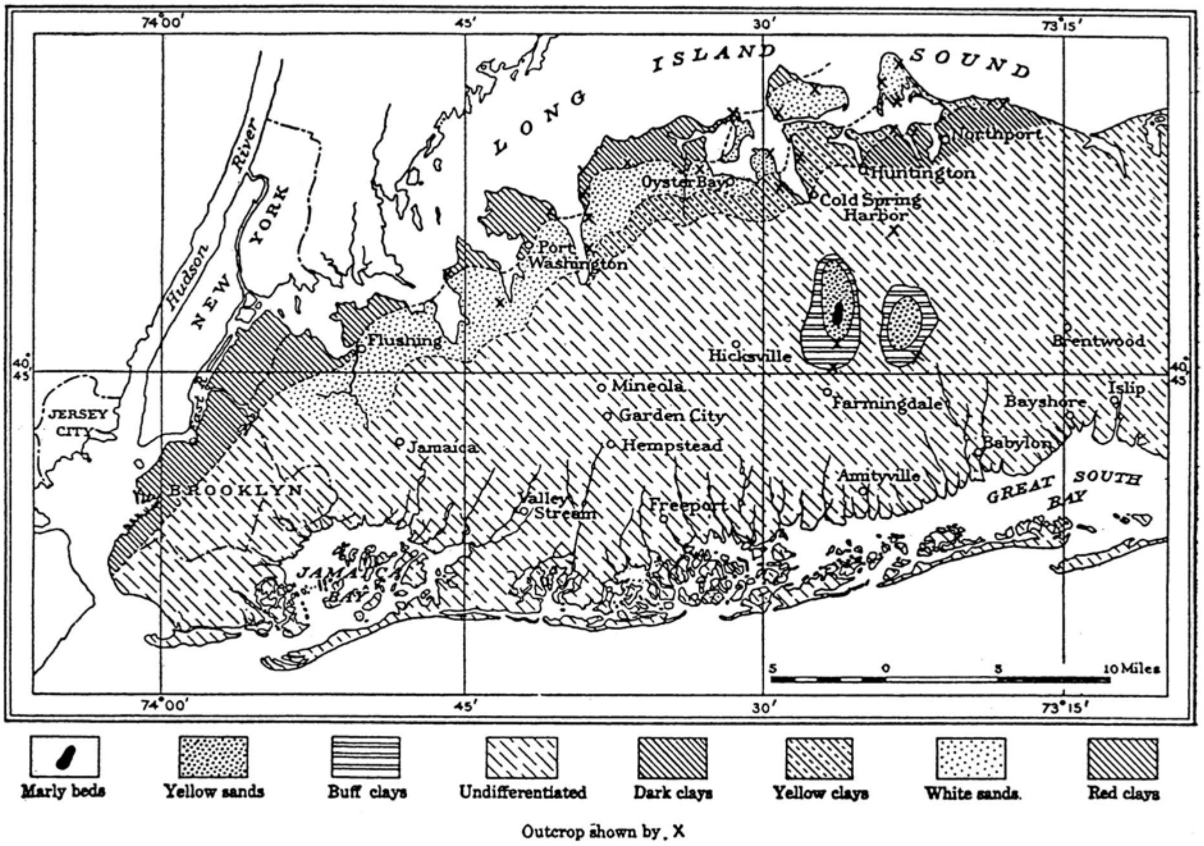


Figure 25. Map of western Long Island showing distribution of lithologic units in the Upper Cretaceous coastal-plain strata and locations of outcrops. (M. L. Fuller, 1914, fig. 56, p. 69.)

The coastal-plain strata beneath Long Island consist of a lower nonmarine part and an upper, marine part. The names of New Jersey formations have been applied on Long Island. Initially, only two New Jersey names were used: the Raritan, with basal Lloyd sand and overlying clay member, and Magothy(?) for the nonmarine units (Fuller, 1914; Suter, deLaguna, and Perlmutter, 1949; Perlmutter, Geraghty, and Upson, 1959). Later, the marine strata of the Monmouth Group were found in samples from a deep boring on Fire Island (Perlmutter and Todd, 1965). Based on a reexamination of the strata and a study of the pollen, Sirkin (1974) identified four New Jersey units, from base upward: Raritan, Magothy, Matawan, and Monmouth. Sirkin's correlation chart shows no sand in the Raritan Formation (in contrast to the basal sand earlier workers had assigned to the Lloyd). Sirkin identified with query a Lloyd Sand Member of the Magothy Formation (1974, p. 433; but see also Sirkin and Mills, 1975, p. 300, which includes the statement that:

"The main water bearing (sic) stratum, the Lloyd Sand, may include thick sands deposited during both Raritan and Magothy time and separated occasionally by thin clay lenses").

The recharge area for supplies of potable water (=ground water) within the Lloyd Sand (whatever is its correct formational assignment) is Long Island itself. No long-distance subsurface route exists, as it does, for example, at Atlantic City. (See inset profile in Figure 23.) At Atlantic City, deep wells tap ground water from a formation that is exposed at the land surface in the New Jersey pine barrens. By contrast, in New York state, as shown previously in Figure 4, the Cretaceous strata generally stop along the south edge of Long Island Sound. A few remnants are known out in the Sound (example: Stratford Shoal; see continuous seismic-reflection profiles of Tagg and Uchupi, 1967; Grim, Drake, and Heirtzler, 1970), and some Cretaceous strata may be preserved as the fillings of deep valleys (as in the West Haven valley found seismically by Sanders in 1965; see also Haeni and Sanders, 1974; and Sanders, 1989 ms., 1994b; and for eastern Long Island Sound, Lewis and Needell, 1987).

The deep wells that supply water to Jones Beach and Robert Moses State Parks (stored in the tall towers in the traffic circles at each park) tap the Lloyd Sand. Immediately beneath the Pleistocene formations in the park wells are Upper Cretaceous marine formations (Perlmutter and Todd, 1965). No Tertiary formations are present (as was incorrectly shown on the original version of the Raisz block diagram [See Figure 2.], but we have changed the label to show the correct relationships).

The Cretaceous of the north-shore cliffs has been described as consisting of:

"...tan (sic) and orange colored (sic) sand, red (sic) and gray clay, white sand and gravel with a clay binder, and occasional lenses of lignite (sic). There are also abundant concretions, ranging from iron-oxide nodules surrounding lignite (sic) or plant debris, pipes and paint pots of probable ground water (sic) origin, and marcasite (sic) and pyrite nodules" (Sirkin and Mills, 1975, p. 300). [Note: In our experience, much of what has been referred to in the geologic literature written about the Cretaceous strata as lignite is not true lignite, which is brown, but rather black charcoal.]

The episode of coastal-plain sediment accumulation that began late in the Cretaceous Period (~95 Ma) continued until the Miocene Epoch (~25 Ma). From the record in New Jersey, we can infer that a series of fans built southeastward from the rising Appalachians. These fans pushed the shoreline southeastward and ended the episode of accumulation of marine sediments in what is now New Jersey. (However, marine sediments continued to accumulate in areas now submerged.) In the Pliocene Epoch (starting about 6 Ma), regional uplift, possibly combined with the first of many episodes of eustatic lowering of sea level, enabled deep valleys to be eroded. One such valley, named a strike valley because it is parallel to the strike of the gently tilted coastal-plain strata, formed along the eroded updip edge of the preserved Cretaceous strata. (This feature has also been named the inner-cuesta lowland.) The depression that has been filled with sea water and forms Long Island Sound began its career as such a stream-eroded strike-valley lowland.

Other deep valleys that trend across the strike of the gently dipping coastal-plain strata have been incised into the top of the Cretaceous. Some of these have been completely filled with sediments so that they lack topographic expression on the modern land surface.

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

REGOLITH: UNIT (1): THE GLACIAL SEDIMENTS

Overlying all the foregoing units is a discontinous blanket of materials that is collectively designated as "regolith." (Regolith is something one can dig with a shovel as contrasted with pounding on the bedrock with a hammer). Regolith is an "umbrella" term that covers many contrasting kinds of materials; most engineers apply the term "soil" as a synonym of the geologists' term regolith. Some regolith, such as soils (in the agricultural sense) are residual deposits that formed by extensive chemical alteration of the underlying bedrock. Much regolith has been transported and may or may not have been derived from the underlying bedrock. Hereabouts, most of the regolith rests on a fresh bedrock surface that has been smoothed, rounded, polished, and in some cases, scored with remarkable sets of linear, parallel grooves and striae (Figure 26).

Although at least 1500 mi separates New York City from the nearest modern glacier, in many parts of the city, the telltale signs left behind by former glaciers are present. Studies of modern glaciers and the effects of glaciers flowing over a particular region began in Switzerland. In the decade 1786-1796, Horace-Benedict de Saussure [1740-1799] published detailed accounts about the geologic work of alpine glaciers in Switzerland that presented geologists who had never seen a glacier with an clear understanding of what glaciers can do to a bedrock surface over which they flow, of their great long-distance block/boulder-transporting power, and of the distinctive ridges of bouldery morainal debris heaped up at the glacier's terminus. The lessons of de Saussure were appreciated by many readers of his books. Among these were James Hutton in Scotland (Playfair, 1802, section 349) and Sir Charles Lyell (who adopted a glacial origin for the landforms known as moraines in Scotland, but held to the concept of a marine origin for the "drift" deposits elsewhere in the British Isles) (Flint, 1947, p. 4). Others who wrote about the geologic work of glaciers prior to 1840 were K□hn (1787; 1808) and Hugi (1828, 1831).

Based on these classic studies, geologists are able to use characteristic glacial features to speak confidently of past glaciers and to reconstruct the directions of flow and former extents of long-gone glaciers. We present the evidence geologists use to infer the former presence of a continental glacier where no such glacier exists today; we emphasize the features that can be used to reconstruct the flow direction.

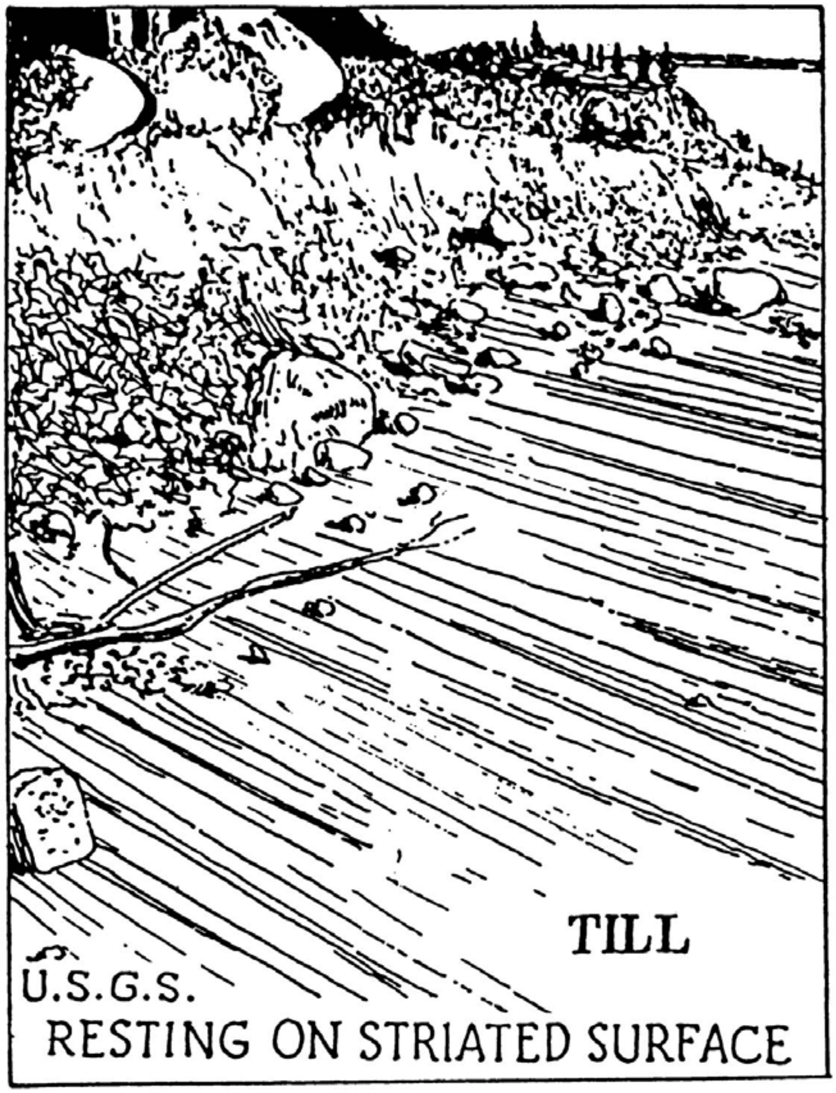


Figure 26. Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

Kinds of Features Glaciers Erode on Bedrock That Can Be Used For Inferring Ice-flow Direction(s)

Features that a glacier erodes on the bedrock that can be used to infer ice-flow direction include striae and grooves, crescentic marks, long axes of roche moutonnées and "roche-moutonnée structures" and long axes of rock drumlins. We describe each of these briefly and show their value in reconstructing ancient ice-flow directions.

Striae and Grooves

Glaciers are one of the few geologic agents known to create extensive sets of parallel scratches and even large parallel grooves on solid bedrock. (See Figure 26.) The ice flowed along the trend of the linear elongate features.

Crescentic Marks

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable, Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 27).

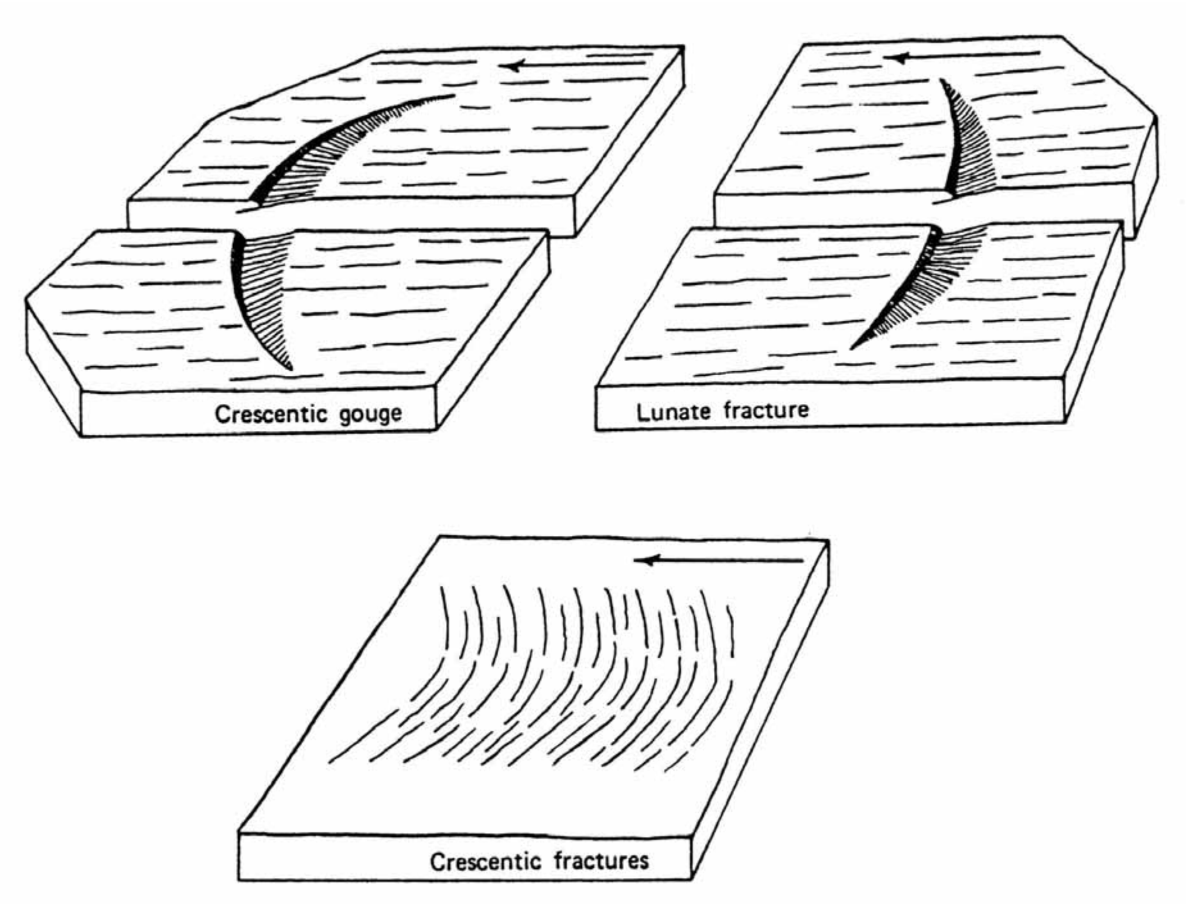


Figure 27. Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Orientations of Long Axes of Roche Moutonnées and "Roche-moutonnée," Structures

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roche moutonnées (Figure 28). These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow); but jagged, irregular, and steep on the side toward which the ice flowed (a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction).

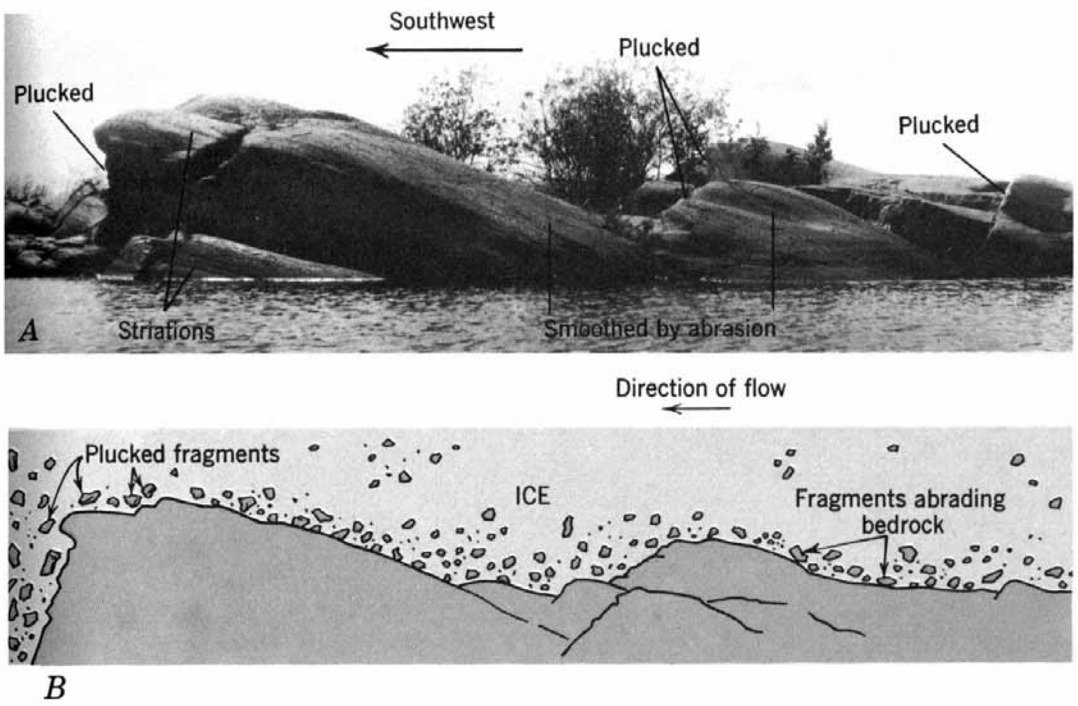


Figure 28. Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, we have found many features displaying only part of the morphologic expression of a classic roche moutonnée. The rounded, gently dipping part is present, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by one glacier has been modified by flow across and over it of a glacier flowing from a direction that differs by about 45° from the direction of the first glacier.

In our studies of ice-flow directions we have made use of the orientation of the median axis of the elongate, rounded up-ice side of a classic roche moutonnée (Figure 29). We have been using the informal term "roche-moutonnée structure" for these.

Figure 29. Sketch showing roche-moutonnée structure (above) and three-dimensional views of roche moutonnées (below). Arrow indicates direction of ice movement. (Lobeck, 1939, part of figure on p. 298.)

Orientations of Long Axes of Rock Drumlins

Drumlins are elongate streamlined hills shaped by the flow of a glacier; the long axis of a drumlin is parallel to the flow direction of the ice and the steeper side is toward the direction from which the ice came. Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consistis of both till and of bedrock. Rock drumlins consist only of bedrock. Because most drumlins consist of till, we discuss them in a following section devoted to glacial sediments. In this section, we include only rock drumlins. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée, or vice versa.) Fort Tryon Park is built on a prominent rock drumlin that was formed by a glacier flowing from NNE to SSW but was later modified by ice flowing from NW to SE (Figure 30).

Flow-directional Aspects of Glacial Sediments

Glacial sediments contain several flow-directional aspects such as composition (including erratic boulders) and asymmetric flow features such as drumlins and ice-push structures.

Composition

The composition of glacial sediments is determined by the kind of bedrock over which the ice flowed. This aspect of glacial sediments is generally known as provenance; it includes everything from erratic boulders to the color of the till.

Glacial Erratics and Indicator Stones

Erratic boulders, that is, any boulder consisting of a kind of rock that differs from the bedrock on beneath it, were one of the first attributes noticed. They provide convincing evidence of glacial action. If the parent bedrock source of an erratic is known, then it becomes an indicator stone.

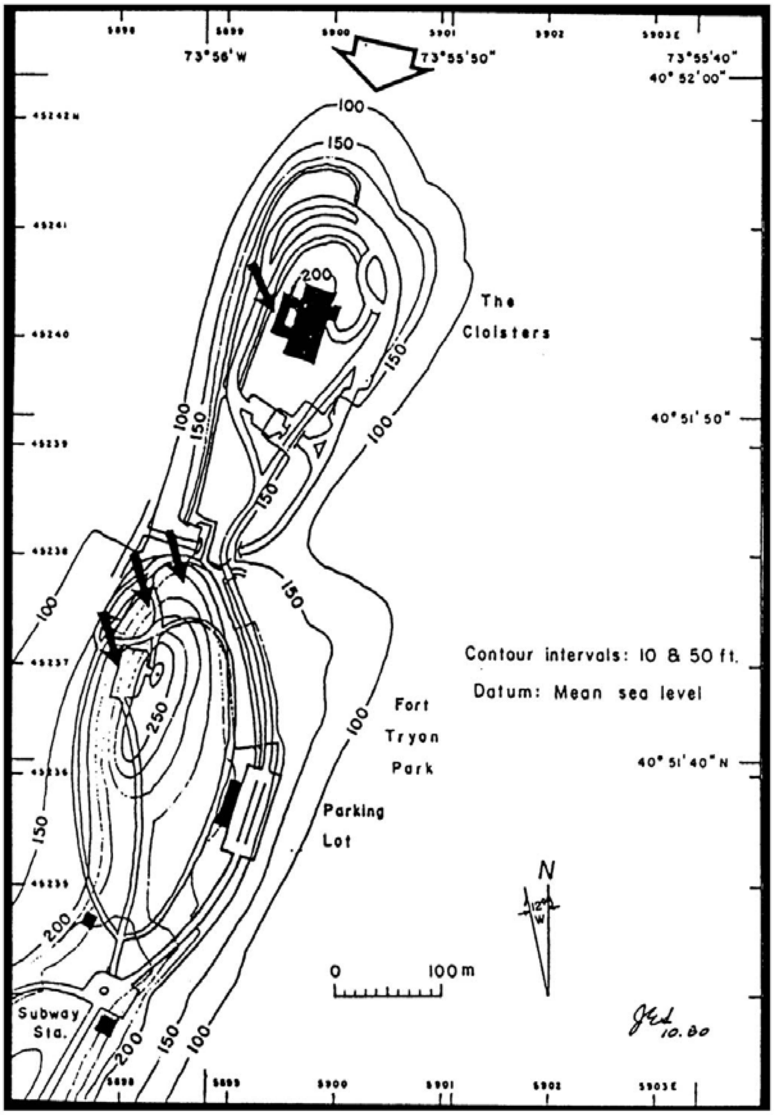


Figure 30. Enlarged topographic map of the Cloister area, Fort Tryon Park showing the two rock drumlins oriented NNE-SSW. (Enlarged and redrafted from USGS Central Park 7.5-minute quadrangle by J. E. Sanders.)

Color of the Till

Because of the pattern of distribution of the preserved remnants of reddish-brown sediments that filled the Newark and Hartford basins (Figure 31), color of till and outwash can be a useful indicator of ice-flow direction. For example, in New York City, ice that flowed in a direction that is down the Hudson Valley (from NNE to SSW) did not encounter any Newark basin-filling strata. Accordingly, the color of till deposited by these glaciers is gray or yellowish brown. By contrast, ice that flowed in a direction that is across the Hudson Valley (from NNW to SSE) did encounter Newark basin-filling strata and thus acquired a distinctive reddish-brown color.

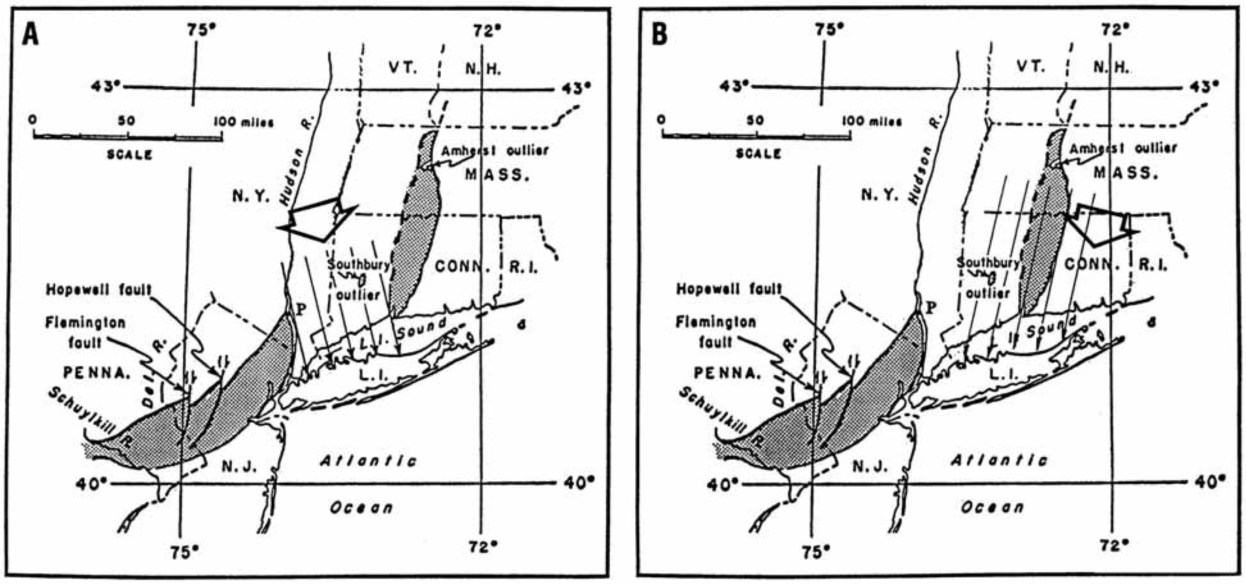


Figure 31. Regional map of part of northeastern United States showing locations of preserved filling strata of Newark Basin (NJ and PA) and of Hartford Basin (CT and MA) (light gray tone). Parallel line segments show how glacial ice flowing from each of the observed dominant directions distributes diagnostic erratics. (Base map from J. E. Sanders, 1963, fig. 7, p. 513.)

A. Flow from NNW to SSE, across the "crystalline corridor" between the fillings of these two basins, deposits reddish-brown erratics in extreme W and extreme E Long Island, but throughout a substantial stretch along the N shore of Long Island, did not deposit any reddish-brown Newark-type erratics. The distribution of erratics in the Harbor Hill Moraine and in the Ronkonkoma Moraine matches that associated with glacial flow from NNW to SSE.

B. Flow from NNE to SSW, as in the Woodfordian glacier, distributes reddish-brown erratics from the Hartford basin in CT and MA to the WSW. The absence of such erratics in the Woodfordian glacier's SSW downflow path along the N shore of Long Island suggests that the Woodfordian glacier did not reach much of Long Island and therefore did not deposit Long Island's two famous terminal-moraine ridges.

Asymmetric Flow Features

Drumlins

The long axes of the elongate, streamlined, asymmetric hills composed of till that are drumlins are parallel to the direction of flow of the glacier and the steeper side faces the direction from which the ice came. In this respect, the asymmetry of a drumlin is just the opposite of that displayed by a roche moutonnée, or a roche-moutonnée structure.

Ice-push Structures

Includes recumbent folds and other glaciotectonic features such as thrust ramps. Tectonic analysis of the structural features usually enables a general sense of ice flow to be inferred. In some cases, one might also find soft-sediment "slickensides".

Near the navigation tower along the shores of Princes Bay, Staten Island (Arthur Kill quadrangle; UTM grid coordinates 566.70E, 4484.20N), roughly 1.5 km WSW of Seguine Point, is a coastal cliff in the Harbor Hill Moraine. Erosion of this cliff has exposed yellowish-weathering-, gray-, and brownish Cretaceous sediments that are enclosed within reddish-brown Pleistocene deposits. The Cretaceous strata here have been studied by many geologists; these strata are generally presumed to be in situ (Schuberth, 1968).

The inference that the Cretaceous strata are not in situ is based on finding Pleistocene-type sediments (tills and outwash sands) beneath the Cretaceous, both in the coastal cliff and in borings made for the sewer line beneath Hylan Boulevard. The Cretaceous strata in the coastal cliff clearly are not in situ but have been subjected to ice-thrust deformation that has formed a recumbent fold (Figure 32). The orientation of the recumbent fold here implies that the glacier responsible for the deformation and associated Harbor Hill Moraine flowed from NNW to SSE (Sanders, Merguerian and Okulewicz, 1995a, b).

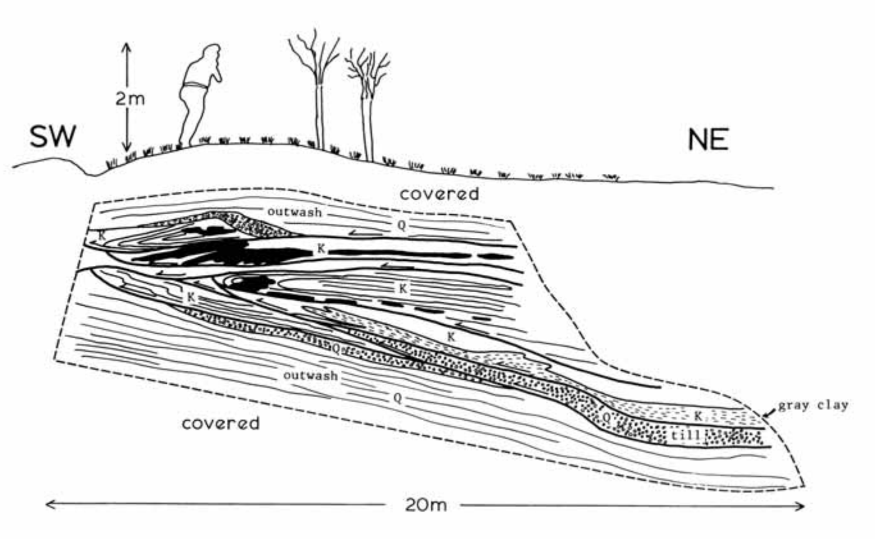


Figure 32. Examples of ice-thrust tectonics exposed in the eroding cliff by light tower on shore of Princes Bay, Staten Island. The cliff section includes numerous low-angle "thrusts" and a major recumbent fold with a sheared out lower limb. This fold plunges roughly 17° into S60°W; its axial surface is oriented N4°E, 20°NW. Within- and below the Cretaceous sequence are at least seven low-angle imbricate ice-thrust surfaces. The hematite-cemented ironstone layer has been brecciated in situ and possibly has been duplicated along a thrust. Thus, the Upper Cretaceous here has been thrust against itself and also above younger, deformed, red-brown Pleistocene sediments (also involved in thrusting). K = Cretaceous, Q = Pleistocene. Black = Cretaceous ironstones. Drafted by CM from field sketches and photographs as datum, no V.E. (Sanders, Merguerian, and Okulewicz, 1995, fig. 5, p. 112.)

Many examples are known from Long Island and Gardiners Island (Fuller, 1914). Glacial "thrusts" are well exposed in the former sand pits at Port Washington (Mills and Wells, 1974).

MORPHOLOGY OF EARTH'S SURFACE; TALE OF OUR TWO STRIKE VALLEYS

The three major bedrock units just mentioned all come together on Staten Island (Figure 33). Elsewhere, their relationships to one another can be expressed as a tale not of two cities but rather a "Tale of Two Strike Valleys." A strike valley is an elongate lowland that forms after initially horizontal strata of varying resistance to erosion have been tilted and eroded. The lowland forms where weak rocks are worn down between adjacent more-resistant rocks. Two of our prominent water bodies, the Hudson River and Long Island Sound, follow special kinds of strike valleys that we shall call basal strike valleys because they form along the geologic boundary where the base of one unit rests on older rocks.

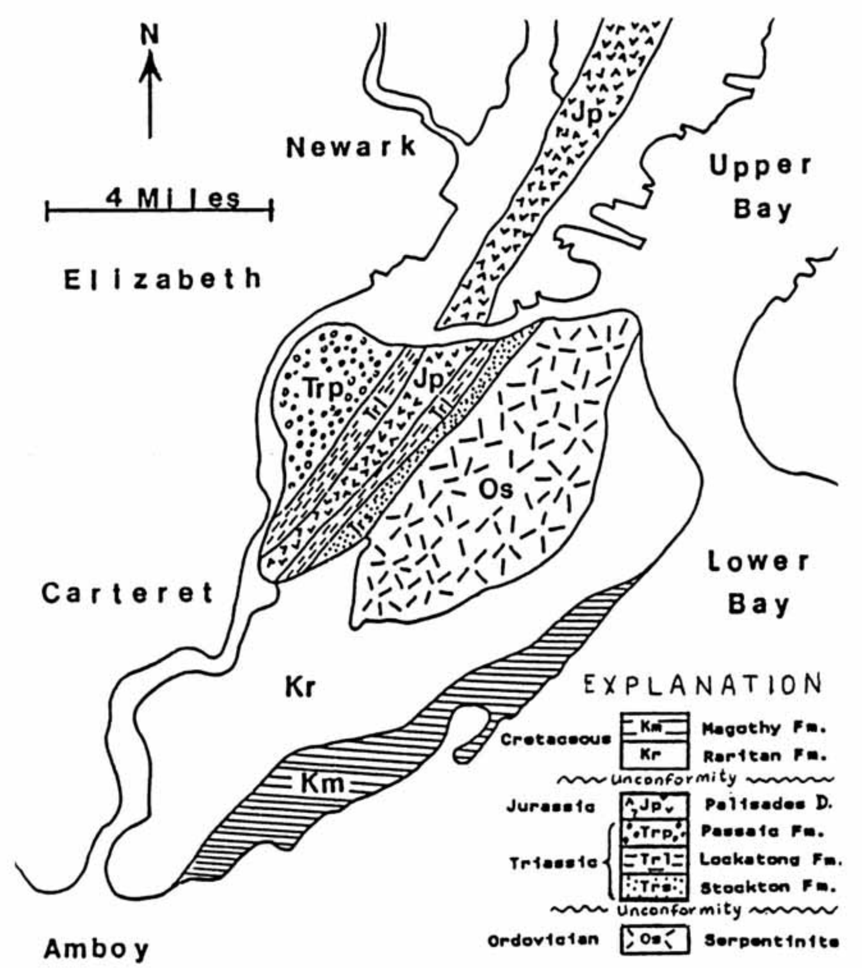


Figure 33. Geologic map of Staten Island, with extension of Palisades Intrusive Sheet northeastward onto mainland. (After Okulewicz, 1988, from Lyttle and Epstein, 1987.)

Basal-Newark Strike Valley: Hudson River (Haverstraw-Hoboken)

From Hoboken, NJ to Haverstraw, NY, the Hudson River flows along the boundary between the Newark basin-filling strata and Palisades sheet of igneous rock of bedrock Unit (3) on the WNW and the "basement complex" of bedrock Unit (4) that underlies Manhattan, The Bronx, and Westchester County on the ESE (Figure 34). Opposite Hoboken, the river makes a sharp bend to its L (viewed looking downstream) and flows out of the basal-Newark strike valley (in a N-S-trending reach that leads to The Narrows; See Figure 1 [cover], 2 and 6). Borings indicate that this basal-Newark strike valley continues to the SW but has been completely filled with sediments. On Staten Island, this valley extends beneath the Upper Cretaceous coastal-plain strata (Figure 35).

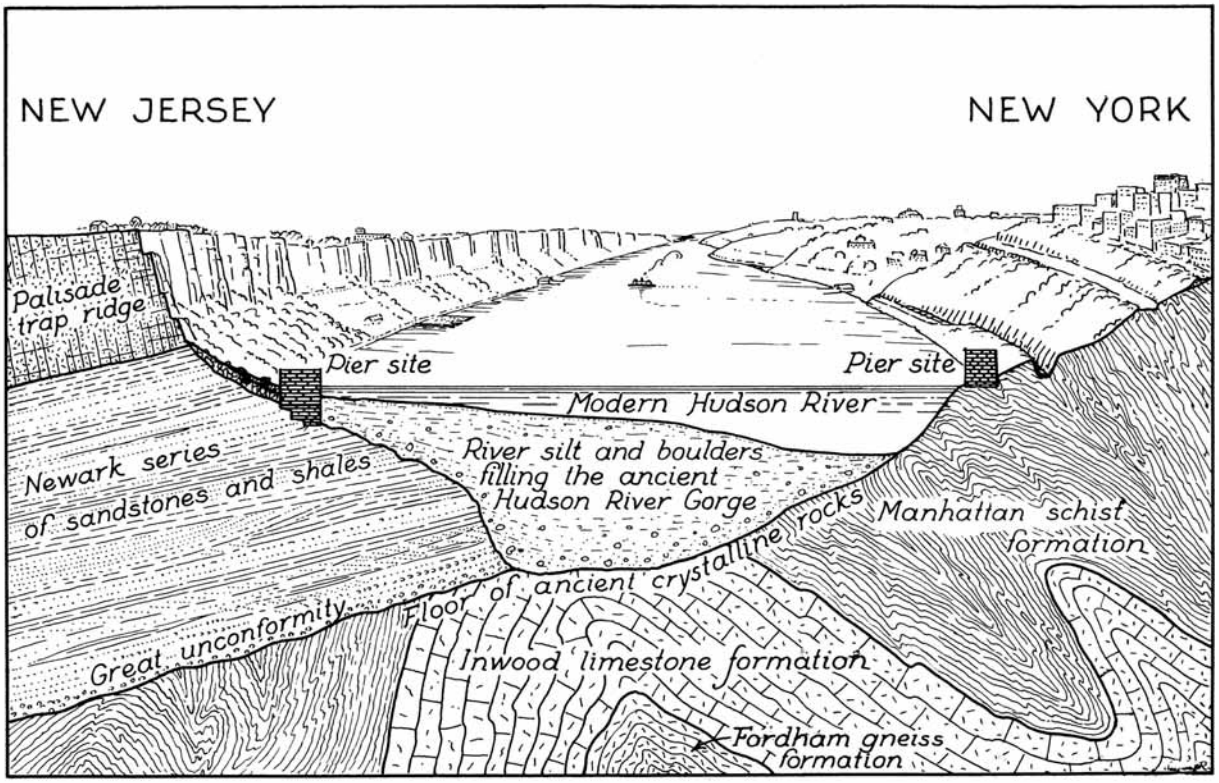


Figure 34. Interpretive geologic section across the Hudson River in the vicinity of the George Washington Bridge. (Berkey, 1948.)

Basal-Coastal-Plain Strike Valley: Long Island Sound

Similarly, but with less topographic relief and lacking the striking Palisades sheet of igneous rock, Long Island Sound (See Figure 2.) follows the boundary where the coastal-plain strata of bedrock Unit (2) overlap the rocks of the "basement complex" of bedrock Unit (4).

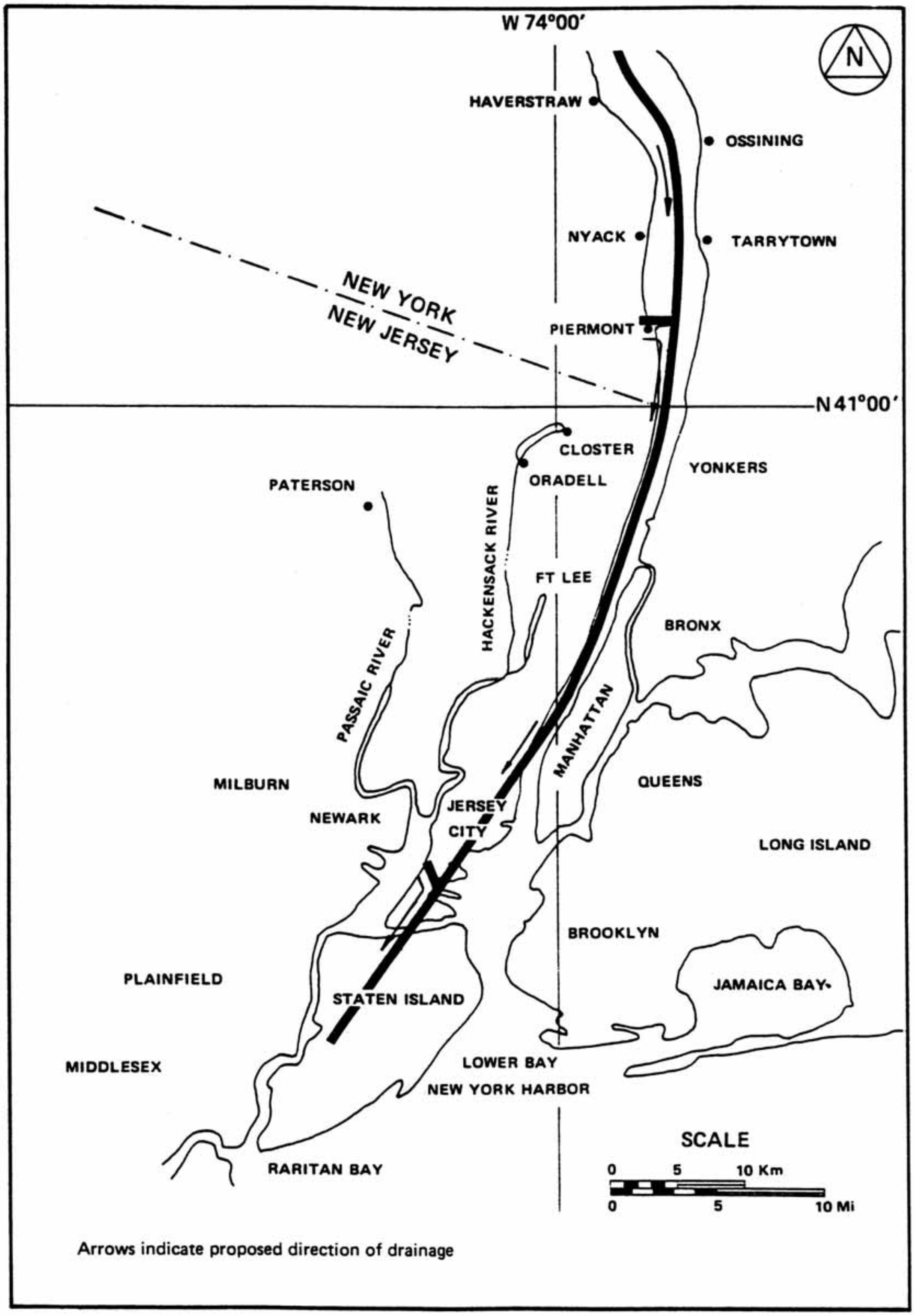


Figure 35. Strike valley at base of Newark Supergroup as inferred during the late Cretaceous, after tilting and erosion of Newark strata but prior to submergence and deposition of coastal-plain strata. (J. R. Lovegreen, 1974 ms., fig. 19, p. 148.)

HOW MANY PLEISTOCENE GLACIATIONS AFFECTED NEW YORK CITY?

Although all geologists agree that New York City and vicinity have been glaciated, they do not agree on the interpretation of the local Pleistocene record with regard to number of glaciations represented. Previously published interpretations about the number of the Pleistocene continental glaciers that visited the New York City region have vacillated between one and four; we think the correct number should be five (as outlined below and in Table 3).

The first geologists who considered this question could not agree, some saying more than one, but they were pushed into the background by the loudest- and most-prestigious one-glacier voice, that of Professor T. C. Chamberlin [1843-1928] from the University of Chicago.

The next phase of investigations of the local Pleistocene deposits included detailed mapping. The two chief local mappers both demonstrated that the deposits of more than one glaciation are present on Long Island. Based on his monographic study of the geology of Long Island, published in 1914 by the U. S. Geological Survey, Myron L. Fuller made a case for a four-glacier interpretation.

Starting in the mid-1930's revisionist-minded "Friends of the Pleistocene," who evidently never read Woodworth's (1901) New York State Museum Bulletin and cavalierly cast aside Fuller's four-glacier classification, adopted that "old-time religion," namely a belief that nearly all of our glacial features had been made during the latest glacial episode, the "Wisconsinan."

Until recently, nearly all contemporary specialists in Pleistocene geology have followed this revisionist viewpoint that one glacier--the "Wisconsinan"--did it all. However, curiously enough, starting in the 1960's, R. F. Flint (1961), probably the single most-influential individual behind the revisionistic return to the one-glacier viewpoint, found evidence that south-central Connecticut had been affected by two glaciers moving from contrasting directions. Thus began what became known as "the two-till problem" (Pessl and Schafer, 1968). The late C. A. Kaye (1964b,c,d; 1982) presented evidence for a multi-glacial interpretation of southeastern Massachusetts, emphasizing the importance of the Illinoian glaciation and the evidence that glaciers had flowed from two discrete directions, NNE to SSW and NW to SE. Subsequently, stratigraphic evidence from coastal-cliff sections cut in the drumlins in Boston Harbor (W. A. Newman, Berg, Rosen and Glass, 1987; W. A. Newman and Mickelson, 1994) and at Sankaty Head, Nantucket (Oldale, 1982; Oldale and others, 1982; Oldale and Eskenasy, 1983; Oldale and Colman, 1992), has substantiated the importance of the Illinoian glaciation.

We review the highlights of the birth of the one-glacier interpretation, summarize the results of the detailed mapping by J. B. Woodworth (1901) and M. L. Fuller (1914), present the arguments used by the revisionists in their return to the one-glacier interpretation, discuss some recent research that includes evidence supporting a multi-glacial view, and conclude with our proposed new classification that is based on a resurrection and modification of Fuller's scheme.

BIRTH OF THE ONE-GLACIER INTERPRETATION

The most-prominent features of the Long Island landscape are the famous "twin" terminal-moraine ridges that extend nearly the entire length of the island, the Ronkonkoma Moraine on the south and the Harbor Hill Moraine on the north (Figure 36). These two moraines form the highest parts of Long Island, the so-called "backbone" or "spines" of the island (for much of its length, the Long Island Expressway is built on top of the Harbor Hill Moraine).

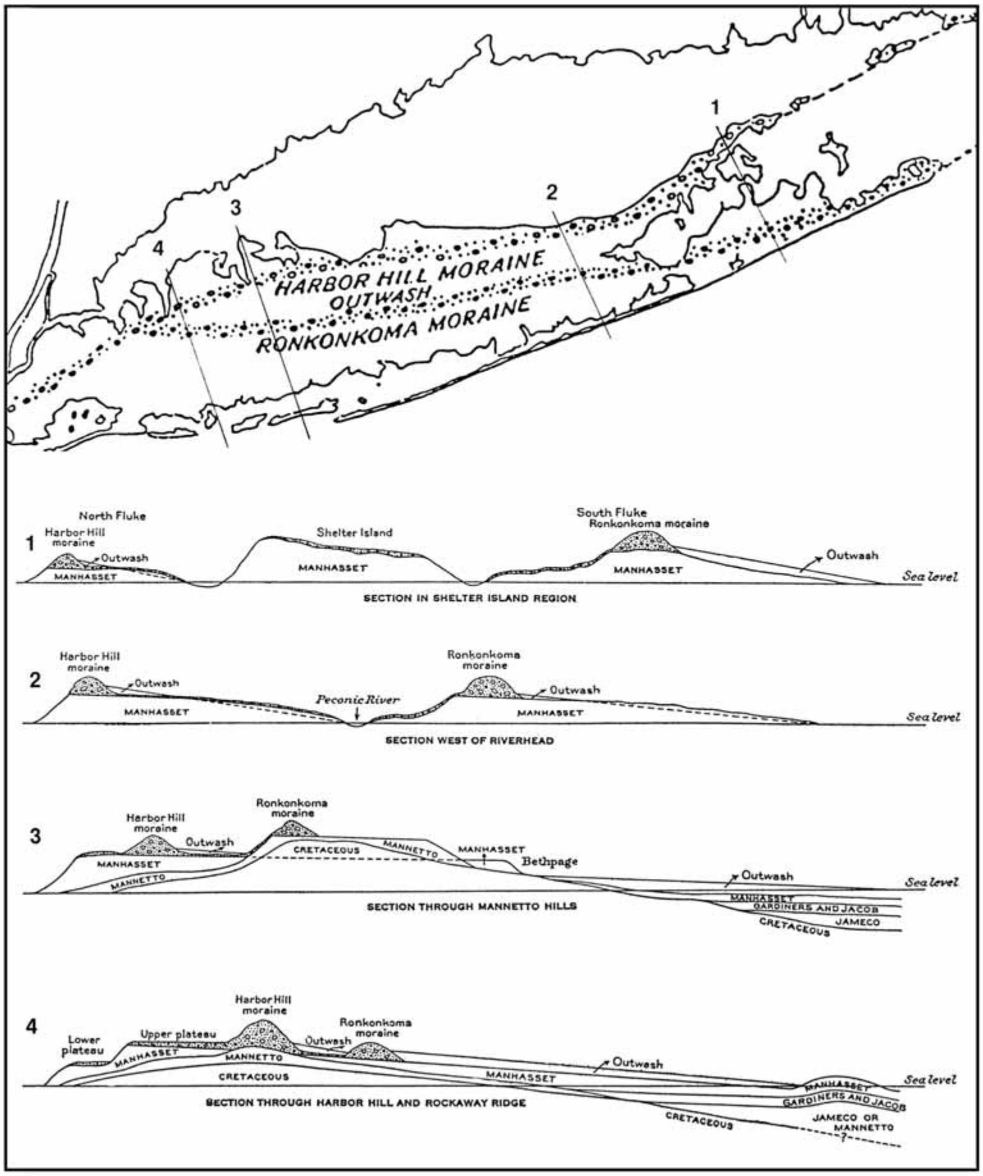


Figure 36. Map of Long Island showing the two prominent terminal-moraine ridges and profile-sections illustrating Fuller's interpretation of the subsurface relationships. Further explanation in text. (Map from A. K. Lobeck, 1939, fig. on p. 309 with location lines of Fuller's sections added by JES; profile-sections from M. L. Fuller, 1914, fig. 107, p. 120, rearranged to place easternmost section at top, westernmost at bottom.)

The first geologist who identified these ridges as glacial moraines, Warren Upham [1850-1934] (1879), inferred that they had been deposited by two different glaciers (from the "First" and "Second" glacial epochs of his classification). Based on the general uniformity of the state of stream dissection of the outwash plains lying south of each moraine, Professor T. C. Chamberlin (1883) made a persuasive case for concluding that these two moraines had been deposited by the same glacier. Chamberlin argued that if each moraine and outwash plain had been deposited by a different glacier, then the older, southern deposits left by the first glacier would have been notably dissected by streams during the interglacial interval prior to the advance of the second glacier. Most geologists have accepted Chamberlin's same-glacier interpretation.

A favorite pastime among these early specialists in glacial geology was inferring the flow lines within the glacier. Figure 37 shows what was essentially T. C. Chamberlin's version of the flow lines in the last glacier. Two points about this map merit discussion: (1) the linear zones of presumed divergent flow (as in the Hudson Valley) and (2) the relationship to Long Island's two famous "twin" terminal moraines.

If the Hudson-Valley flow divergence advocated by Chamberlin extended all the way to the mouth of the Hudson in New York Harbor, then striae atop the Palisades Ridge should be oriented NNE to SSW and the erratics should be derived from localities to the NE. Chamberlin's junior colleage at the University of Chicago, Rollin T. Salisbury [1858-1922] spent many summers mapping the glacial deposits in New Jersey and paid particular attention to the Palisades (Salisbury and Peet, 1894; Salisbury and others 1902). They showed that orientations of virtually all the striae are NW-SE. Thus, they concluded that the axis of fastest flow, and thus of flow divergence, could not have been in the Hudson Valley, as Chamberlin had postulated, but rather must have been west of the Palisades, in the Hackensack Lowland. Thus was born the oft-repeated flow-lobe map (Figure 38). In a following section, we present our arguments in support of the interpretation that the Chamblerin-Alden-Salisbury flow-lobe scheme confuses the effects of two different glaciers.

Alden's version of the Chamberlin map showed the last glacier forming Long Island's two terminal-moraine ridges. Figure 39 shows a more-recent version of the same relationship, one glacier, the most-recent one, depositing both terminal-moraine ridges. Farther along, we present evidence supporting a totally different interpretation, namely that two older glaciers were responsible, one for each moraine, and that the latest glacier (purportedly shown in Figures 37 and 39) did not reach most of Long Island.

DETAILED MAPPING SHOWS EVIDENCE FOR SEVERAL GLACIATIONS

Early in the twentieth century, the post-Cretaceous sediments on Long Island were mapped in detail. Those who did this mapping, first J. B. Woodworth [1865-1925] (1901) in Queens and western Nassau Co., and slightly later, M. L. Fuller [1873-1943] (1914) for all of Long Island, found convincing evidence of deposits from more than one glaciation.

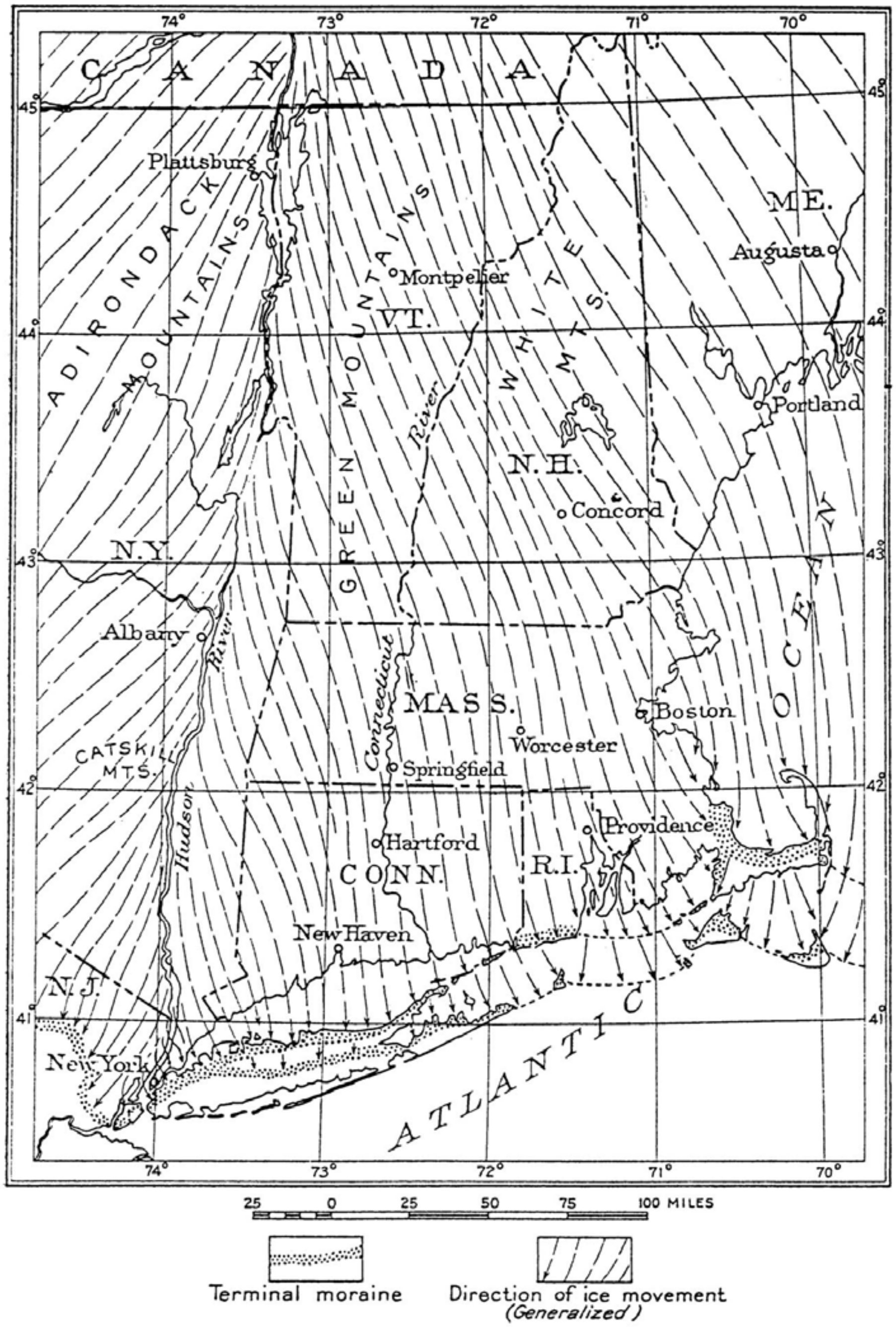


Figure 37. Map of last Pleistocene continental glacier in New England showing inferred flow lines according to T. C. Chamberlin's version of accelerated flow down the Hudson Valley with corresponding flow divergence away from this valley on both sides (but incorporating Salisbury's modification of the shift of the locus of accelerated flow into the Hackensack Valley to account for the data on striae orientation on top of the Palisades Ridge) and also Chamberlin's concept that this last glacier deposited both of Long Island's terminal moraines. According to Sanders and Merguerian, this map combines the effects of at least three different glacial advances, the two older than the "last" glacier being responsible for depositing Long Island's terminal moraines. (Compiled by W. C. Alden; Laurence LaForge, 1931, fig. 4, p. 53.)

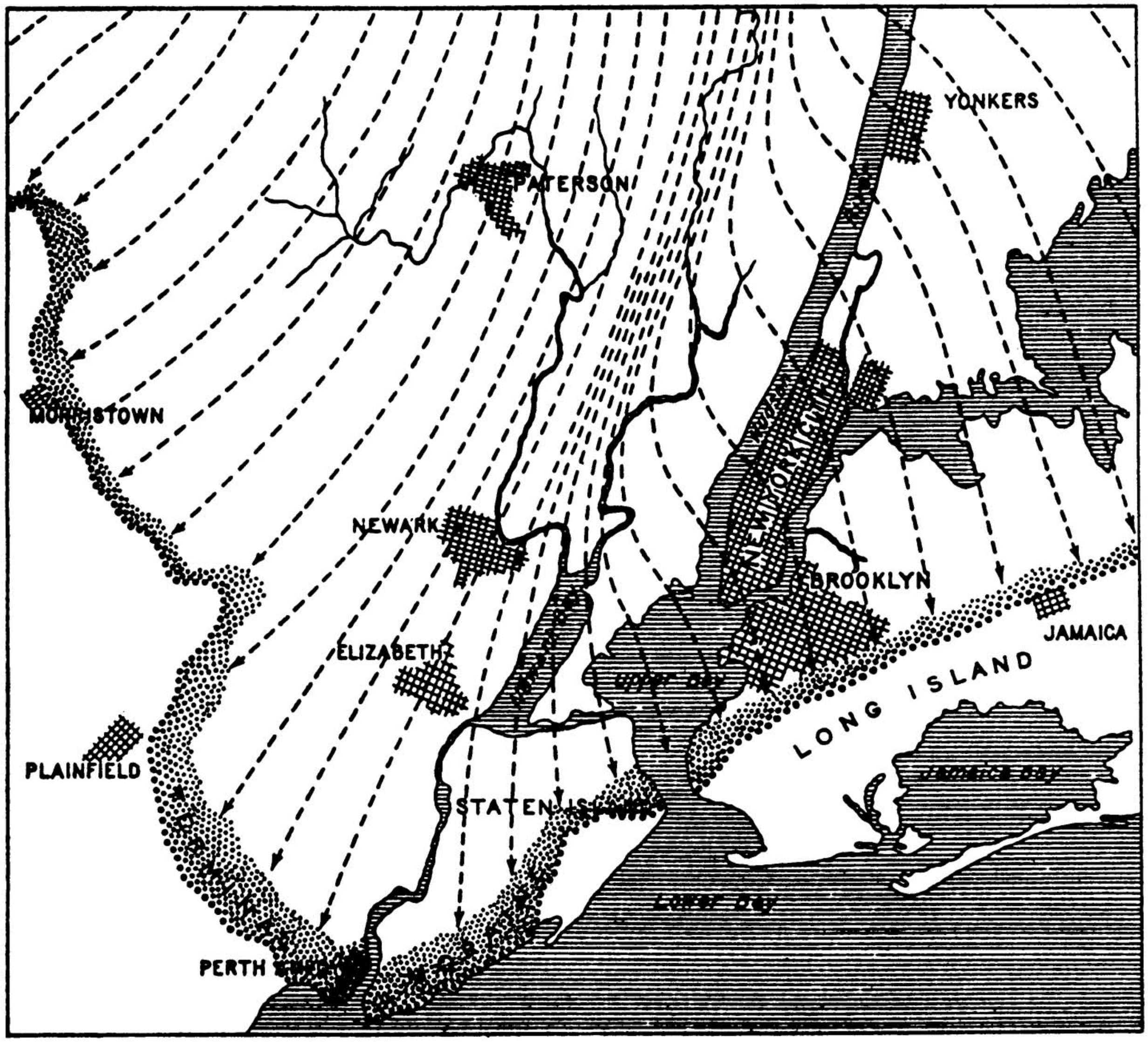


Figure 38. Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (R. D. Salisbury, 1908, fig. 11.)

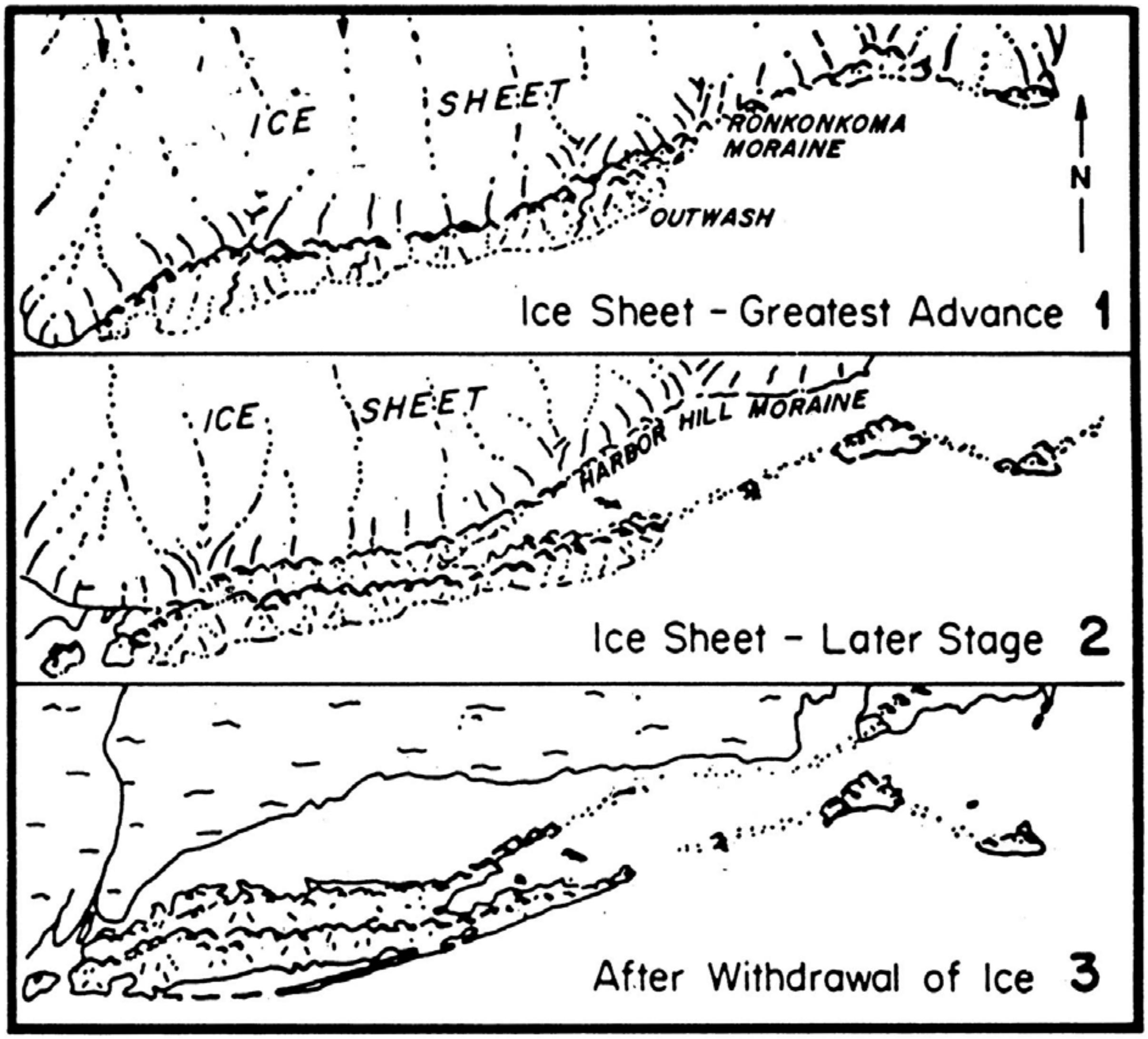


Figure 39. Sketch maps showing area of Long Island and mainland to the north illustrating concept of deposition of terminal-moraine ridges by the fluctuating margin of Woodfordian glacier. Not accurately rendered is the relationship near Lake Success, Long Island, where the Harbor Hill Moraine truncates the Ronkonkoma Moraine. (Y. W. Isachsen; Ed Landing; J. M. Lauber; L. V. Rickard; and W. B. Rogers, eds., 1991, fig. 12.21A, p. 177.)

J. B. Woodworth (1901) Finds At Least Two Tills in Queens

After he had examined the Pleistocene deposits of Queens County, Woodworth (1901) wrote the following about inferred directions of flow of the glacier(s):

"Frontal moraines mark the position of the ice front. The motion of the ice, at least near its margin, will tend to be toward that front; hence, since (sic) the moraine in this part of the island trends to the south of west, forming a lobate line across this region and that adjacent in New Jersey, glacial striae in this part of the island should run (sic) to the east of south. A number of ledges of gneiss in Long Island City meet (sic) this requirement."

"The southeastward movement of the ice on this side of the Hudson valley is further attested by the drift. The moraine from Brooklyn as far east as Oyster Bay contains trap boulders, the nearest known site of which rocks is in the Palisade trap ridge on the west bank of the Hudson river.

"Stratified red sands, also undoubtedly derived from the area of Triassic red sandstones now found only on the west bank of the Hudson, occur in a section by the roadside from Corona to Astoria, being there overlain by 8 or 9 feet of gray till... " (Woodworth, 1901, p. 652),

With respect to divergent flow directions, Woodworth wrote: "This fanning of the ice sheet to the eastward on the east side of the lower Hudson and to the westward on the west side is consistent with the form of the moraine across the mouth of the river. The axis of the lobe thus indicated has been fixed by Salisbury on the west side of the Palisade trap ridge. (ftn. 1)

Ftn. 1: "Salisbury, R. D. N. J. geol. sur. An. rep't state geol. for 1893. 1894, p. 161." (Woodworth, 1901, p. 653).

Woodworth discussed ancient glacial lakes that lay between the high parts of Long Island and/or a terminal-moraine ridge, or high-standing hills underlain by Cretaceous strata, on the S and the glacier itself on the N and sandy/gravelly delta deposits built into such lakes. He included, as Plate 8, a photograph by Heinrich Ries of Gilbert-type delta foresets and -topsets taken in the large Port Washington sand pit during the early days of its active phase (Figure 40). In Figure 41 we have modified Woodworth's figure 9 (p. 658) to show a gap between the ice front and a terminal moraine on the S which could serve as a dam to hold in the water of a proglacial lake. Woodward's map and text clearly indicate that is what he had in mind even though in his figure 9, he showed other relationships.

Woodworth also discussed examples of older gravels he assigned to the Columbia Formation (p. 624-637) that include an interstratified thin unit of boulder-bearing till [his "boulder clay (sic) bed" of p. 627]. He described it as follows:

"The boulder clay (sic) bed. In many of the coastal sections on the north shore an unstratified (sic) mixture of pebbles, sand and clay in a bed varying from 3 to 10 feet in thickness may be seen in a position to indicated that it is interstratified with these older gravels; but it is only in the sand pits on Hempstead bay that a bed of this character (sic) is fully revealed. About half way up the bluff, or about 100 feet above the bay, there is a bed of boulder clay from 2 to 3 feet thick, traceable in all the pits open in 1900 south of Bar beach. The matrix of this bed is an unctuous dark blue (sic) clay locally sandy or gravelly. Scattered through it and sometimes in close contact with each other (sic) are glaciated boulders ofter over (sic) 1 foot in diameter and numerous pebbles attesting the glacial origin of the deposit. Several large boulders examined in 1901 by Dr. F. J. H. Merrill and the writer were recognized by the first named as having been transported in all probability from the Adirondacks. Other small boulders carrying Silurian fossils indicated their origin in the Hudson Valley north of the Highlands. The longest journey made by these materials appears to exceed 200 miles" (Woodworth, 1901, p. 627?).

Figure 40. Photo (by H. Ries) of horizontal topsets (top, beneath trees, and inclined foresets of a Gilbert-type delta exposed in 1901 in a Port Washington sand pit. (J. B. Woodworth, 1901, plate 2.)

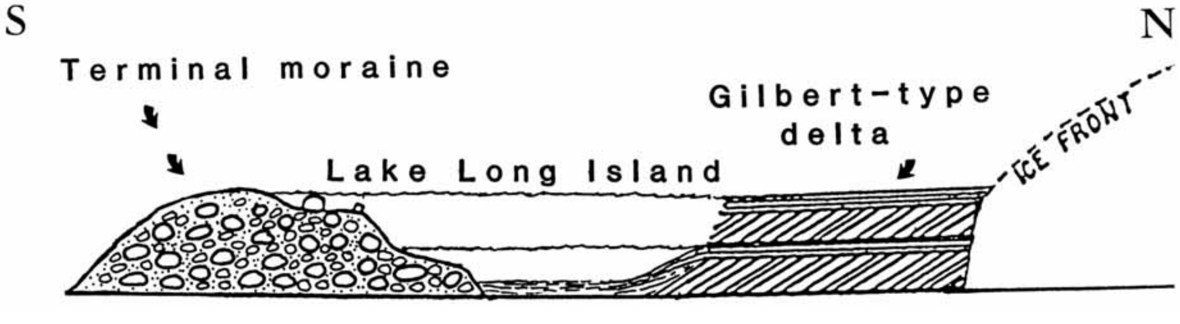


Figure 41. Schematic profile-section showing Gilbert-type deltas on N side of Lake Long Island, which formed in the lowland beteen the ice front on the N and the terminal-moraine ridge on the S. Two levels are shown: the lower at +40 feet and the upper at +80 feet (referenced to modern sea level). Highlands of Long Island, underlain by Cretaceous strata, could also serve as a dam for the lake on the S side. (Modified from J. B. Woodworth, 1901, fig. 9, p. 658.)

M. L. Fuller (1914): Four Pleistocene Glaciers Affected Long Island

The fundamental study of the stratigraphy of the glacial deposits in the New York metropolitan region is Fuller's (1914) monumental treatise on the geology of Long Island. Fuller found deposits that he interpreted as products of four glacial advances; between some of the glacial sediments, he found nonglacial strata. Table 4 shows the names- and stratigraphic relationships of Fuller's units. Four aspects of Fuller's classification: (1) Age(s) of Long Island's "twin" terminal-moraine ridges, (2) the north-flaring embayments along Long Island's NW coast, (3) the Manhasset Formation, and (4) the Gardiners Clay and associated Jacob Sand have become controversial topics. A fifth, the pre-Gardiners units, has not attracted much attention.

Age(s) of Long Island's "Twin" Terminal-moraine Ridges

Fuller assigned the Harbor Hill Moraine and the Ronkonkoma Moraine to the "post-Illinoian" ("Early Wisconsinan"). Fuller accepted Chamberlin's concept that the "twin" moraines had been deposited by the fluctuating margin of a single glacier, but inferred they are both younger than the Vineyard unconformity. Fuller classified them as being "Early Wisconsinan." [Later workers, for example, E. H. Muller, 1965, table 2, p. 104, changed Fuller's "Early Wisconsinan" age assignment by showing these moraines as being "latest Wisconsinan," or "Woodfordian."]

In addition to debating the ages of the moraines, Fuller also dealt with their morphologic aspects and regional relationships. For example, he noted (1914, p. 35) that on the north fork, near its NE end, a moraine-like landscape consists of windblown dunes. Fuller (1914, p. 35) referred to these features as "pseudomoraines."

Near Lake Success, NY, the Harbor Hill Moraine truncates the Ronkonkoma Moraine, and continues on to the west. [According to Fuller (1914, p. 15), this relationship between the two moraines was first pointed out by J. B. Woodworth and J. E. Woodman in their contribution to the (1901) Geologic Map of New York State, Long Island and Lower Hudson sheets.] The Harbor Hill Moraine crosses Queens and Brooklyn, forms The Narrows that separates Upper New York Bay from Lower New York Bay, and extends southwestward across Staten Island.

To the south of each of these "twin" moraines is an adjacent lowland outwash plain that is underlain by coalesced fan sediments. As emphasized by W. L. S. Fleming (1935) and supported by our observations, much of the material in the moraine ridges more closely resembles outwash than till. On Long Island, in fact, till is rare. It is present at the extreme western- and eastern ends of the island, but is hard to find in between.

These two moraine ridges lie on the depositional top of the Manhasset Formation (in most localities, as in profile-sections 1 and 2 of Figure 36) or on older units, such as the Mannetto or Cretaceous (as in profile-sections 3 and 4 of Figure 36).

North-flaring Embayments Along Long Island's NW Coast

Long Island's northwest coastal sector is distinguished by a series of deep, north-flaring embayments and intervening broad headlands or "necks (Figure 42). Several points of view have been expressed about the times of- and mechanisms of origin of the embayments. Crosby (1908) and Fuller (1914) interpreted them as drowned valleys that had been eroded by north-flowing rivers, but they disagreed as to when this erosion had taken place. By contrast, W. L. S. Fleming (1935) and MacClintock and Richards (1936) postulated that these embayments had not been eroded by rivers, but rather marked the sites where narrow tongues of ice from the latest glacier had been buried by outwash sand/gravel. After the ice melted, the embayments appeared, more or less in the same way that a kettle forms when a block of stagnant ice, buried in outwash, melts and the surface collapses. We review the implications of these contrasting ideas, beginning with Crosby's and Fuller's hypotheses of stream erosion.

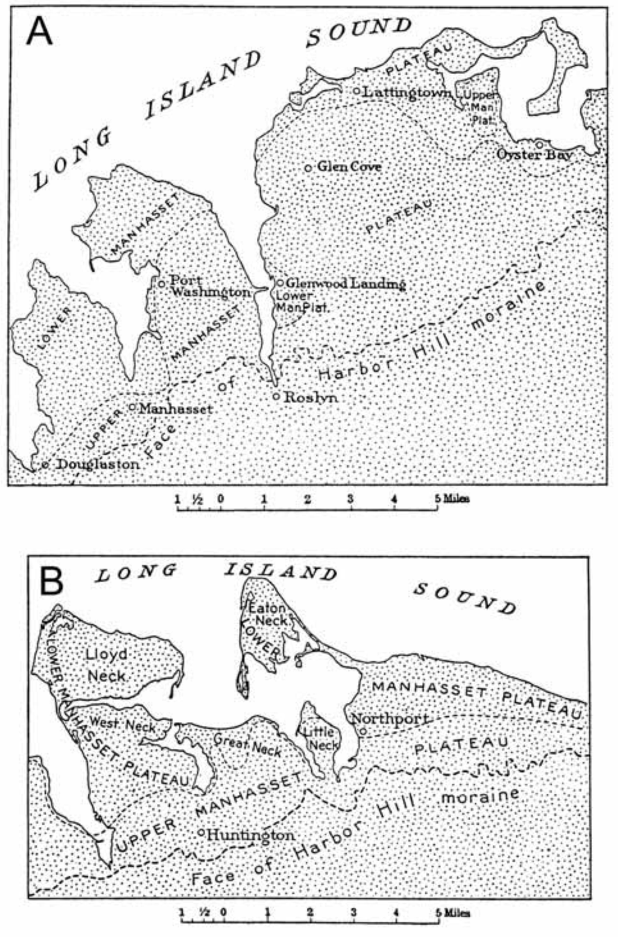


Figure 42. Sketch maps of two sectors NW coast of Long Island showing locations of two "plateau" surfaces (lower- and upper Manhasset, formed by depositional tops of lower- and upper parts of the Manhasset Formation, respectively) and the Harbor Hill Moraine. (M. L. Fuller, 1914, A, fig. 7, p. 30; B, fig. 8, p. 31.)

A. Douglaston to Oyster Bay.

B. Huntington-Northport area.

The most-obvious implication of the stream-erosion hypothesis is that such erosion would be possible only if rivers had been greatly rejuvenated by a large drop in base level. Crosby inferred that this condition had prevailed during the interval when the inner lowland, later to become Long Island Sound, was eroded. According to our interpretation of the late Cenozoic history, this would have been during the Pliocene, when New England was elevated and sea level dropped. Thus, according to Crosby, the age of the embayments is pre-glacial. By contrast, Fuller inferred that deep valley erosion had happened during the Vineyard erosion interval, which he assigned to the "Sangamonian" interglacial interval. Although Fuller did not discuss the relationship between glaciation and low sea level as contrasted with "interglacial" conditions and high sea level, he did realize that the extensive valley erosion he assigned to this interval required that base level be relatively low with respect to Long Island. He attributed the low base level to uplift of Long Island.

As a first approximation, the base-level requirement would appear to go against Fuller's age assignment. The reason is the presumption that during the "Sangamonian" interglacial episode, the Earth's climate was warm and sea level stood high. A high sea level and the required low base level are obviously incompatible. But, the latest results from the electrical logging of the Greenland ice cores suggests that climate during the Sangamonian "interglacial" was not exactly the long warm interval it has always been held to be, and thus the level of the sea may not have been high as it would be during a long warm interval. Instead, the ice-core record suggests that no warm "interglacial" episodes, such as that of the Holocene, which began about 10,000 yr ago, lasted longer than 10,000 yr (Tayler and 9 others, 1993).

Rather, the record consists of "rapid transitions between Dansgaard-Oeschger (D-O) events"... ("named in honor of two of the heroes of ice-core research") which punctuated the period between about 65,000 and 25,000 yr ago. During this interval, the "climate leaped back and forth between states of intermediate cold and extreme cold. The median temperature at this site during the ice age has now been well established, through thermal profiles in the ice itself, to have been on the average 16°C colder than during the past 10,000 yr (Cuffey et al., 1995)" (Broecker, 1997, p. 2). During these D-O cold events, sea level probably was "low" rather than "high." Therefore, for reasons not known to Fuller (nor anybody else), base level may have been low exactly when Fuller's hypothesis of "Sangamonian" deep stream dissection required it to be.

We think that the ideas of Crosby and Fuller need not be mutually exclusive. In other words, vigorous stream erosion could have taken place more than once, including the times suggested by each: Crosby's "pre-glacial" of Crosby and Fuller's last "interglacial." Moreover, the possibility should not be excluded that more than two different times of "interglacial" low base level may have happened.

W. L. S. Fleming's (1935) idea (accepted by MacClintock and Richards, 1936) of the synglacial age of the embayments was proposed as a basis for re-assigning Fuller's Manhasset Formation from the "Illinoian" (pre-"Sangamonian") to the Wisconsinan. As mentioned, according to the ice-tongue hypothesis, the embayments are present in places that were not aggraded upward when the vast bodies of ouwash now underlying the "necks" were being deposited. If the buried-ice-tongue hypothesis is correct, then the age of the embayments is the same as that of the Manhasset outwash and cannot be used as an argument for the preembayment age of the Manhasset Formation. As we explain in a following section, we think other evidence, not related to the age(s) of the north-flaring embayments, demonstrates the "Illinoian" age of Fuller's Manhasset Formation.

Finally, if pre-glacial embayments were present, they may have been filled will glacial ice which would have tended to perpetuate the depressions. All parties to the debate, therefore, may have been partly correct. But we conclude that the age(s) of the north-flaring embayments is not relevant to the age of the Manhasset Formation.

Manhasset Formation

Fuller applied the name "Manhasset formation" (with upper Hempstead gravel member, middle Montauk till member, and lower Herod gravel member) to the strata that J. B. Woodworth (1901) had referred to the "Columbia formation." Because, as mentioned, Fuller inferred that the extensive network of north-flaring embayments had formed as valleys eroded into the Manhasset Formation, he classified this formation as being older than the Vineyard erosion interval, the time when he thought deep valley erosion had taken place, and thus assigned the Manhasset to the Illinoian. Fuller thought that the Manhasset Formation is entirely older than the Ronkonkoma Moraine, one of the few Fuller points that we contest, as is explained farther along.

Fuller drew many sketches of Manhasset strata exposed in coastal cliffs. In addition, he illustrated the relationship between members of the Manhasset Formation and the typical morphologic expression along Long Island's north shore. In many localities, a low plateau is underlain by the basal Herod Member and a higher plateau, by the upper Hempstead Member. The Montauk Till Member typically caps the low plateau (Figure 43A, B). The Manhasset Formation forms the bulk of Long Island.

Jacob Sand and Gardiners Clay

Underlying the Manhasset Formation Fuller recognized two units, the Jacob Sand and Gardiners Clay. The name Jacob comes from Jacob Hill, "a high point on the north shore of Long Island, 8 miles northeast of Riverhead, near which the formation is well exposed" (Fuller, 1914, p. 107).

He described this sand as follows: "In its most characteristic (sic) form the Jacob sand consists of exceedingly fine sands, mainly quartz flour, but with many grains of white mica and some of dark-colored minerals. In color the sands commonly range from a very light gray to yellowish (sic) and buff tints, but where laminae of true clay are present they may be stained reddish externally. They are everywhere clearly stratified, although individual beds several feet thick and appearing structureless to the eye are encountered. When wet most of them are somewhat plastic but lack the toughness of true clay; all are decidedly gritty to the teeth and most of them to the touch. Interbedded with the fine varieties of the Jacob deposits are some more distinctly (sic) sandy beds, usually buff or yellowish, and several feet thick, in which particles of fairly fresh granitic minerals can be recognized" (Fuller, 1914, p. 107).

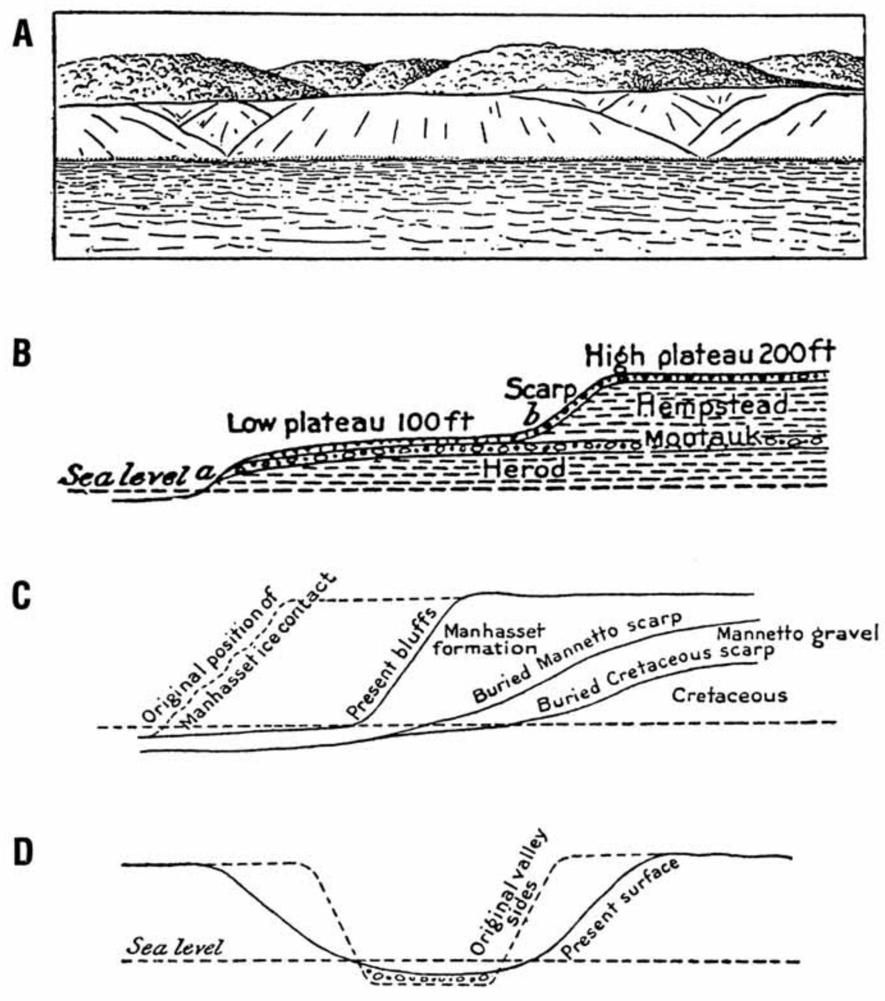


Figure 43. Fuller's sketches of some of Long Island's prominent physiographic features. (M. L. Fuller, 1914, A, fig. 3, p. 22; B, fig. 9, p. 31; C, fig. 5, p. 25; D, fig. 6, p. 26.)
A. View of north-shore bluff of Long Island from Long Island Sound emphasizing the depositional top surface of the lower part of the Manhasset Formation (Manhasset "plateau;" flat surface at elevation +100 ft. in middle) beyond which is the higher, irregular landscape of the Harbor Hill Moraine.
B. Schematic N-S profile-section through coastal region of NW Long Island showing Long Island Sound (at L), modern coastal bluff (a) and two "plateau" surfaces (depositional tops of lower- (Herod-Montauk members) and upper (Hempstead Member) of the Manhasset Formation, respectively, both veneered with younger glacial sediments (of Early Wisconsinan age according to Fuller). Scarp at b is thought to be a modified ice-contact scarp, where the ice stood while the Hempstead Member was being deposited.
C. Schematic N-S profile-section through north-shore bluff, E Long Island, showing relationships among Cretaceous core (lower R), buried Mannetto scarp, and present-day bluffs, cut in Manhasset Formation with estimated original ice-contact position (at L). No "low plateau" is present as in NW Long Island.
D. Schematic E-W profile across typical north-shore coastal embayment, western Long Island, showing relationship between present surface and inferred original valley sides.

Fuller (1914, p. 113) assigned the Jacob Sand to the "Illinoian," but considered it to be transitional between the interglacial "Yarmouthian" Gardiners Clay below and overlying "Illionian" glacial materials of the Manhasset Formation.

"There is reason to believe that the change in deposition, as was pointed out in the discussion of the source of the material (p. 107), was caused by the advent of glacial silts brought down from the north during the advance of the Montauk ice, but long before it invaded the region under discussion" (Fuller, 1914, p. 113).

The name Gardiners, applied to a widespread fossiliferous "clay," comes from "Gardiners Island, situated between the North and South flukes at the east end of Long Island, on which several clay beds with included sands are well exposed at a number of points" (Fuller, 1914, p. 92).

"On western Long Island, where the formation reaches its maximum development, the Gardiners clay consists of irregular dark-colored beds alternating with layers (sic) or lenses of sand and fine gravel and attaining near Brooklyn an aggregate thickness of 150 feet. In this region the clays, unlike those in the localities farther east, grade downward through glauconitic (sic) and locally fossiliferous sand into the Jameco gravel, representing in fact transitional deposits. The clays themselves consist of a very fine silt, dark from the contained organic matter and carrying more or less lignitized wood. The included sandy layers are commonly from 5 to 10 feet thick and at some places have yielded fossil remains (Fuller, 1914, p. 93).

"The great body of the Gardiners clay rests upon the Jameco gravel, but along the borders of the Jameco next to the Cretaceous land mass, especially along the edges of the great depression in the vicinity of Jamaica Bay, the clay laps up on the eroded surfaces of the Cretaceous and Mannetto (fig. 57) or even upon the metamorphic rocks (fig. 62), with sharp erosion (sic) and overlap unconformities (sic)" (Fuller, 1914, p. 94).

Fuller assigned the Gardiners Clay to the "Yarmouthian" Interglacial Stage.

Pre-Gardiners Units

Fuller's two oldest units, the Jameco Gravel above and Mannetto Gravel below, which underlie the Gardiners Clay, are known mostly from wells drilled into bodies of valley-filling materials. The Mannetto Gravel completely fills the oldest valleys on Long Island that were cut into the underlying Upper Cretaceous coastal-plain strata (Fuller, 1914, p. 44). The Jameco Valley cuts the Mannetto Gravel; it in turn has been filled in by the Jameco Gravel, which filled the valley and obliterated it as a landscape feature.

Fuller took the name Jameco Gravel "from the Jameco pumping station, near Jamaica South, 3 miles south of Jamaica, in western Long Island," where Veatch first recognized- and named these deposits from deep wells.

"The Jameco gravel, although it has not been definitely recognized at the surface at any point on Long Island, has been encountered in a considerable number of wells. In its type locality, in the area extending from Jamaica Bay northward toward Whitestone, it occupies a broad depression in the underlying rocks (either Cretaceous or Mannetto). It is easily recognized in the wells in this locality because of its striking dissimilarity to all other Pleistocene beds (except the Montauk till member of the Manhasset formation) and to the Cretaceous formations. The difference between the Jameco gravel and the Mannetto gravel is especially marked. Although the older beds are prevailingly light-colored (sic) and composed principally of quartz, the Jameco is generally a very coarse dark-colored gravel containing a predominance of granitic pebbles with a few streaks of black (sic) or other dark sands or finer silts...

"Where lithologic characteristics are not determinative, the formation is recognized by its position beneath the fossiliferous Gardiners clay" (Fuller, 1914, p. 85-86).

"The Mannetto gravel was named from the Mannetto Hills (West Hills), on the crest of which just west of Melville some of the best exposures of this gravel on the island were found" (Fuller, 1914, p. 80).

It *"consists of stratified (sic) and in some places cross-bedded gravels composed mainly of well-rounded pebbles of quartz from half an inch to an inch in diameter mixed with coarse yellowish quartz sand, but carrying everywhere a few deeply weathered granitic pebbles and scattered large bowlders of crystalline rock, also deeply weathered or disintegrated. It includes a few thin intercalated beds of yellowish clay. The granitic fragments can usually be crushed by the finger or by a slight blow of a hammer, and even the quartz is far more friable than fresh fragments. The quartzose (sic) and stained character (sic) of the gravels, the deep weathering of the pebbles, and the complex flow and plunge (sic) structure are the distinguishing features of the formation " (Fuller, 1914, p.80).*

We note a distinctive anomaly in the relationships Fuller described for the Jameco and contrasted with the Mannetto gravels. Both are prominent subsurface units in western Long Island where the upper unit, the Jameco, fills a major depression eroded in the Mannetto and is therefore the younger unit. Fuller reported that the Jameco is not known at the surface on Long Island. By contrast, the type locality of the Mannetto is on the surface in the Mannetto Hills.

The key feature that Fuller used to identify the Mannetto is the decayed granitic pebbles. Such decayed pebbles can originate in two ways. (1) They can be distinctive erratics, indicator stones, for example, of a region of pre-glacial decayed bedrock, such as is found in the northernmost 500 feet of the Garrison tunnel of New York City's Catksill aqueduct (Berkey and Rice, 1921, p. 101-103; Berkey and Fluhr, 1948) or even of Cretaceous bauxite (Kaye, 1967); or (2) they can be the result of intensive in-situ chemical weathering after deposition and thus indicate great age.

Two indices of the first alternative are that (a) the pre-glacial (probably even pre-Late Cretaceous; Blank, 1978) decomposition of the feldspars was accompanied by the dissolution of quartz; and (b) other stones do not show comparably advanced states of decomposition.

The distinctive aspect of the second alternative is that all stones display the effects of advanced stages of decomposition. We have not checked the surface exposures that Fuller assigned to the Mannetto Gravel to see if the quartz has been dissolved, but have noticed a contrast in states of decomposition: only in the granitic rocks has the feldspar turned into clay. In other kinds of pebbles, only the effects of incipient decomposition are visible. Therefore, the decay of the feldspars should not be considered a badge of extremely ancient age (as we have previously supposed).

Given the validity of the first alternative, we raise the possibility that the Mannetto Gravel of the surface exposures may not be correlative with the subsurface unit Fuller assigned to the Mannetto Gravel in wells from western Long Island. This possibility would be highly likely if the degree of decomposition of the pebbles in the subsurface units assigned to the Mannetto is more or less uniform throughout in contrast to decay of granitic pebbles only in the surface exposures. Whatever is the outcome of this discussion about the Mannetto, the message is clear: decayed feldspars by themselves do not necessarily prove an early Pleistocene age.

MID-1930's: REVISIONISTS RESURRECT THE ONE-GLACIER VIEWPOINT

Fuller's (1914) classification of the Pleistocene deposits on Long Island has been out of favor since the mid-1930's. Several of his key age assignments are commonly characterized as "having been abandoned" and, presumably, therefore, not correct. The general trend of all the revisionism has been to reclassify units as younger than Fuller considered them to be and to replace Fuller's multi-glacial interpretation with something closely resembling T. C. Chamberlin's "one-glacier-did-it-all" view. Involved in the changed age assignments are: (1) the "coastal end moraines," on Long Island the two terminal-moraine ridges (Ronkonkoma on the south and Harbor Hill on the north; reassigned from Fuller's "Early Wisconsin" to "Late Wisconsinan"); (2) Manhasset Formation (reclassified from Fuller's "Illinoian" to "Wisconsinan," "Early" by some and "Late" by others); and (3) Gardiners Clay (shifted upward from Fuller's "Yarmouthian" to the revisionists' "Sangamonian").

Coastal End Moraines

As mentioned, the map pattern demonstrates that the Harbor Hill Moraine is the younger, but the map-view truncation does not prove whether these two ridges were deposited by the fluctuating margin of a single glacier or by the margins of two different glaciers. And the map relationships do not indicate the age or ages of the responsible glacier or glaciers.

We still do not know where the change in age assignment of these moraines from Fuller's "Early Wisconsin" to "Late Wisconsinan" was first published. In the Boston area, LaForge (1932) assigned the till in the Boston area to the latest Wisconsinan; by contrast, Judson (1949) preferred an Early Wisconsinan age.

Since the mid-1930's (Fleming, 1935; MacClintock and Richards, 1936, 1937; and despite Fuller's 1937 little-cited but convincing rebuttal to the MacClintock and Richards position), the overwhelming consensus view is that these ridges were deposited at the fluctuating margin of the latest "Wisconsinan" glacier to visit this region. (See Figure 39), (the "Woodfordian" of Cadwell 1986, 1989). (See Tables 3, 4.)

"End moraines on Long Island, believed to represent the approximate outer limit of late Wisconsin glaciation, have been generally correlated with similar features south of the Great Lakes, 14C-dated at around 18,000 yr B. P. The more direct (sic) dating of these (sic) and related moraines in southern New England, about which there is disagreement, is discussed by Schafer and Hartshorn (1965, p. 119)" Flint and Gebert, 1976, p. 186).

"The sketch map (Fig. 4) shows end moraines and related features in the region surrounding the study area of this paper. The dominant units are the conspicuous moraines believed to mark the outer margins of the Laurentide Ice Sheet when it stood at one or more maximum positions during the Wisconsin Glaciation. Some moraines in Martha's Vineyard and Nantucket Island have been thought to be older (Kaye, 1964a, 1964b)" (Flint and Gebert, 1976, p. 187).

Notice two points from these two quotations. (1) The operative word with respect to the ages of the conspicuous moraines is "believe." (2) Although Flint and Gebert mentioned Kaye's concept of "older" moraines in Martha's Vineyard and Nantucket Island, they said not another word on this subject so we have no idea how they may have incorporated these possible older moraines into their classification. We reproduce the Flint-Gebert figure 4 as our Figure 44.

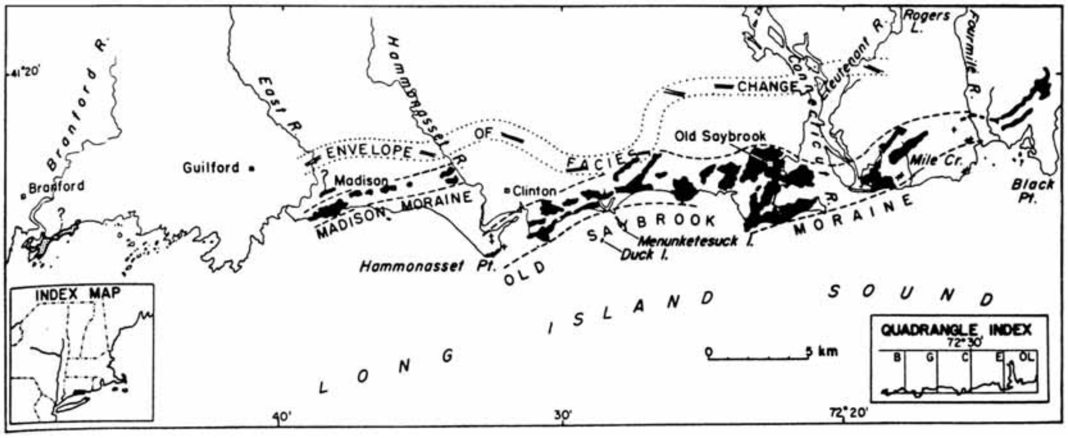


Figure 44. Sketch map of southern Connecticut and vicinity showing end moraines deposited by the last glacier to visit this region. Based on provenance relationships and flow-directonal data, we interpret this moraine as the terminal moraine of the Woodfordian glacier, which did not reach most of Long Island. The Long Island moraines are older. Further discussion in text. (R. F. Flint and J. A. Gebert, 1976, fig. 4.)

Sirkin (1968, Table 1, p. 234) initially assigned the two moraines to a pre-Cary Wisconsinan age. At Harbor Hill, Roslyn, "...the type locality of the Harbor Hill Moraine and the Harbor Hill Till..." the till/outwash contact is visible (p. 250). The long axes of pebbles from the Harbor Hill till at Alley Pond Borrow Pit "point generally NNW" (p. 248). At the intersection of Lakeville Road and the Northern State Parkway, Sirkin found "about 5 feet of

Harbor Hill till overlying 20 + feet of stratified lacustrine sands with thin clay partings (Plate 1, figures 2, 3, and 4)" (p. 249). Subsequently, Sirkin proposed the term Roslyn Till for the "Harbor Hill Till" at Harbor Hill, Roslyn.

Another example of a regional correlation of moraine ridges. also based on the supposed latest Wisconsinan age of Long Island's terminal moraines, is contained in the following quotation from Oldale (1982, p. 4).

"Morphostratigraphic correlation from Long Island, New York, to Cape Cod and the islands along the two major belts of coastal end moraines (Figure 2) has been proposed by many workers (Upham, 1897; Fuller, 1914; Johnson, 1925; Woodworth and Wigglesworth, 1934; Schafer, 1961; and Schafer and Hartshorn, 1965). The moraines on Nantucket, Martha's Vineyard, and Nomans Land are considered to be the morphostratigraphic equivalents of the Block Island Moraine and the Ronkonkoma Moraine on Long Island. The Sandwich Moraine and the Buzzards Bay Moraine, which includes the Elizabeth Islands, are considered to be the morphostratigraphic equivalents to the Point Judith and Charlestown Moraines of Rhode Island, the Fishers Island Moraine in Connectciut, and the Harbor Hill Moraine of Long Island."

We have included as our Figure 45 Oldale's figure 2 mentioned above that illustrates Oldale's matching of the moraine ridges. Farther along, we give our reasons for challenging these correlations.

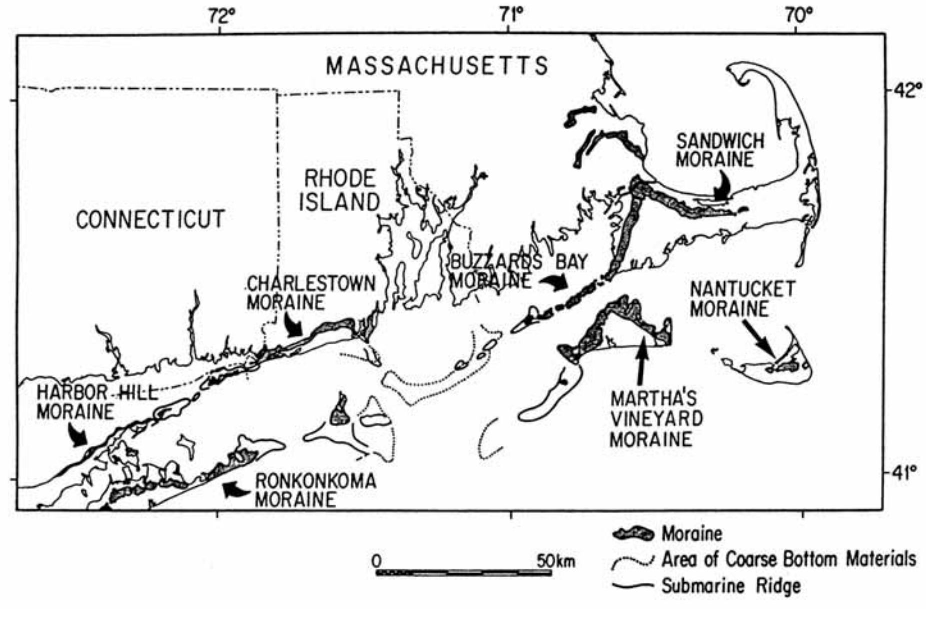


Figure 45. Map of southeastern Massachusetts and vicinity showing correlation of "coastal end moraines" according to R. N. Oldale. According to us, the Buzzards Bay-Sandwich Moraine, correlated here with the Harbor Hill Morain of eastern Long Island, should betied to the older Ronkonkoma Moraine. We correlate the Nantucket-Martha's Vineyard Moraine with a pre-Ronkonkoma Moraine that served as a dam to confine the waters of Proglacial Lake Long Island in which the lake sediments of the Manhasset Formation were deposited. (R. N. Oldale, 1982, fig. 2, p. 5.)

Manhasset Formation

W. L. S. Fleming (1935; repeated by Donner, 1964) argued that the similarity of stages of relative decomposition of stones in the sediments of the Manhasset Formation with those in Long Island's two moraines implied that they were both essentially the same age. Because he believed in a "late Wisconsinan" age for the moraines, he rejected Fuller's "Illinoian" assignment of the Manhasset. Instead, Fleming shifted the assignment of the Manhasset upward into the "Wisconsinan." This topic of comparable stages of decomposition of the stones could also have been resolved by shifting the ages of the two moraines downward to bring them closer to the age of the Manhasset Formation. In our modification of Fuller's classification, we do just that for the Ronkonkoma Moraine.

Fleming was also impressed by the depositional aspect of the landscape morphology and pointed out the difficulty of invoking a low base level during an interglacial stage, typified by a high sea level (discussed in a previous section). None of the revisionists who advocated a "Wisconsinan" age for the Manhasset Formation was aware of the extensive lake deposits and of the paleogeographic requirements of the dam to confine this lake on the south.

Gardiners Clay

In his attempts to answer the question: "How many glacial stages are recorded in New England?" R. F. Flint compared Woodworth and Wigglesworth's then-new (1934) results from Cape Cod and the adjacent islands with Fuller's (1917) results on Long Island. Flint accepted Fleming's (1935) and Wells' (1935) rejection of the "Illinoian" age assignment of the Manhasset formation (as defined by Fuller on Long Island) and recognized the importance of the underlying Gardiners clay in the following words (Flint, 1935, p. 777):

"But in spite of (sic) the doubt, the Gardiners clay is definitely marine and reasonably distinctive, and therefore serves as a kind of key bed or reference bed. Below it we have at least one till; above it we have at least the Wisconsin sequence."

Accordingly, Flint's answer to his question on the number of glacial stages represented in New England was not four (the number inferred by Fuller and by Woodworth and Wigglesworth), but two, one above- and the other below the Gardiners Clay. Flint did not comment on the age of the Gardiners Clay, which both Fuller (1914) and Woodworth and Wigglesworth (1934) assigned to the "Yarmouthian." A "Yarmouthian" age left open the possibility that in the post-Gardiners strata, an "Illinoian" glacial stage could be represented. (Recall that Flint accepted only a single post-Gardiners glacial stage, i. e., the "Wisconsin sequence.")

Flint's concept of a single post-Gardiners glacial stage received a great boost from MacClintock and Richards (1936) when they decided to move the Gardiners from "Yarmouthian" to "Sangamonian."

SOUTHERN NEW ENGLAND'S "TWO-TILL PROBLEM"

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 further 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 a self-generating 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 altered the direction of 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 quasi-radial 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 retreat, 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.

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 tend to obliterate all traces of the older one, Flint opposed the multiple-glacier hypothesis. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one. On the Glacial Geologic Map of North America, Flint (1945) mapped the two contrasting flow directions, one from the NNE to the SSW and the other from NW to SE.

The first post-Fuller challenge to the one-glacier-did-it-all school of thought came from one of the staunchest one-glacier partisans, Richard Foster Flint (1961). In south-central Connecticut, Flint found two tills in direct superposition. He gave the name Hamden Till to the upper till, whose flow indicators imply glacier movement from NNE to SSW. He proposed the name Lake Chamberlain Till for the lower till, whose flow indicators showed glacier movement from NNW to SSE.

Despite Flint's results, Sirkin (1968, 1971, 1977, 1982) has attached to his noteworthy paleobotanical contributions a strong adherence to the one-glacier interpretation. Because he disagreed with some of Fuller's correlations, Sirkin swept aside all Fuller's work. Recently, however, Sirkin (1997) has admitted the possibility that two glaciers might have visited Long Island.

OTHER EVIDENCE FOR MULTIPLE GLACIATIONS

Sanders (1974a) first published the idea that Long Island's prominent terminal-moraine ridges had not been made by the very youngest glacier (I of Table 3), whose direction of flow is known to be from from NNE to SSW (Figure 46; the same flow pattern displayed by the Hamden Till of south-central Connecticut described by Flint, 1961), but rather were the products of two different glaciers (II and III of Table 3) that had crossed the region from NW to SE (Figure 47). This interpretation specifically excluded the possibility that a single glacier had been responsible for the two moraine ridges and furthermore, that the responsible glaciers had flowed from NW to SE rather than from NNE to SSW.

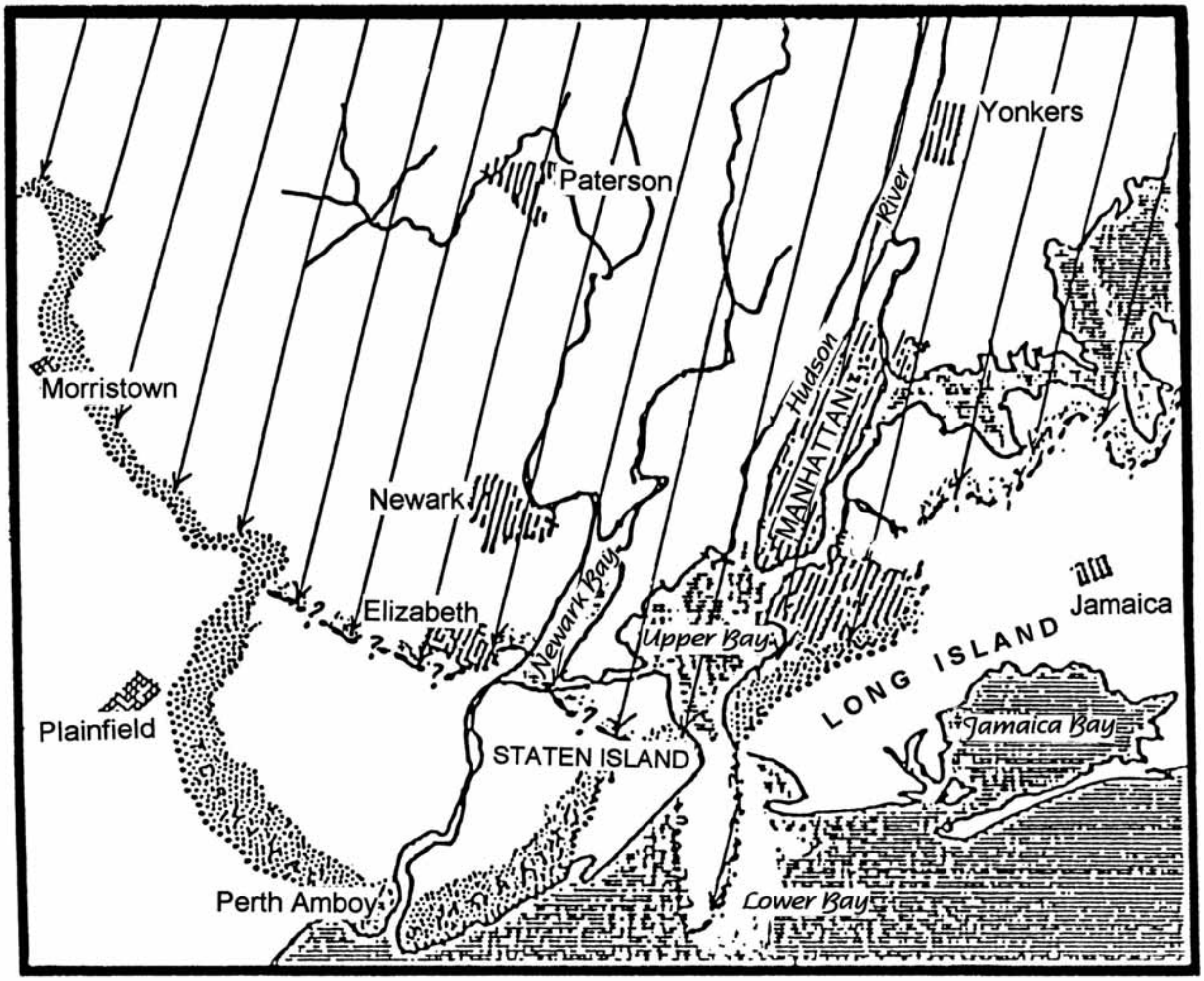


Figure 46. Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

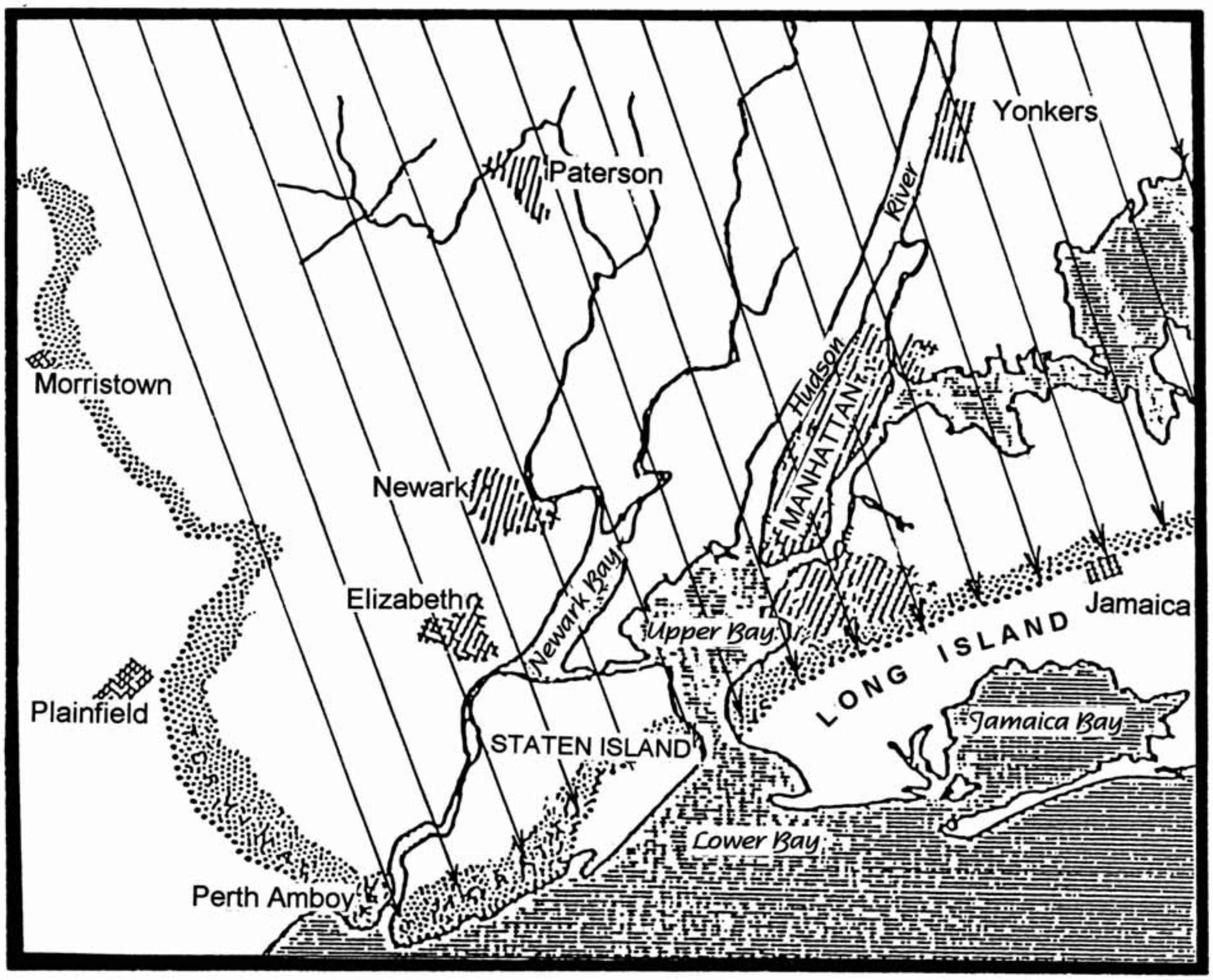


Figure 47. Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. We infer that the Illinoian-age glaciers flowed as shown here. (J. E. Sanders).

In his study of the Quaternary sediments in the Boston area, Kaye (1982) found deposits that he ascribed to several Wisconsinan glaciers. Kaye's inferred flow directions of these Boston glaciers are virtually identical to those that we infer for the ancient glaciers in the New York City region. To quote from Kaye's paper:

> "The direction of ice flow in the Boston Basin and adjoining uplands was studied by means of the orientation of striations (sic) and grooves on the bedrock surface, the orientation (sic) of the long axes of drumlins, the direction of transport of erratics in till, and the direction of thrusting and overturning of bedding in glacially deformed drift.

> These data range through 360 degrees in azimuth. Analysis of this confusing message shows the existence not of an ever-shifting ice current but of at least four separate and distinct ice currents of different ages. Three of these flowed fairly rectilinearly, but one (the last) was multicomponent and marked by strong lobation" (1982, p. 31).

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

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

Recently, Sirkin has moderated his one-glacier viewpoint. In an open-pit mine at Sanford Hill, in the central Adirondacks, Muller, Sirkin, and Craft (1993) described two tills separated by 3.6 m of brown Tahawus lake- or pond clay containing wood fragments older than 55,000 radiocarbon years B. P. that were exposed in 1963 in the National Lead Company's (now NL Industries) open-pit mine. They assigned the Tahawus clay to the Sangamonian; according to them, it contains "an interglacial pollen record, the first one identified in northeastern New York" Muller, Sirkin, and Craft, 1993, p. 163).

In their summary of the glacial events in New York State, Muller and Calkin (1993) did not recognize any pre-Wisconsinan tills in the New York City region. They wrote: "The pre-Wisconsinan record involves saprolith and till in the Adirondack Mountains, marine clay on Long Island, multiple tills at Fernbank, Otto, and Gowanda, and major drainage derangement of the Allegheny River" (Muller and Calkin, 1993, p. 1829).

After summarizing the amino-acid-racemization results (to be discussed in the next section), they continued:

> "...it is difficult to escape the conclusion that two temporally distinct stratigraphic units are involved. Indeed, Stone and Borns (1986) propose that the name Gardiners Clay be reserved for brown marine clay and silt (sic) with interbedded sand and gravel of probable Sangamonian to Eowisconsinan age (Table 3). This action clarifies the age of the Gardiners Clay, and implicitly acknowledges the probability that marine clays of both Sangamonian and pre-Sangamonian age are present" (Muller and Calkin, 1993, p. 1830).

OUR BASES FOR RESURRECTING- AND MODIFYING FULLER'S (1914) CLASSIFICATION

In this modern age of isotope chronostratigraphic information and other wonders, it is especially desirable to support any revisions of Quaternary stratigraphic units with numerical information on ages. We lament that we have not found anything new in the way of chronostratigraphic data. Moreover, as will be seen, in one case, at least, the two most-favored chronostratigraphic methods, radiocarbon dating and amino-acid racemization of the organic matter in shells, yield conflicting results. Therefore, we shall follow the time-honored practice among geochemists of accepting as valid the numbers that agree with our interpretation and of rejecting all others as invalid.

Because use of names for Quaternary subdivisions seems to imply in the minds of many readers a specific chronostratigraphic correlation, we shall mention such names only as they have appeared in previously published work and when we do so, we enclose such names in quotation marks. For designating glaciers and tills, we prefer to modify the practice of C. A. Kaye in the Boston area. Kay used Roman-numeral designations for tills, with I the oldest and III, the youngest. Unlike Kaye, however, we prefer to count down from the top, and thus assign I to the youngest till and higher numerals to progressively older tills.

Another language problem has arisen from application of the word "Last" as a stratigraphic term. For example, Fleming (1935) classified Long Island's two terminal moraines, the older Ronkonkoma and younger Harbor Hill, as being products of the "Last glaciation." As we elaborate father along, we agree that the Harbor Hill Moraine is a product of the "last glacier" to visit eastern Long Island. But we totally disagree with the concept that "last" on eastern Long Island equals "very latest" (or in the usage of many authors, "Woodfordian") glacial stage.

After showing why we think it was a mistake to abandon Fuller's classification, we discuss our reasons for proposing some significant modifications to Fuller's scheme. These are: (1) the stratigraphic implications of Lake Long Island sediments; (2) the subsurface relationships at Jones Beach; and (3) our discovery of two much-weathered tills that we assign to the Early Pleistocene.

BASES FOR RESURRECTING FULLER

Our two main reasons for resurrecting Fuller's (1914) classification are derived from new evidence that supports Fuller's "Yarmouthian" age assignment of the Gardiners Clay and of the "pre-Late Wisconsinan" age of the Harbor Hill Moraine. If we have correctly interpreted this new evidence, then both of these units are definitely older than most modern workers generally believe. Moreover, such older age assignments conclusively refute the reasons that were advanced in the mid-1930's for abandoning Fuller's classification.

"Yarmouthian," Not "Sangamonian," Age of the Gardiners Clay

New-, and to us convincing, chronostratigraphic information on the age of the Gardiners Clay came from H. C. Ricketts (1986), who collected shell material from two borings into the Gardiners Clay made near Kings Point (on Great Neck, west side of Manhasset Bay). Ricketts also collected shells from the shell-bearing gray silts, not the Gardiners Clay, exposed in the Port Washington sand pits, on Manhasset Neck, W side of Hempstead Harbor. Ricketts submitted these shells to Professor J. H. Wehmiller, of the University of Delaware, who is a specialist in determining the ages of shells by the changes with time (racemization) of the original amino acids. On the specimens collected from the Gardiners Clay, Wehmiller found D/L leucine values between 0.26 and 0.34, which implies that the age of the shells is about 225,000 years [225 ka]. (By comparison, a D/L value in shells from Nantucket that are thought to be 125,000 years old is about 0.20; Oldale and others, 1982.) In a general way, the age of the "Yarmouth" interglacial stage is 250,000 years, and that of the "Sangamon" interglacial, about 125,000 years.

A conflict of testimony comes from the shells from the gray silt formerly exposed in the Port Washington sand pits. This is the type locality of Sirkin and Stuckenrath's (1980) mid-Wisconsinan "Portwashingtonian warm interval." A radiocarbon date on shells Sirkin submitted came out at about 40 ka. Shells that Ricketts collected and sent to Wehmiller yielded D/L leucene values comparable to those from the shells from the Gardiners Clay in the Great Neck borings and thus imply an age of 225,000 years.

So now, which, if either of these dates is correct? They can both be wrong, but only one of them can be correct. We think that other compelling evidence supports Fuller's original age assignment for the Gardiners Clay to the "Yarmouth" interglacial stage. Accordingly, we accept Wehmiller's results based on the Ricketts specimens, and reject the radiocarbon results on which Sirkin has depended. In their discussion of the timing of Pleistocene events in New York State, Muller and Calkin (1993) reviewed this matter, but did not resolve it. They indicated (p. 1830) that:

"Stone and Borns (1986) propose that the name Gardiners Clay be reserved for brown marine clay and silt (sic) with interbedded sand and gravel of probable Sangamonian to Eowisconsinan age (Table 3). This action clarifies the age of the Gardiners Clay, and implicitly acknowledges the probability that marine clays of both Sangamonian and pre-Sangamonian age are present.")

We reject the Stone and Borns proposal. Although we agree with Muller and Calkin that it recognizes the possibility that two marine clays are present where only one has been generally believed, we think it definitely does not clarify the age of the Gardiners Clay but is nothing more than a gratuitous act of codifying a great error.

Pre-Late Wisconsinan" Age of the Harbor Hill Moraine

Much-neglected implications about provenance of the materials composing Long Island's two prominent moraines, Harbor Hill on the north and Ronkonkoma on the south, totally contradict the widely "believed" "Late Wisconsinan" age assignment that the revisionists accept as established fact and partly support Fuller's classification of their "Early Wisconsinan" age.

Part of the provenance data come from the published work of Sir Charles Lyell (1845) and J. B. Woodworth (1901) but much of it is based on our own research.

Sir Charles Lyell spent the winter of 1841-42 in New York City, during which time he made a few field trips to study the "drift," which at that time he believed had formed as a result of marine submergence and action of sediment-charged icebergs. He described what he saw in Brooklyn as follows:

"Long Island is about 130 miles in length, and the town of Brooklyn, on its western extremity, may be considered as a suburb of New York. This low island is every where (sic) covered with an enormous mass of drift or diluvium, and is the most southern (sic) point in the United States, where I saw large erratic blocks in great numbers. Excavations recently made in the Navy Yard at Brooklyn have exposed the boulder formation to the depth of thirty feet; the lowest portion there seen consisting of red clay and loam, with boulders of trap and sandstone, is evidently the detritus of the New Red Sandstone formation of New Jersey. This mass, in the sections where I observed it, was about 18 feet thick, and rudely stratified. Above it lay an unstratified (sic) gray loam, partly of coarse (sic) and partly of fine materials, with boulders and angular blocks of gneiss, syenitic greenstone, and other crystalline rocks, dispersed at random through the loamy base, the whole being covered with loam eight feet thick. One angular block of gneiss, which I measured, was thirteen feet long, by nine in breadth, and five feet high, but masses still larger have been met with, and broken up by gunpowder. Mr. Redfield, who accompanied me to Brooklyn, suggested that the inferior red drift may have been accumulated first when the red sandstone of the neighbouring country was denuded, and that afterwards, when the land was submerged to a greater depth, and when the gneiss and hypogene mountains of the highlands alone protruded above the waters, the upper drift with its erratics may have been thrown down. I am well disposed to adopt this view, because it coincides with conclusions to which I was led by independent evidence, after examining the districts around Lakes Erie and Ontario, viz. that the drift was deposited during the successive submergence of a region which had been previously elevated and denuded, and which had already acquired its present leading geographical features and superficial configuration" (Lyell, 1852, p. 189-190).

In modern terms, most geologists would now describe these two layers as consisting of till. The idea that submergence was involved in their origin is no longer accepted. We ascribe the color differences mentioned to flow of ice from different directions. We regard the upper gray till as being a product of the most-recent glacier to visit this area, which flowed from NNE to SSW, a direction that is down the Hudson Valley. The lower reddish till is a product of an older glacier that flowed from NNW to SSE, across the Hudson Valley. Nothing mentioned by Lyell establishes the age of this lower reddish till, but we correlate it with the deposits of the glacier responsible for the Harbor Hill Moraine.

As a result of his mapping of the glacial deposits of NW Long Island, Woodworth (1901) found the reddish-brown materials forming the Harbor Hill Moraine resting on a striated bedrock surface (in Long Island City, Queens); the striae were oriented NNW to SSE. This relationship proves that at least part of the Harbor Hill Moraine was deposited by a glacier that flowed across the Newark basin and across the Hudson River on a path from the NNW to the SSE. (See Figure 47.) Moreover, Woodworth found that these reddish-brown glacial sediments were not the youngest glacial deposits in the area, but were overlain by non-reddish till. [Walter S. Newman (1973, 1977) and W. S. Newman and Pike (1975) reported finding a till younger than that forming the Harbor Hill Moraine in western Long Island. We do not know what, if any, relationship exists between the post-Harbor-Hill till mentioned by W. S. Newman and W. S. Newman and Pike and Woodworth's non-reddish till.]

Our studies of the Pleistocene deposits and of glacially sculpted features on bedrock surfaces in New York City and vicinity (Merguerian and Sanders 1990, 1991a, d; 1992b; 1993a, b; 1994c; Sanders and Merguerian, 1991a, 1992, 1994b) re-affirm what J. B. Woodworth (1901) discovered in Queens, but that most subsequent workers have ignored. According to us, the distribution of stones in the Harbor Hill Moraine indicates that the flow pattern of the responsible glacier must have been from NNW to SSE. If this is correct, then the Harbor Hill Moraine was not deposited by the youngest (i. e., the so-called "Woodfordian") glacier, whose flow direction was from NNE to SSW. (See Figure 46, Table 3.)

We have found additional evidence on Staten Island that the glacier responsible for the Harbor Hill Moraine there flowed from NNW to SSE. This evidence consists of the orientation of a well-exposed glacial-tectonic recumbent fold in a displaced slab of Upper Cretaceous sediments exposed in the shore cliffs at Princes Bay, Staten Island (Sanders, Merguerian, and Okulewicz, 1995a, b). (See Figure 32.) We regard this new evidence that the Harbor Hill Moraine was deposited by glacial ice flowing from NNW to SSE as a further compelling argument that this moraine was not deposited by the so-called "Woodfordian" glacier, whose direction of flow was from NNE to SSW.

A key factor involved in this debate is direction of flow of the glacial ice. One of the chief contributions that we have made to knowledge of the local Pleistocene record is an emphasis on the features by which the direction of flow of a former glacier can be established. We follow the principle that a continental glacier can be characterized locally by a distinctive flow direction. We reject the concept that valley-glacier-like lobes can exist within a continental glacier.

Application of this principle has led us into direct conflict with one of the most-sacred of the beliefs zealously guarded by the local specialists in Pleistocene geology, namely that one glacier, the most-recent one, deposited both of Long Island's terminal-moraine ridges. (See Figures 37 and 39.) We have used the inferred ice-flow direction and composition of glacial sediments to test this concept. First the flow direction. In Connecticut; in Westchester County, NY; in Rockland Co., NY; and in northern New Jersey, the demonstrated direction of flow of the ice that deposited the youngest till is from NNE to SSW, a direction that is essentially DOWN the Hudson Valley. (See Figure 46.) Now for the composition. Because of the distribution of reddish-brown Newark type sedimentary rocks in Bedrock Unit 2 (See Figure 31), at our disposal are color-coded indicator stones that are uniquely valuable for reconstructing ice-flow patterns.

Now, if we suppose that the direction of flow of the last ice sheet was from NNE to SSW and that it flowed across Connecticut over to what is now the north shore of Long Island to deposit the Harbor Hill terminal moraine, then we can predict where reddish-brown rock fragments from central Connecticut should be present in the sediments being eroded along the N shore of Long Island. We have not found reddish-brown rock fragments in places where they should be present. In short, the test fails. Something is not correct. Is it the ice-flow direction? No, that has been confirmed throughout the region. What other options exist? We think as follows: The last glacier, the one that flowed from NNE to SSW, never reached most of Long Island. Rather, its terminus remained along the S coast of Connecticut. (See Figure 44.)

So much for what the Harbor Hill moraine is not. Let us now examine what it is. We start with J. T. Woodworth's data from Long Island City, where opposite the Queens County Courthouse, he found reddish-brown sediments composing the Harbor Hill Moraine resting on striated bedrock. The orientation of the parallel striae: N25°W to S25°E. Proof that this direction is not just a local aberration related to a flow lobe in the Hackensack Valley as in Salisbury's map (See Figure 38.) is shown by the finding of indicator stones of anthracite coal and the Green Pond Conglomerate (Figure 48). This absolutely convinces us that the latest glacier, which flowed from NNE to SSW, could not possibly have deposited the Harbor Hill Moraine.

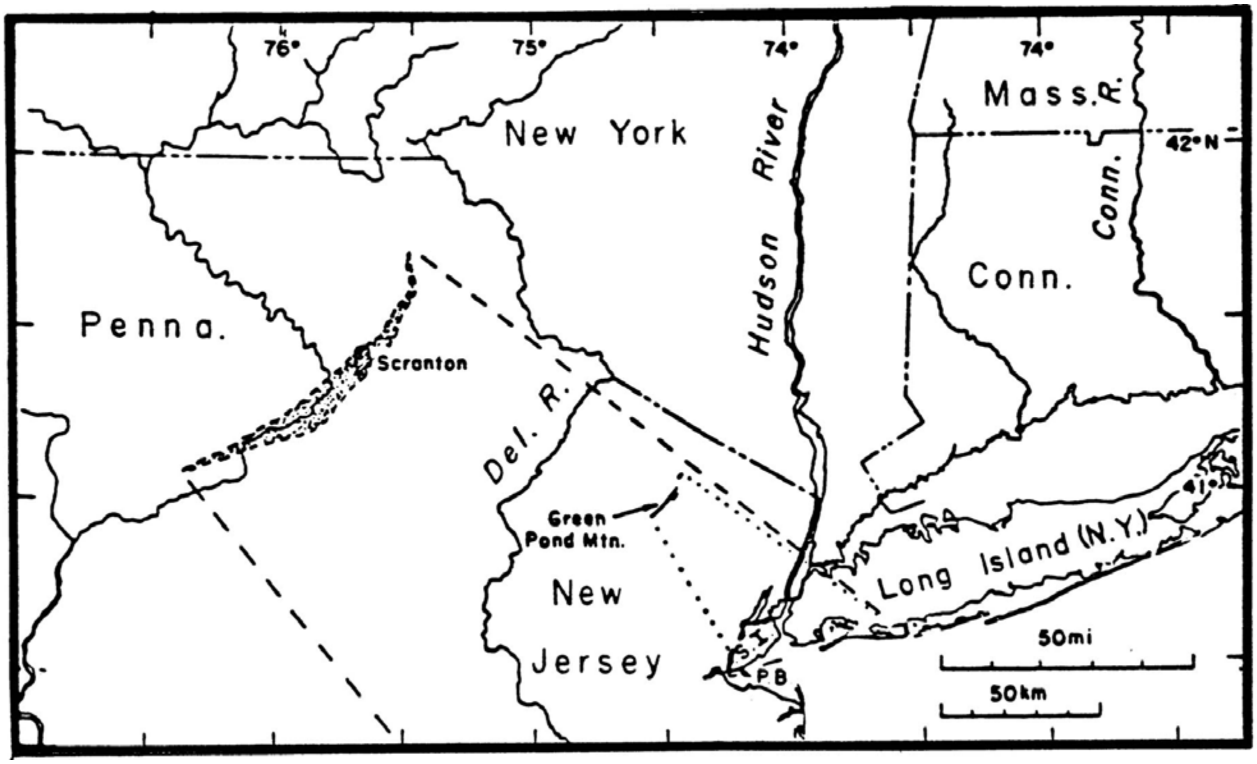


Figure 48. Distinctive indicator stones found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten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

Other evidence that the Harbor Hill Moraine is older than advertised is the well-developed paleosol that caps it, as seen in the cliffs along Princes Bay, SW Staten Island. Putting these two factors together indicates that J. H. Wilson's flow-line map drawn in 1906 is correct in showing regional rectilinear flow from NNW to SSE for the Harbor Hill Moraine but wrong with respect to age and its presumption that the same glacier deposited both of Long Island's terminal moraines.

BASES FOR MODIFYING FULLER'S CLASSIFICATION

Our reasons for proposing modifications to Fuller's classification are based partly on our own research, both in the field and in the library, and partly on the published work of others that many specialists have been ignoring. Our own research has covered the provenance implications with respect to age of Long Island's two prominent moraines; on new evidence we have found demonstrating the regional significance of lake deposits in Fuller's Manhasset Formation; on the subsurface relationships at Jones Beach, Long Island, between inferred outwash units and marginal-marine strata of possible "Sangamonian" age; and on our discovery of two much-weathered, probable Early Pleistocene sediments.

Stratigraphic Implications of Lake Long Island Sediments

The finding that a proglacial lake existed near- or on Long Island is not particularly newsworthy. Previous workers have found typical laminated proglacial lake deposits in the subsurface around Flushing Bay (Lake Flushing) found on continuous-seismic-reflection profiles in Long Island Sound (Block Island, etc.). Already mentioned was the lake backed up the Hudson Valley behind the dam at The Narrows that reached all the way to Albany and received the overflow from the Great Lakes when the ice blocked the St. Lawrence lowland. What is so special about what we are calling Proglacial Lake Long Island is our finding of demonstrable lake sediments in the lower part of Fuller's Manhasset Formation, which he interpreted as stream deposits on outwash fans. We elaborate on the paleogeographic significance of the difference between deposits on fans and in a lake in a following section.

We first discovered south-dipping layers of sediment along the N shore of Long Island during our On-The-Rocks Trip 15 to Sands Point on 17 November 1990. Just a few days prior to our trip, storm waves had stripped away all the fan sediments that had accumulated at the base of the bluff and had also removed most of the beach sediments. While we were walking around marvelling at all the storm-related changes, I noticed a series of parallel lines on the ground that I interpreted as the outcrop of dipping layers of sediment. We dug a small trench perpendicular to shore and found an extensive series of south-dipping brown sandy sediments underlying a thin veneer of black rippled beach sediment. On 29 June 1991, we led the annual field trip of the Long Island Geologists Association to this locality and were able to dig another trench to show the S-dipping layers. By then, the thickness of beach sediments had built up to 30 cm. or so. We offered the interpretation that the S-dipping brown sands might be of Cretaceous age and had acquired such a dip from ice-thrust action (as is known from the exposures in the Port Washington sand pits not far to the SW). One of the trip participants, Mr. Steven E. Englebright, from SUNY Stony Brook, suggested another possible interpretation for the south dip: rotation of Pleistocene strata on a curving slump surface.

On 15 April 1993, we revisited Sands Point to see what had happened during the winter storms of late 1992-early 1993. Looking E from where the trail leads to the beach, we noticed extensive S-dipping layers in the bluff, and thought at first we were seeing the kind of thing Engelbright had mentioned. But, when we got "up close and personal" and did some digging, we found a third, totally unexpected (yet absolutely convincing) possibility, namely the south-dipping layers are the foreset parts of a Gilbert-type delta (Figure 49) that had been built into a proglacial lake. The horizontal contact between horizontal topset layers overlying the truncated dipping foreset layers not only demonstrates an origin on a Gilbert-type delta but also indicates the former water level of the vanished proglacial lake. These newly exposed deltaic sediments were exactly similar to those illustrated- and discussed by J. B. Woodworth in 1901.

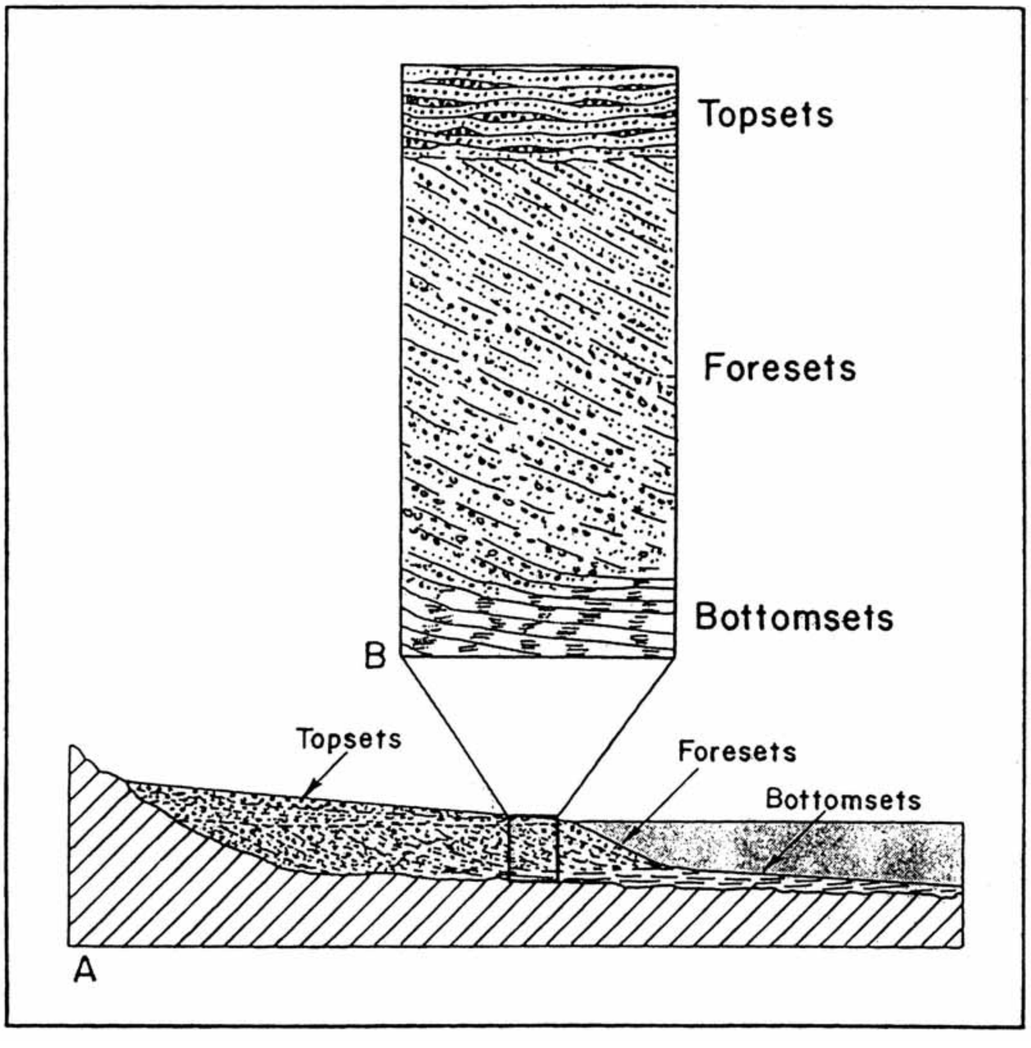


Figure 49. Three contrasting strata deposited on a Gilbert-type delta, where a shallow channel debouches into water that is much deeper than the channel. Note that horizontal topsets truncate dipping foresets. (G. M. Friedman and J. E. Sanders, 1978, fig. B-7,A, p. 502.)

Subsequently, we have found deltaic strata at every exposure along the N coast of Long Island from Sands Point to Jacobs Point and at Montauk Point on the S coast. The finding of proglacial lake sediments along the N coast does not present any unusual paleogeographic difficulties with respect to how a lake could have formed with its water plane 60 feet or more above existing sea level. The glacier itself made a very effective dam to the north. (See Figure 41.) But, the exposures at Montauk Point are something else again.

At Caumsett State Park, these deltaic sediments contain abundant gravel including partly decomposed stones. At Target Rock, bottomset beds rest on Till IV. At Montauk Point, we interpret the dipping layers of poorly sorted Manhasset rudites as sketched by Fuller in his figure 156, p. 143 (Figure 50), and considered by some as ice-deformed tills, as being sublacustrine-deltaic debris-flow deposits (visible only before the U. S. Army Corps of Engineers tried to stop erosion at Montauk by installing erosion-protective structures near Montauk Lighthouse. These sublacustrine debris-flow deposits may be restricted to eastern Long Island. If so, then their absence in the deltaic sediments farther W can be logically explained as being controlled by facies changes.

In many localities, lake-marginal coarse sediments grade into lake-bottom silts and -clays. The relationships at Montauk Point imply that Lake Long Island was there dammed on the S by a now-vanished natural dam. Only two possibilities need be considered: a peripheral bulge or a terminal-moraine ridge.

In light of the compelling evidence from eastern Long Island that a now-vanished terminal moraine must have been present to confine the waters of Lake Long Island on the south, we propose significant revisions to the morphostratigraphic correlations mentioned above. We think that the Ronkonkoma Moraine should be tied to the Buzzards Bay-Sandwich Moraine. (See Figure 45.) What becomes of the Charlestown Moraine on the E side of Narragansett Bay is not clear. The Nantucket-Martha's Vineyard moraines should not be tied to the Ronkonkama Moraine, but rather to the much-submerged pre-Ronkonkoma Moraine that held in the waters of Proglacial Lake Long Island and possibly also the delta-forming lake of Cape Cod Bay, etc., held in by the now-submerged moraine shown as boulder shoals on continuous seismic-reflection profiles. It would be the southernmost moraine of the "triplets."

Such revised morphostratigraphic correlations of the moraines imply that in southeastern Massachusetts, much-older tills than supposed are present.

According to Fuller, the Manhasset Formation overlies the Gardiners Clay, which he assigned to the "Kansan/Illinoian" interval ("Yarmouthian" interglacial). If this is correct, then the age of these extensive proglacial-lake deposits could be "Illinoian." The only way they could be any older is if the age of the Gardiners Clay is not correct. As mentioned in a foregoing paragraph, MacClintock and Richards (1936) reclassified the Gardiners Clay as Sangamonian. They considered this change as supporting the interpretation that Fuller's Manhasset Formation belonged in the "Wisconsinan."

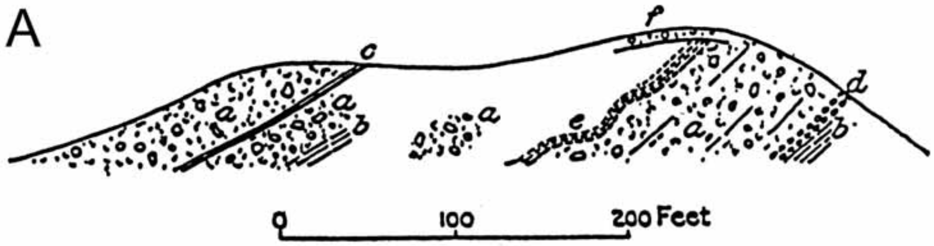


FIGURE 157.—Section half a mile south of Culloden Point, Montauk, showing intercalated sand and clays in Montauk till member. *a*, Montauk till member; *b*, clayey sand; *c*, clay; *d*, gravel; *e*, sand; *f*, Wisconsin till.

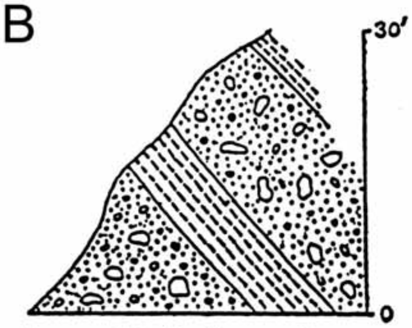


FIGURE 156.—Section 1 mile west of Rocky Point, Montauk, showing intercalated bed of gravel in Montauk till member.

Figure 50. Dipping interbedded strata composed of diamictons and clays, coastal cliffs near Mauntauk Point, NY. Fuller inferred that the coarse units were the Montauk Till, but we have reinterpreted these as subaqueous debris-flow deposits belonging to the deltaic facies of the Manhasset Formation. (M. L. Fuller, 1914, A, fig. 157; B, fig. 156, both on p. 143.)

Subsurface Relationships at Jones Beach: Sangamonian Interstadial Deposits?

The finding by Rampino (1978 ms.) of two pebbly sands separated by gray shell-bearing silts/sands in numerous shallow borings made in the vicinity of Jones Beach (Figure 51) provided other evidence bearing on the relationships of the Harbor Hill- and Ronkonkoma moraines. Formal stratigraphic names have been proposed for these units, each new name accompanied by a described section in a designated type boring (Rampino and Sanders, 1981, p. 118-121; 127). From base upward, these names are: Merrick Formation (for the lower pebbly sand, inferred outwash); Wantagh Formation (for the gray shelly silt/sand unit); and Bellmore Formation (for the upper pebbly sand, inferred outwash). Rampino and Sanders inferred that the lower outwash (Merrick Formation) was related to the Ronkonkama terminal-moraine ridge; and the upper outwash (Bellmore Formation), to the Harbor HIll terminal-moraine ridge.

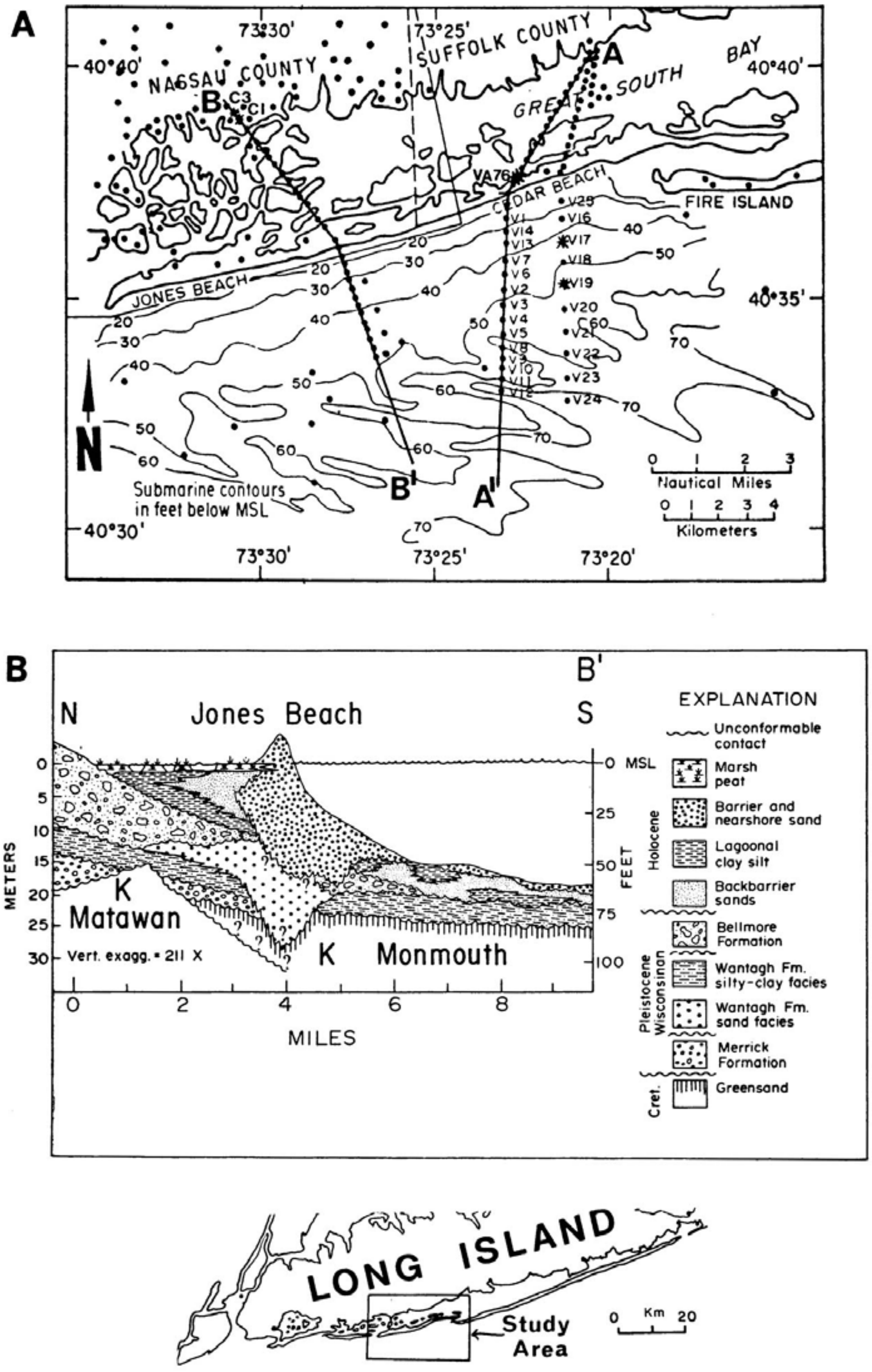


Figure 51. Shallow subsurface relationships, Jones Beach and vicinity. (M. R. Rampino and J. E. Sanders, 1981b; a, fig. 3, p. 118; b, fig. 4, p. 119.)

A. Location map of lines of borings used to prepare stratigraphic profile-sections. Line B-B' locates Jones Beach profile-section. Rectangle on map of part of Long Island locates the borings-index map.

B. Jones Beach profile-section showing tripartite Pleistocene succession consisting of Merrick Formation, Wantagh Formation, and Bellmore Formation. Further explanation in text.

The Wantagh Formation is the same unit as the "20-foot clay" of the U. S. Geological Survey (Perlmutter, Geraghty, and Upson, 1959, Table 1, p. 420, p. 422; Doriski and Wilde-Katz, 1983) and may be the same as the gray, silty shell-bearing unit formerly exposed in the Port Washington sand pits. Clearly, the Wantagh Formation qualifies as being "interglacial"; it is the product of deposition along the edge of a high-standing sea. It also separates two units of inferred outwash. Although no other chronostratigraphic information is available, the appearance between two outwashes of a marginal-marine formation implies that the two outwashes were not deposited by the fluctuating margin of a single glacier, but rather are products of discrete glacial stages. At the present time, our best guess is that the age of the Wantagh Formation is "Sangamonian." Based on the descriptions in Oldale (1982), we think that the Wantagh Formation may be correlative with the Sankaty Sand exposed at Sankaty Head, Nantucket Island, Massachusetts:

"The marine beds exposed at Sankaty Head appear to be Sangamonian in age. This is based on D/L Leucene (sic) values which suggest that the Sankaty Sand is no younger than 80,000 yrs BP and no older than 200,000 yrs BP, and that the lower (sic) and upper parts are, within a few thousand years, the same age. Specifically, the D/L Leucene (sic) values tend to favor an age estimate of about 120,000 to 140,000 yrs BP (J. F. Wehmiller and D. F. Belknap, written commun., 1981). Detrital coral from the upper part of the Sankaty Sand also provide (sic) a `no older than' (sic) age of 133,000 ñ 7,000 yrs BP (B. J. Szabo, written commun., 1981). Taken together this (sic) absolute age (sic) data clearly suggests (sic) an early Sangamonian age for the marine beds. The radiocarbon dates on shell material and wood deposits are too young. The shells dated have been contaminated by biocarbonate and recrystallized and the wood samples have been contaminated by modern roots and younger humic acid (E. C. Spiker, written commun., 1981). However, the ages of the dated material, given that they are older than the radiocarbon ages, indicate that the marine beds are older than mid-Wisconsinan and are not correlative to the middle Wisconsinan warm interval proposed by Sirkin and Stuckenrath (1980)" (Oldale, 1982, p. 13-14)

[We add that Sirkin and Stuckenrath's radiocarbon dates, which Oldale and Sirkin accept as correct, are subject to the same problems for the Massachusetts mentioned by Oldale. If the Port Washington radiocarbon dates are not currect, then the mid-Wisconsinan age goes out the window and these units may be correlative after all, and thus the age of both would be "Sangamonian." Oldale doesn't mention the Rampino subsurface work at Jones Beach.]

Quoting further from Oldale:

"Since (sic) the lower drift at Sankaty Head underlies marine deposits of probable Sangamonian age it is reasonable to assume that it is Illinoian or older in age. A finite radiocarbon date of 26,200 ñ 500 yrs BP (W-4615, Table 2) from the lower drift is unreliable and hence cannot be used to establish a maximum (sic) or "no older than" (sic) age for the lower drift. The problem with this date is clearly shown on Table 2 for it occurs stratigraphically below much older (sic) dates. This is probably the result of the wood sample being contaminated by modern roots and younger humic acid.

Our Discovery of Two Much-Weathered, Probable Early Pleistocene Tills

At Croton Point Park, Westchester County, NY, the stratigraphic superposition of at least 3, possibly 4 tills can be demonstrated (Figure 52). The oldest, exposed at the water's edge at Enoch's Nose, is a gray till containing erratics of ultramafic rocks from the Cortlandt Complex and decayed granitic stones. We assign it to Till IV [possibly = "Kansan"(?)]. Till IV is overlain by reddish-brown till III containing partly decayed mafic stones. If pressed for a guess on its age, we would vote "Illinoian." Gray varved lake deposits containing isolated dropstones overlie this reddish-brown till III. We assign the gray clay to the deglacial episode of Glacier I ("Woodfordian" of local usage). Farther north along the shore of the Hudson River, the gray clay is not present, but two red-brown tills (II and III?) are separated by red-brown outwash (Merguerian and Sanders, 1990a, 1992c; Sanders and Merguerian, 1991, 1994b). We assign the upper of these two reddish-brown tills to Till II ("Early Wisconsinan" according to Fuller, 1914) and the lower, to till III possibly the "Illinoian." The upper red-brown till is overlain by a yellowish-brown till shaped into a drumlin having a long axis trending N-S, which we assign to Till I (the "Woodfordian" of local usage).

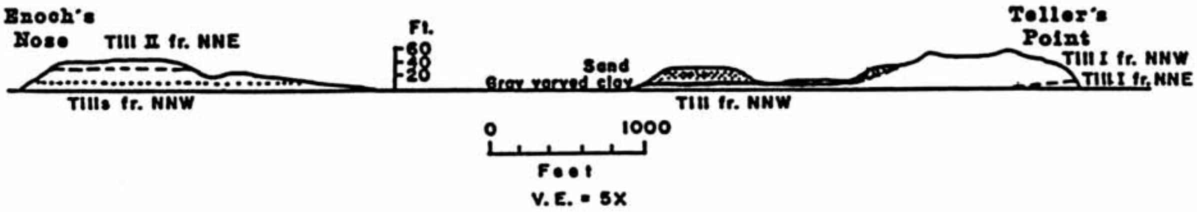


Figure 52. Profile-section of Pleistocene sediments along a N-S line from Enoch's Nose to Teller's Point, Croton Point Park, Westchester County, NY, drawn using Geraghty and Miller's June 1974 topographic map (Figure GG-28). The numbering system of the tills shown is by age and flow direction. In Table GG-2, Till II from the NNE is Till IV; the tills from the NNW are Tills III and II, respectively; and Till I from the NNE is Till 1. (J. E. Sanders, in Merguerian and Sanders, 1992e, fig. 42, p. 109.)

At the AKR Excavating Company in SW Staten Island, the oldest till in the region, that we assign to the Nebraskan(?), is well exposed.

At Garvies Point, red-brown till containing decayed stones cuts into white Cretaceous sand. We infer that this decayed-stone, red-brown till correlates with the old brown till at AKR.

CONCLUSIONS

In conclusion, we have found additional evidence from the published-, but generally overlooked, work of others that likewise supports Fuller's age assignments, both with respect to the age of the Harbor Hill Moraine and to the assignment of the Gardiners Clay to the "Yarmouthian" of Fuller (NOT the "Sangamonian" of the revisionists). Finally, foreset beds of Gilbert-type deltas in the Lower Manhasset Formation, recently exposed in localities from Sands Point, on the NW, to Montauk Point, at the extreme SE corner of Long Island, are distinctive parts of the complex of lacustrine sediments deposited in Lake Long Island. Exposures of these lacustrine sediments in a coastal cliff facing the open Atlantic Ocean at Montauk Point oblige us ask what kind of natural dam existed out there to confine the waters? Was what is now the ocean bottom formerly bulged up far enough at the periphery of the glacier to have been the dam? Or should we invoke the former existence of a third significant terminal moraine, one that lay south of and was older than the Ronkonkoma Moraine and that has been submerged and converted into a bouldery shoal? Without bothering about the details, J. B. Woodworth (1901), the only previous worker who recognized these lake sediments, concluded that a terminal moraine answered for the "missing" dam that held in the waters of Lake Long Island on the south and east. As far as we can determine, Fuller was not aware that the Manhasset Formation consisted of widespread lacustrine deposits and hence he did not have to face the "missing"-dam question, nor did he imagine that the family of Long Island moraines might consist not of twins but possibly of triplets. We propose to restore the Manhasset Formation to Fuller's "Illinoian" position. If we are correct in associating the Montauk Till with the Ronkonkoma Moraine, then this moraine must be shifted downward from Fuller's "Early Wisconsinan" position to the "Illinoian."

Thus, our five main reasons for resurrecting- and modifying Fuller's (1914) classification are: (1) provenance data indicating that the latest-Wisconsinan ("Woodfordian" of authors) glacier, which flowed from NNE to SSW, did not reach most of eastern Long Island; (2) provenance- and structural data supporting the interpretation that the glacier which deposited the Harbor Hill Moraine flowed regionally from NNW to SSE and was of pre-"Woodfordian" age (we accept Fuller's "Early Wisconsinan" assignment); (3) subsurface data from the vicinity of Jones Beach suggesting an "Illinoian" age for the glacier that deposited the Ronkonkoma Moraine (earlier than Fuller's "Early Wisconsin"), and Gilbert-type deltas in the Herod Gravel Member of Fuller's Manhasset Formation (Sanders, Merguerian, and Mills, 1993; Sanders and Merguerian, 1994b) that not only absolutely destroys the basis for the revisionists' "Wisconsinan" age reclassification of Fuller's Manhasset Formation but also requires Fuller's non-lacustrine paleoenvironmental analysis to be significantly modified by including the requirements for impounding a large lake, probably requiring a now-eroded, pre-Ronkonoma terminal moraine; (4) the new-, and to us convincing, chronostratigraphic information supporting Fuller's "Yarmouthian" age of the Gardiners Clay that H. C. Ricketts (1986) collected from two borings made near Kings Point (on Great Neck, west side of Manhasset Bay) on which J. H. Wehmiller, of the University of Delaware, found D/L leucene values between 0.26 and 0.34, which implies that the age of the shells is about 225,000 years [225 Ka]; and (5) our discovery of two much-weathered tills, not yet dated but presumably of Early Pleistocene ages.

Our proposed classification of the Pleistocene deposits of the New York City region is close to Fuller's but differs in that we recognize products of five (not four) glacial advances. (See Table 3.) Because we lack evidence for assigning ages to the products of these various glacial episodes, the best we can do is count them down from the top. Accordingly, we designate each of the tills (and its formative glacier) by a roman numeral, starting with I, the youngest, at the top, and ending with V, the oldest, at the bottom. (See Table 3.)

According to us, Glacier I flowed from NNE to SSW and did not reach most of Long Island; it deposited the fields of drumlins in Rockland County, NY and the yellowish-brown till forming a single drumlin at Enoch's Nose, Croton Point Park, Westchester County, NY; the Hamden Till in south-central Connecticut; and a terminal moraine along the S coast of Connecticut (SW of the Norwalk Islands, it crossed what is now Long Island Sound and covered Queens, Brooklyn, and at least some of Staten Island). At Pelham Bay Park, it deposited the ultramafic Cortlandt erratics and locally cuts down to bedrock (Sanders, Merguerian, Levine, and Carter, 1997). Here, till- and outwash strata have been repeated by ice-thrust deformation. Based on the freshness of the component minerals, infer that it occurred during Glacier I time. A possible Glacier I/II interglacial deposit is the paleosol capping the reddish-brown till in the coastal bluffs of SW Staten Island.

Glacier II, flowing from NNW to SSE reached all of Long Island and deposited the Harbor Hill Moraine and reddish-brown till at Croton Point Park and other localities on the E side of the Hudson River in Westchester County and New York City, the upper red till at Pelham Bay Park, and possibly also the Lake Chamberlain Till of south-central Connecticut. Glacier II/III interglacial marginal-marine sediments include the Wantagh Formation of the Jones Beach subsurface (the "20-foot clay" of geologists from the U. S. Geological Survey Water Resources Branch).

Glacier III, the most-extensive of them all, also flowed from NNW to SSE and featured three fluctuations; its earliest advance deposited a now-vanished and -submerged terminal-moraine; the ice front then retreated and a regionally extensive proglacial Lake Long Island formed in which the lacustrine sediments forming the lower member of Fuller's Manhasset Formation were deposited; a subsequent readvance deposited the Montauk Till; and after another retreat and deposition of outwash sediments, a final readvance deposited the Ronkonkoma Moraine. Glacier III/IV interglacial deposits include the Gardiners Clay.

Glacier IV flowed from the NNE to the SSW, deposited a gray-brown till exposed at water's edge, Teller's Point, Croton Point Park and in the lower part of the coastal bluff at Target Rock National Wildlife Refuge, Long Island; and sculpted many rock exposures in the Hudson Highlands, in northern Manhattan, and in the New York Botanical Garden and the roche-moutonnée structure at the N end of Pelham Bay Park, both in The Bronx. We have not found any Glacier IV/V interglacial deposits.

Glacier V flowed from NNW to SSE and deposited the much-decomposed reddish-brown tills resting on the Upper Cretaceous coastal-plain strata at the AKR Excavating Company, SW Staten Island, and at Garvies Point, Long Island.

Our modified-Fuller scheme (See Table 3) revives the all-but-defunct multi-glacial interpretation, downplays the importance in most of Long Island of the latest Wisconsinan ice sheet (we think it did not extend as far south as Nassau and Suffolk counties), and emphasizes the vast regional importance- and complexity of the "Illinoian" glaciation. Acceptance of our classification sounds the death knell to all regional correlations of Pleistocene sediments that are in any way tied to the revisionist age assignments of Fuller's Long Island units; it puts these correlations in the category of "ideas lacking visible means of support."

APPENDIX 1: HUMAN ALTERATION OF NEW YORK'S LANDSCAPE

The effects of human beings on the landscape of New York City have been considerable. Lowlands and coastal marshes have been filled in and on top of the fill, streets and railways have been built. Subways and water tunnels have been excavated. Bridges have been constructed. The most-comprehensive human-created changes to the local landscape are the work of Robert Moses [1888-1981]. During his unparalleled 44-year career, Moses extensively altered all City parks and added hundreds of new ones. He built six major bridges (Henry Hudson, Triborough, Marine Parkway, Bronx-Whitestone, Throgs Neck, Verrazano-Narrows), the United Nations building, Shea Stadium, the Coliseum, the Interstate highways, and nearly all of the public-housing projects (Caro, 1974). The following quotations are from Robert Caro's (1974) book: The power broker. Robert Moses and the fall of New York: New York, NY, Alfrd A. Knopf, 1246 p. + index xxxiv
p.

(p.330) "In a weed-filled vacant lot in Riverdale just north of the Harlem River stood a marble column a hundred feet high with a strangely unfinished look about its top. There was (sic) supposed to be a statue up there, a statue of Hendrick Hudson, for the vacant lot had been purchased by the city as the northern bridgehead of a `Hendrick Hudson Bridge' that was supposed to ease the congestion on the Broadway drawbridge, and a statue of the Great Navigator was supposed to look down on the span that bore his name. But although the lot had been purchased, and the column erected, in 1909, in 1932 work had still not started on the statue--or the bridge."

"And marching across low-lying Ward's Island in the East River were seventeen massive masonry piers, each of them forty feet thick, eighty feet long, more than a hundred feet high. These piers had been erected to support the central span of the `triborough bridge,' first proposed in 1910, that would link together at last Manhattan, the Bronx and Queens. But in 1932 the piers had been standing for more than two years, and there was (sic) still no bridge for them to support--and the hope that there ever would be (sic) was rapidly fading."

(p.331) "Some of the city's choicest public beach front--in Wolfe's Pond Park on Staten Island and at Orchard Beach in the Bronx, for example--was rented to political insiders, who, for a fee of fifteen dollars, were allowed to erect private bungalows on it, and to form `civic associations' that promulgated regulations closing the beaches to the public."

(p.340) "And Moses gave the reformers something as valuable as his organization. He gave them his vision. No sooner had he become chairman of the Metropolitan Park Conference than he began driving endlessly around New York. The big black Packard that had once been pulled up in the yards of Long Island farmhouses was parked now at the edge of the lonely marshes on the shore of Jamaica Bay, in the empty, rocky fields on a deserted Bronx// (p. 341) peninsula known as Ferry Point; and at the spot on Riverside Drive to which, twenty years before, he had taken taxicabs while he was conceiving his great highway along the Hudson. And while his chauffeur waited in the car, he was walking around, with the same long, restless strides with which he had covered Long Island, lost in concentration, occasionally making sketches on a yellow legal note pad.

"On February 25, 1930, before five hundred civic leaders gathered in the Grand Ballroom of the Hotel Commodore for the Park Association's annual dinner, Robert Moses, dressed in tuxedo and black tie (tied by Mary), rose to his feet and tugged a cord which dramatically pulled the drapery from a huge map of New York City hanging behind the dais. Running across the map were heavy red lines. One, which started in Brooklyn at the Brooklyn Bridge, ran (sic) along the borough's western (sic) and southern shores, skirting Jamaica Bay, and then, in Queens, headed north along the city's eastern boundary. The shore-front portion, Moses said, was a `Marginal Boulevard'--he had not yet named it the `Belt Parkway'--which would provide a quick circumferential passage around Brooklyn. The portion that ran (sic) north along the city boundary was a `Cross Island Parkway.' A third of the way up its length, it crossed and linked up with the Southern State Parkway. Two-thirds of the way up, it crossed and linked up with the Northern State and with the proposed Grand Central Parkway. And at its end was a bridge--a `Ferry Point-Whitestone Bridge,' he called it, not yet having named it the `Bronx-Whitestone'--that would enable motorists to speed across Long Island Sound. And then...

"The audience's eyes followed the pointer in Moses' hand. At the northern end of the Ferry Point-Whitestone Bridge was another line, heading northeast to link up with the Hutchinson River Parkway that he had already built in Westchester County almost as far north as the Connecticut border. This, Moses said, was a `Hutchinson River Parkway Extension.'"

(p.363) "Moses himself spent a lot of time at Orchard Beach, a very low, very narrow sand bar that linked together the eastern edges of Hunters Island and Rodman Neck, two of the little wooded pieces of land at the eastern fringe of Pelham Bay Park that were washed by the water of Long Island Sound. Here, in New York's northeastern corner, so far from any built-up areas in 1934 that visitors could hardly believe they were still within the borders of America's largest city, was located New York's most ambitious (sic) park project. When Moses arrived, $346,750 had been spent on bathhouses, a breakwater (sic) and a retaining wall running behind the sand bar and designed to turn the bar into a bathing beach convenient to the bungalows of the six hundred families, Bronx Democratic stalwarts all, to whom most of Hunters Island and Rodman Neck had been leased. The engineer who designed the bathhouses, which were constructed of granite paving stones and had cost $84,000 apiece, had apparently been inspired by the Black Hole of Calcutta; the only ventilation in the thirty-foot-high buildings was provided by a few narrow slits near the ceilings. The breakwater (sic) had been run out into the Sound through the very center of the beach, thereby splitting it in two and// (p. 364) forcing anyone wanting to get from one half to the other to climb over the top--which wasn't easy, since (sic) the breakwater designer had neglected to include steps. But the location of the retaining wall made reservations about the splitting of the beach irrelevant. The engineer who designed the wall had apparently seen the sand bar only at low tide; he had placed the wall so close to the water that, for most of the day, the waves lapped right up against it--and there was (sic) no longer any beach left to be split."

(p.364) "Moses dispatched teams of engineers to `inventory' New York City's parks--their acreage [incredibly no one knew their exact size (sic)], the buildings, paths, roadways, statues and equipment in them, the condition of these items and the type (sic) and amount of labor and materials that would be required to renovate them. He filed this information in a loose-leaf notebook kept atop his desk. By the time he was (sic) sworn in as Park Commissioner, the notebook was more than a foot thick, and he had a list of 1,800 urgent renovation projects on which 80,000 men could immediately be put to work.

"But renovation was only a small part of Moses' plan. Day after day during the bitterly cold November and early December of 1933, while the great city lay inert in the grip of its long malaise, Robert Moses was being chauffeured around it in the big Packard, Hazel Tappan beside him with a stenographer's note pad open in her lap. Twenty years before, as a young staffer at the Bureau of Municipal Research, Robert Moses had wandered around New York City `burning up with ideas, just burning up with them.' Now Moses was not young--one of the days he spent in the big Packard was his forty-fifth birthday--but he was still burning. `Sometimes it seemed to me that his voice never stopped,' Miss Tappan recalls. `Things just kept pouring out of him. I remember once we were downtown someplace and he wanted to see some underground garage--for sanitation trucks or something--under a city building there to see if it would interfere with some plans he had for putting a park on the street near it and we started to go down this spiral ramp and it was getting darker and darker and he was still dictating. And finally it was almost pitch-black (sic) and he was still dictating. To this day I can see it getting darker and darker and that voice going on and on. Until finally I had to say, `Mr. M! Mr. M! Wait a minute! I can't see!"

"By late December, the outline of his ideas for large-scale park construction (sic) projects was ready, and now, crowded into the Packard with him and Miss Tappan were his Long Island engineers. They came in relays. One crew would drive with him to certain parks--describing these trips, one engineer echoed Frances Perkins' words of two decades before, `Everything he saw made him think of some way it could be better'--and then that crew would go back to Babylon and translate his ideas into general engineering plans while another would head out with him to other parks.

"Relays were needed to keep up with him. `His orders just poured out,' recalls the engineer. `Bam! Bam! Bam! So fast that we used to all try to take them down at once so that when we got out to Babylon we could put them together and maybe get one complete list of everything he wanted. You'd start at dawn--hell, sometimes we'd start before dawn; I remember// (p. 365) driving around Manhattan when everybody was still sleeping except the milkmen, maybe, and the cops on the beats. I remember once a cop really jumping when that big black car filled with men came around a corner in front of him--and by late afternoon, I can tell you, your head would be just absolutely spinning. But he'd still be firing things at you.' Didn't they break for lunch? `You didn't break for lunch when you were out driving around with Robert Moses.'

"Soon the engineers' concepts of his ideas were being presented for his approval.

"With few exceptions--City Hall is perhaps the most notable--the public works of New York City were hack work designed by hacks. But the men driving around with Robert Moses were not hacks. They included the unknown young architects, landscape architects and engineers--the Herbert Magoons and Earle Andrewses--responsible for Jones Beach and the other highly acclaimed Long Island parks. And they included Major Gilmore D. Clarke and Aymar Embury II. Clarke, designer of the Bronx River Parkway and other outstanding examples of highway beautification, was in 1934 the most famous (sic) landscape architect in the United States; he had been in the process of retiring from public work to accept lucrative private assignments. Embury, an architect, had designed Princeton University's classic Class of 1915 Dormitory and many of Long Island's most beautiful (sic) estates--parks in themselves. In 1934, he had waiting for him `more private business commissions than he could handle in a decade.' Moses persuaded Clarke and Embury to come to work on New York's parks.

(p.365) "As had been the case with the famous architects who had gathered around him on the barren sand bar called Jones Beach a decade earlier, however, some of the men with him in the big Packard in 1934 had difficulty grasping the extent of his vision. When the plans came in for Riverside Park, where twenty years before, he had dreamed of a great highway along the water, a highway that would cover the ugly tracks and cleanse the West Side of Manhattan of the smoke (sic) and stench from the trains that ran along it, they left the tracks uncovered. The engineers told him that to cover them would add millions to the cost of the park development--for which at the moment there was (sic) almost no money at all in sight, not to mention the additional millions that would be needed to build the Henry Hudson Bridge across Harlem River Ship Canal and a parkway linking the bridge with the Saw Mill River Parkway. Moses told them to worry only about the plans; he would worry about getting the money for them.

"Exasperated with their plans for Orchard Beach, he loaded the architects into the big Packard and drove out onto barren, snow-covered Hunters Island.

"Standing under winter-stripped trees on a little hill that rose (sic) out of the marshes that fringed the islet, he looked across at Rodman Neck, four hundred yards away, at the sand bar, covered now with a thin scum of ice, that held them tenuously together, at the Tammany-built breakwater (sic) and Hole of Calcutta (sic) bathhouses, and at the six hundred private bungalows. // (p.366)

"The sand bar would never be a decent bathing beach as long as those monstrosities were there, he said. He wanted them torn down; he didn't care how much they had cost--tear them down! And tear down those goddamned bungalows--yes, all six hundred of them. He had been spending a lot of time wandering around up here in the afternoons, he said, and he had decided that the beach should consist of more than just the sand bar. If it extended all the way around the eastern shore of both Hunters Island and Rodman Neck, it would be almost a mile long and almost crescent-shaped (sic). In fact, if it extended over to the Twin Islands--he pointed to two islets to the northeast separated from Hunters Island by two narrow strips of water--the length could be a full mile and the shape of the crescent perfect. He wanted the beach extended to the Twin Islands, he said; the strips of water couldn't be very deep; fill them in. And he wanted the sand on the beach to be gleaming white ocean sand like the kinds at Jones Beach and the Rockaway beaches, not their present coarse, pebble-filled gray Long Island Sound sand. The sand could be dredged off the Rockaway beaches and then brought here by barge, up the East River to the Sound. Behind the beach, paralleling its mile-long crescent, he wanted a bathhouse--designed with the same imagination, the same attention to detail, as the bathhouses at Jones beach, he said; he didn't want it looking like the typical public bathhouse. But that didn't mean it should look like the Jones Beach bathhouses, he said; if his men looked around him, they would see that the setting here was very different from that at Jones Beach. The setting there was the long, low sweep of sand and sea; here it was hills and trees. The Jones Beach bathhouse had been long and low, its lines horizontal; the lines here should be more vertical--perhaps they should start thinking about columns, maybe even a colonnade. He would leave it to them, but he didn't want any of them forgetting that the function of a bathhouse wasn't to impress or overawe; it was to help people have a good time--he wanted it light, airy and gay. And for God's sake, he said, use this kind of imagination on the city's other parks--all the city's parks."

(p.508) "During the 1930's, Robert Moses reshaped the face of the greatest city in the New World.

"He gouged great gashes across it, gashes that once had contained houses by the hundreds and apartment houses by the score. He laid great swaths of concrete across it. He made it grayer, not only with his highways but with parking fields, like the one on Randall's Island that held 4,000 cars, the one at Orchard Beach that held 8,000 and the one at Jacob Riis Park that held 9,000, that together covered with asphalt a full square mile of the 319 in the city. And he made it greener, planting within its borders two and a half million trees, shrubs, and vines, bringing a million others back to bloom, reseeding lawns whose area totaled four square miles and creating a full square mile more of new ones. He filled in its marshes and made them parks. He yanked railroad trestles off its avenues, clearing an even dozen from Brooklyn's Atlantic Avenue alone as part of a grade-crossing elimination (sic) program he considered so minor that he seldom mentioned it. He brought stars down to it, arranging, in a brief interval crammed in between more important (sic) projects, for the financing of Hayden Planetarium. He changed its very shape: the millions of cubic feet of rock and shale and sand and stone that the long convoys of his barges and the endless caravans of his trucks dumped behind the steel bulkheads that he rammed out away from its shoreline into the muck beneath rivers and harbors hardened into new land, more than 5,000 acres of new land, and thus expanded and transformed its physical contours, adding to Manhattan Island alone an area as large as the island from river to river between Fifty-ninth and Eighty-sixth streets. He joined together small islands within its borders with earth, blending Ward's Island into Randall's and Hunters and Twin Islands into Rodman Neck. He soldered together the larger islands that were its boroughs with steel, linking three of them together at once with the Triborough Bridge, tying the West Bronx to Manhattan with the Henry Hudson, drawing the far-flung Rockaways closer to the rest of metropolis with the Marine Parkway span. In the five years after he became Park Commissioner, in a city in which the parks had been barren for decades, he made the parks bloom. In a city in which there had been (sic) only 119 playgrounds, he built 255 new ones. In a city in which not a mile of new arterial highway had been built in fifteen years, he built fifty miles of arterial highway. In a city in which a new bridge had not been built in a quarter of a century he built not only the three new big bridges--Triborough, Henry Hudson and Marine Parkway--but 110 smaller ones to carry local streets across his parkways. Si monumentum requiris, circumspice, reads the inscription on the tomb of Sir Christopher Wren. If you would see his monument, look around. By 1939, the same advice could have been given to a New Yorker asking to see the monuments of Robert Moses. They were everywhere in the great city."

(p.573) "The attitude of the press was reflected in the attitude of the public. At one Kiwanis Club luncheon, held in March 1934, the assembled Kiawanians applauded his speech, but during the question-and-answer period that, under Kiwanian tradition, followed the speech, one member of the audience said that he was disturbed by newspaper reports that Moses was intending to revoke all camping privileges at Orchard Beach immediately. `As one of the campers at Orchard Beach,' he said, `will you grant us the privilege for a committee to interview you and put before you our story about the beach?'

"`No, sir,' Moses replied--`calmly and finally,' according to the Herald Tribune. `The camps are coming down.' The camper tried to protest the arbitrariness of the decision, but he was drowned out--by the strains of the song sung by the rest of the audience to usher Moses out: `For He's a Jolly Good Fellow.'

(p.618) "Robert Moses had built public works on a scale unmatched by any other individual in the history of America. But all the highways and parks and bridges he had built were little more than nothing next to the highways and parks and bridges that Robert Moses wanted to build. He had turned into reality his dream of a great parkway along Manhattan's shoreline, but there was (sic) still the Brooklyn shoreline, and the Staten Island. He wanted parkways there, too--a `Circumferential' or `Belt' for Brooklyn, a `Shore' for Staten Island--and he had wanted them, and had been arguing for their creation for more than ten years. He had built fifty miles of highways in the city, but there were (sic) a hundred more miles that he wanted to build. He had reshaped to his own vision an urban park system that absolutely dwarfed any other urban park system in the United States, but the parks he had created in New York were in their turn dwarfed by the parks that he dreamed of creating; it had been 1930 when he had proposed a Soundview Park and a Flushing Meadows Park and two Marine Parks and a park--the greatest of all urban waterfront parks--in Jamaica Bay, and now it was 1938 and these parks were still only proposals. Where was the Rockaway Improvement? Even those parks that he had been able to create in the city, moreover, had not been created as he wanted; he had been forced to scale them down, to use inferior materials, to compromise. As for bridges, he had built in the city three, including one that was the greatest traffic-moving machine in the history of civilization, but he wanted to build at least four more--including one even larger than Triborough."

(p.828) "The working lifespan of the elemental force that was Robert Moses defied comparison with the working lifespan of other men. Robert Moses had been in power, shaping Long Island, in 1924. He was in power, tirelessly shaping not only Long Island but the great city stretching out toward it, in 1934, and 1944, and 1954, as he would be in 1964--until 1968, in fact. Other men hold real power--shaping power, executive authority--for four years, or eight, or twelve. Robert Moses held shaping power over the New York metropolitan region for forty-four years.

"Was the tirelessness of his work and its duration comparable to a natural force? So was the result of that work--the sum total of the accomplishment, the Things he Got Done. As natural forces shaped the city and its suburbs east of the Hudson, the 2,100-square mile (sic) region on which by 1974 dwelt more than 12,000,000 human beings, so did he.

"He changed the course (sic) of rivers, filling in the beds of the Harlem and the Bronx and cutting new channels for them, shoving to one side the mighty St. Lawrence, making new curves in the swift Niagara. In filled in the city's frayed edges, transforming into solid earth

Great Kills on Staten Island, the Flushing Meadows in Queens, a dozen other vast marshes. Nature gave the region one shoreline; he gave it another, closing inlets in the barrier beaches, cutting new inlets, reshaping miles of beach dunes. For mile after mile, the earth and rock that constitute the shoreline of Brooklyn and Queens, and of Manhattan's Hudson shore are his, the grass and shrubs and trees that adorn them are his--as are the concrete and steel of the marinas, the shoreline overlooks, the parking fields, the bicycle paths, the runways and airport terminals, and, of course, the shoreline parkways. Not nature //(p. 829) but he put them there. His bridges bound together Long Island and the mainland of the continent, torn apart by glaciers eons before. His causeways reunited the Island with its barrier beach. He hacked out lagoons, filled lakes, made beaches, welded islands together, cut, at Inwood Hill, through a primeaval forest substantially unaltered by the hand of man since the dawn of time. He altered the region's skyline, leveling great areas of the low, regular tenement foothills and replacing them with slim, tall spires two hundred, three hundred feet high--civic (sic) and cultural edifices, great groves of apartment houses. By the close of the Age of Moses, for example, the skyline along much of the eastern shore of Manhattan Island that was the heart of metropolis--a skyline that was, to a great extent, Governor Smith Houses, La Guaradia Houses, Corlears Hook Houses, Baruch Houses, Lillian Wald Houses, Jacob Riis Houses, Stuyvesant Town, Peter Cooper Village, Bellevue Hospital, NYU-Bellevue Medical Center, the United Nations, Rockefeller Institute, New York Hospital, East River Houses, Woodrow Wilson Houses, Senator Robert F. Wagner, Sr., Houses, Abraham Lincoln Houses, Riverton Houses, North Harlem Houses, Harlem River Houses, Colonial Park Houses--was, for miles at a time, a Robert Moses creation. Do forces of nature--volcanoes, earthquakes, avalanches--destroy whole towns and villages, forcing populations to flee? What force destroyed Spuyten Duyvil, Sunset Park, the Syrian Quarter near the Battery, a dozen other neighborhoods as big as towns?"

"Robert Moses believed his works would make his name immortal..."

"...the roads of Rome stood for two thousand years and more; who would predict less for the roads of Moses? Who would predict less for his Shea Stadium, a structure consciously shaped to resemble Rome's Colosseum because he was afraid that his convention center (sic)-office tower `Coliseum' didn't make the comparison clear enough? As for the parks he created, fly over New York in the year 1999, and the two thousand acres of Brookhaven Park and the four thousand acres of Connetquot on Long Island and the 21,000 other acres of park that Robert Moses wrested away from the developer's bulldozer to insure that the people of New York would always have green space will still be green, a tribute to his foresight. For //(p. 830) how long will the great bridges that he built--the Verrazano, the Triborough, the Whitestone, the Throgs Neck, the Henry Hudson, the Cross Bay, the Marine--endure. The life of a suspension bridge, engineers tell us, is measureless. Atomic attack or natural catastrophe could render all New York shapeless. Barring such monumental calamity in centuries to come discerning historians will, if they look for it, be able to see writ plain throughout the great city and its suburbs evidence of the shaping hand of Robert Moses."

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	(Passive-margin sequence 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). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported above deposits of continental shelf.
		Shallow-water clastics and carbonates accumulate in west of basin (= Sauk Sequence; protoliths of the Lowerre Quartzite, Inwood Marble, part of Manhattan Schist Fm.).
(Cambrian)		Deep-water terrigenous silts form to east. (= Taconic Sequence; protoliths of Hartland Formation, parts of Manhattan Schist Fm.). (Passive-margin sequence I).

PROTEROZOIC

	570	Period of uplift and erosion followed by subsidence of margin.
(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,	Bellvale Fm., lower unit

marine)	(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].

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

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

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

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Manhattan Schist (Om - lower unit).
Normanskill Fm. / Annsville Phyllite

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

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

LAYER IIA[W] - SAUK SEQUENCE	**LAYER IIA[E] - TACONIC SEQUENCE**
Western shallow-water platform (L. Cambrian-M. Ordovician)	Eastern deep-water zone (L. Cambrian-M. Ordovician)
Copake Limestone	Stockbridge
Rochdale Limestone	or Inwood Marbles
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm.
Stissing Dolostone	(in part).
Poughquag Quartzite	
Lowerre Quartzite [Base not known]	

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus [Layer II = passive continental margin I] ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). Followed by a period of uplift and erosion. 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.

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

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

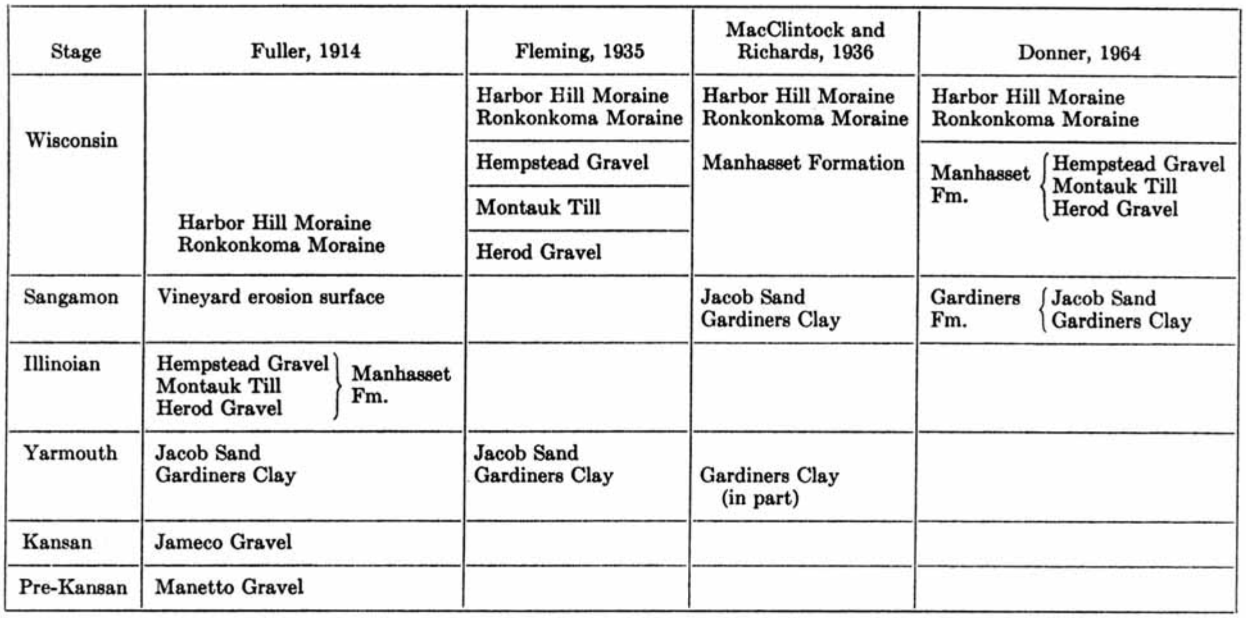
~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~

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

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

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

Table 04 - Formations of Pleistocene age in Long Island showing original arrangement by Fuller (1914) and changes proposed by three subsequent workers. (From Muller, 1965.)



Stage	Fuller, 1914	Fleming, 1935	MacClintock and Richards, 1936	Donner, 1964
Wisconsin	Harbor Hill Moraine Ronkonkoma Moraine	Harbor Hill Moraine Ronkonkoma Moraine Hempstead Gravel Montauk Till Herod Gravel	Harbor Hill Moraine Ronkonkoma Moraine Manhasset Formation	Harbor Hill Moraine Ronkonkoma Moraine Manhasset Fm.: Hempstead Gravel Montauk Till Herod Gravel
Sangamon	Vineyard erosion surface		Jacob Sand Gardiners Clay	Gardiners Fm.: Jacob Sand Gardiners Clay
Illinoian	Manhasset Fm.: Hempstead Gravel Montauk Till Herod Gravel			
Yarmouth	Jacob Sand Gardiners Clay	Jacob Sand Gardiners Clay	Gardiners Clay (in part)	
Kansan	Jameco Gravel			
Pre-Kansan	Manetto Gravel			

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