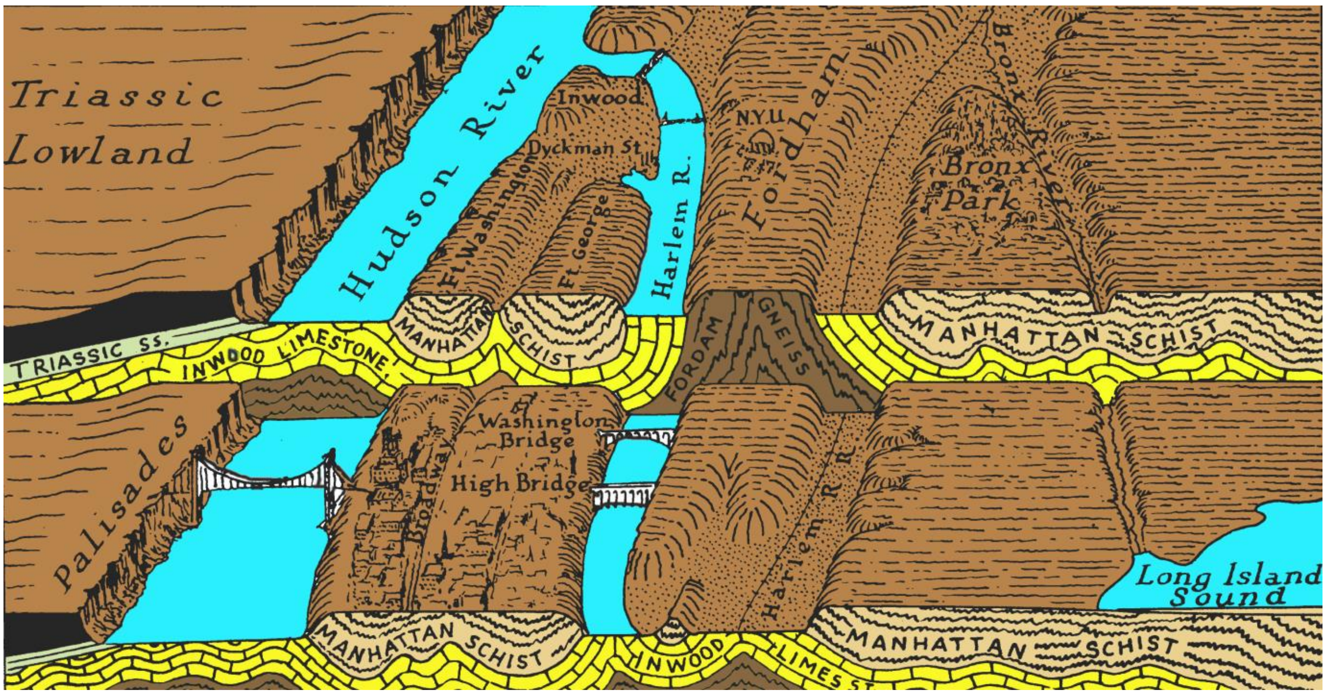
DUKE GEOLOGICAL LABORATORY
**Web: [www.dukelabs.com](http://www.dukelabs.com)**
**E-Mail: info@dukelabs.com**

# Long Island Association of Professional Geologists

## From Rocks to Ice: Geology of the NY Botanical Garden, Bronx, NY

**Saturday, 06 April 2024; 10:30 AM – 12:30 PM**




Physiographic block diagram of the Bronx, northern Manhattan, the Harlem (East River) and Hudson Rivers and New Jersey showing the generalized structural geology and major drainage controls of the region. (Drawing by A. K. Lobeck, Columbia University, 1939. Colorized by CM.)


**Field Trip Notes by:**

**Charles Merguerian, PhD, PG**
**Dukelabs.com**
**Stone Ridge, NY 12484**

**J. Mickey Merguerian, MSci**
**DukelabsDSC.com**
**Westbury, NY 11590**

**CONTENTS**

DUKE

**DUKE GEOLOGICAL LABORATORY**
**FIELD TRIP GUIDEBOOK © 2024**

# Long Island Association of Professional Geologists

## From Rocks to Ice:
## Geology of the NY Botanical Garden, Bronx, NY

**Saturday, 06 April 2024; 10:30 AM – 12:30 PM**

**Logistics:**
**Meet:** 10:15 AM near the Visitor's Center at the Main Entrance gate off Southern Boulevard
**Main Gate Address:** 2900 Southern Boulevard, Bronx, NY 10458
Itinerary: 12 Stops Planned – Return: ~12:30 PM

### INTRODUCTION

Several public parks in the Bronx display relationships that are critical to evaluating older (~1950s) interpretations of the geological structure, glacial history and neotectonics (seismicity) of the New York City (NYC) area. (See cover figure.) The modern refinement and correlation of stratigraphy in metamorphic terrains, structural mapping and identification of major ductile shear zones has allowed for revisions in the plate tectonic interpretation of the NYC area. Studies of glacial features throughout NYC including Long Island have resulted in a complex glacial model for the region. These combined "Rocks to Ice" relationships displayed in the Garden include:

1) the **bedrock layers** - notably the stratigraphy and structure of the Paleozoic schistose rocks and the geometry and structural history of Cameron's Line and the St. Nicholas thrusts), and,
2) the **morphologic history** of the region (particularly the number- and directions of Quaternary glaciations and age of the Bronx River gorge in the New York Botanical Garden), and,
3) that **"valley capture"** of the Bronx River suggests postglacial seismicity and attendant ground offset along the right-lateral NW-trending Mosholu fault which bears on the potential for future earthquakes in NYC.

Today's trip will focus on 12 readily accessible localities ("stops") within the NY Botanical Garden (NYBG) in the Bronx that best demonstrate our views on the bedrock and glacial geology of the Garden (Figure 1). Table 1 is a geological timescale keyed to NYC to help in understanding the following geological discussion. Table 2 lists the layers found here.

For the past fifty years, CM has concentrated his investigative efforts on studying the stratigraphy and structural geology of the Paleozoic metamorphic rocks of NYC with special emphasis on lithostratigraphy and identifying ductile- and brittle faults in the region. Merguerian the younger (JMM), bit his teeth during such bedrock studies as a child as we could not afford a babysitter and he developed a keen eye for geological structure in the meantime. We have conducted research and published field data together for over twenty years.

Today's field "experience" will address three major topics. First, we offer a detailed view of selected bedrock exposures in the Garden where the evidence for collapsed eons of geological time can be visualized. Here, we will focus on the evidence recorded in the rocks of Layer II (See Table 2.) that places the presently exposed rock surface of the Garden within the former deep levels of a 450-million-year-old arc-continent collision zone where the "fire" of plutonism and regional metamorphism resulted from overthickening of continental materials and then ultimately, the creation of alpine mountains. Thus, one goal of today's trip is to present our new geological map of the Garden and to outline the methods we've used in unraveling or "reading" the geology of these complexly deformed metamorphic rocks. We intend to show participants the subtle details of the various schistose rocks of NYC and present tectonic interpretations of the Paleozoic bedrock and in doing so identify the southerly extent of the Taconic allochthon.

A second, allied goal of today's trip is to expose participants to the rich glacial history exposed in the Garden which is based upon joint research performed here with the late Dr. John E. Sanders [1926-1999]. Our joint studies provided hypotheses concerning the glacial- and drainage history of New York City. Here we can visualize the effects of "ice" on the sculpted bedrock outcrops which have now been reduced to mere rolling hills and to determine ancient flow directions of the various Pleistocene glaciers. Indeed, the Garden hosts abundant evidence for multiple glaciations from two contrasting directions – a view not shared by all practicing geologists but emblazoned on the bedrock surfaces and explained in detail by Sanders and Merguerian (1991a, b, 1994b, 1997a, 1998). We intend to present evidence in support of the much-maligned Fuller (1914) stratigraphic interpretation of the Pleistocene glacial deposits of the region.

Thirdly, we will discuss and examine the startling evidence for ground rupture thousands of years ago during a post-glacial NYC earthquake when the Bronx River was diverted away from a former pre-made marble valley (Webster Avenue valley) only to be forced to cut a steep V-shaped canyon through resistant crystalline rocks past the Snuff Mill site. Here, we present new arguments in support of Kemp's (1897) view of the postglacial age of the Bronx River gorge in contrast to the pre-glacial age proposed by Schuberth (1968). Participants will be treated to spirited question and answer sessions throughout the trip with two active research scientists on the geology of the NYBG.

The Garden is centrally located in the Bronx, NY near Fordham University and major roads (Figure 1). Utilizing geologic maps and -cross sections, the following paragraphs describe the geologic background of today's field trip area and present with abridged historical perspective the origins of geological concepts concerning the bedrock that underlies the NYBG.

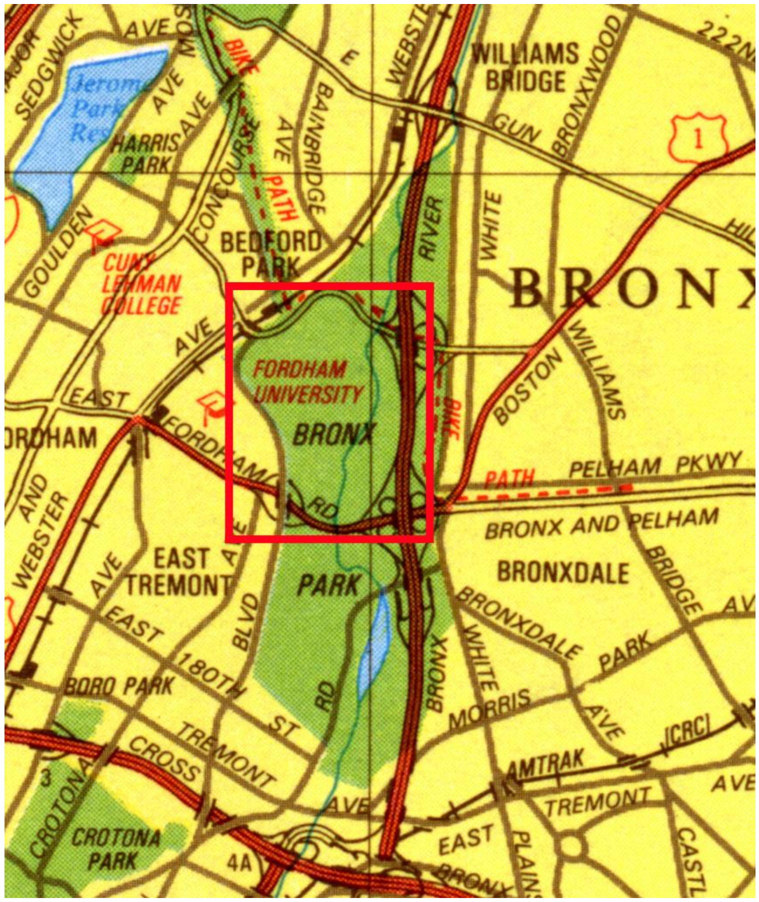



**Figure 1** – Location map of the NY Botanical Garden which is bounded on the east by the Bronx River Parkway, on the south by East Fordham Road, on the west by Southern Boulevard and on the north by the Mosholu Parkway. Rectangular inset shows the Garden footprint. Outline of maps of the NYBG shown as a red rectangle. (Hagstrom).

## GEOLOGIC BACKGROUND

The NYBG is located in the central Bronx, NYC and is situated at the southerly terminus of the Manhattan Prong (Figure 2), a region of low rolling ridges and valleys underlain by a northeast-trending, deeply eroded sequence of Proterozoic- to Lower Paleozoic metamorphosed crystalline rocks. South of NYC, the crystalline rocks of the Manhattan Prong plunge southwestward and disappear beneath a gently inclined covering of Cretaceous coastal-plain sedimentary strata and an overlying blanket of Pleistocene (glacial) drift. A continuation of this same belt of Appalachian metamorphic rocks reappears exposed southward at the Earth's surface in the vicinity of Philadelphia, Pennsylvania and extends from there southwestward along the east coast spine of the United States. Now uplifted, eroded and presented pre-polished at the Earth’s surface we have an opportunity to “read” the rocks on today’s walk through the Garden.

West of Manhattan Island, in New Jersey, the bedrock of NYC is overlain a series of gently west-dipping sedimentary rocks of Late Triassic to Early Jurassic age which overlaps and buries the deeply eroded bedrock series. As indicated in the west-east cross section from New Jersey to Manhattan (Figure 3), the W-dipping Mesozoic sedimentary rocks of the Newark

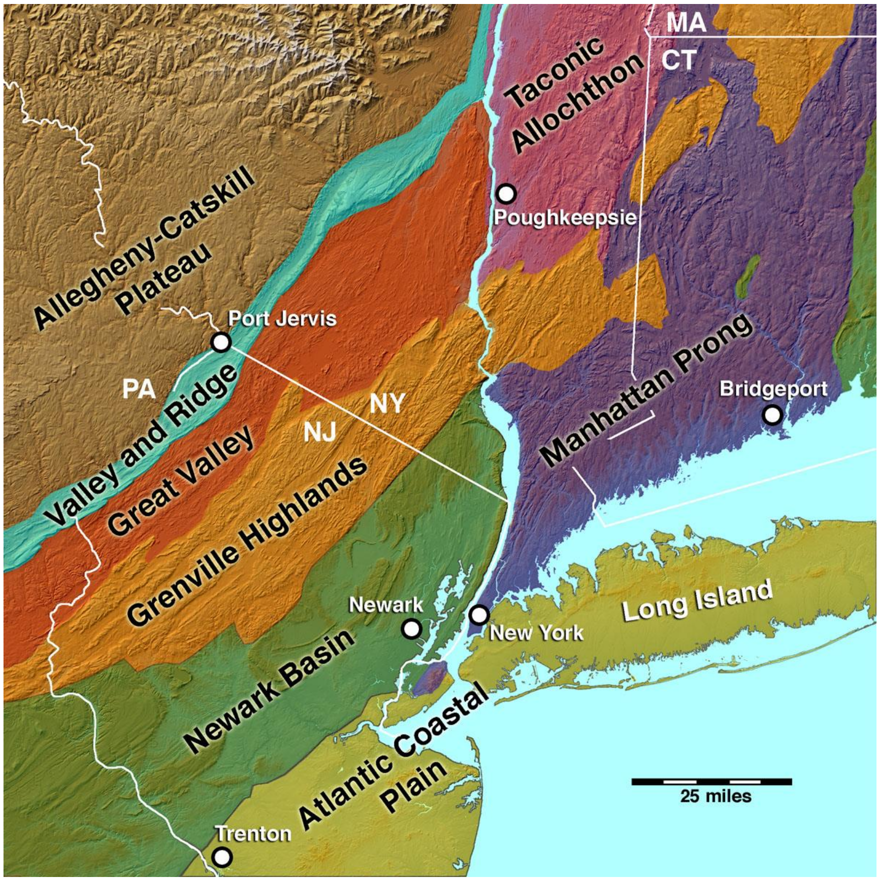



**Figure 2** - Physiographic diagram showing the major geological provinces in southern New York, northern New Jersey, and adjoining states. The NYBG is in the Manhattan Prong. (From Bennington and Merguerian, 2007.)

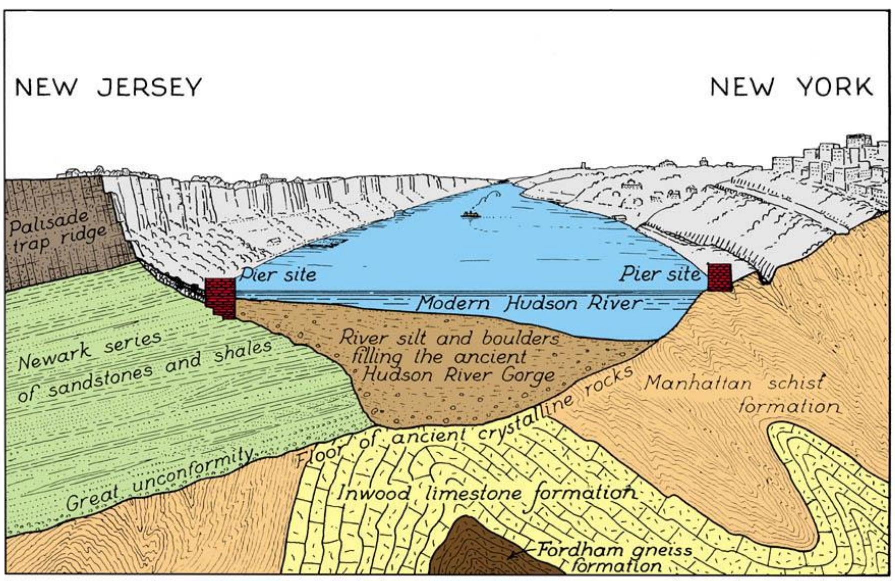



**Figure 3** - West-east profile-section across Hudson River at George Washington bridge, showing geologic relationships determined from study of exposed rocks and of borings made for the footing of the western tower of the bridge. (Colorized by CM from Berkey, 1948.)

Basin have been intruded by the Palisades intrusive sheet whose tilted- and eroded edge forms prominent cliffs along the western margin of the Hudson River channel. The Mesozoic sequence lies on a pre-Triassic surface of unconformity that projects out of the Hudson River valley and skirts over the crystalline rocks of Manhattan and the Bronx. Note, in Figure 3, the asymmetric west-vergent folds in the bedrock units of Manhattan beneath the pre-Triassic planation surface and the depiction of a simple, folded "layer-cake" arrangement of the bedrock units.

**BEDROCK UNITS**

Under this section we describe the history of bedrock investigations, details of the geology of Layers I, IIA, and IIB, and the specifics of the stratigraphy-, geologic structure-, and metamorphic geology of NYC and the Bronx. (See Tables 1, 2.)

Although the rocks underlying the Bronx were first studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, detailed geologic mapping began in the mid- to late 1800s to earliest 1900s by W. W. Mather and F. J. H. Merrill, respectively. The first geologic map of the New York City area was published in Mather's treatise on the Geology of the First District of New York in 1843. Mather's map of New York City (Figure 4) shows the distribution of Primary granite, gneiss, "limestone of New York County", serpentine (on Staten Island), and alluvial sand and marshland. His detailed map of Manhattan shows the topography with limited orientation data on the bedrock strata. Mather's Plate 3 included two geologic cross sections (reproduced in Figure 5) that illustrated the structure of New York City in sections parallel and perpendicular to foliation strike. The sections are not very detailed but show depth to bedrock at numerous places and proposed that the substrate of New York City consists of granite and gneiss of great age (Primitive Series = Proterozoic of modern usage).

By the turn of the century, many geologists were examining New York City as building construction and industrial development blossomed. We direct the interested reader to read Merguerian and Sanders (1991b) for a complete history of NYC bedrock investigations and to consult the original sources including reports by Merrill (1886a, b; 1890, 1891a, b; 1898a, b, and c) on the glacial- and metamorphic geology of New York City, examination of metamorphic rocks in Dutchess County by James D. Dana (1880, 1881, 1884) and the Harrison granodiorite gneiss in adjacent Westchester County by Heinrich Ries (1895), and J. F. Kemp's studies (1887, 1895, 1897), which have together provided important contributions to our knowledge of both the glacial- and bedrock geology of southeastern New York.

In 1890 (p. 390), Merrill named the Manhattan Schist to include all of the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, New York. Merrill (1890) states that *"the name Manhattan Group was proposed by R. P. Stevens, Esq., to include the rocks of New York Island"*.

Merrill proposed "Group" status to include the Manhattan Schist, the Inwood limestone (sic), Fordham Gneiss, and the Yonkers Gneiss. Later, in 1902, Merrill and coworkers correctly correlated the Fordham gneiss with Proterozoic sequences of the Hudson Highlands. Formal

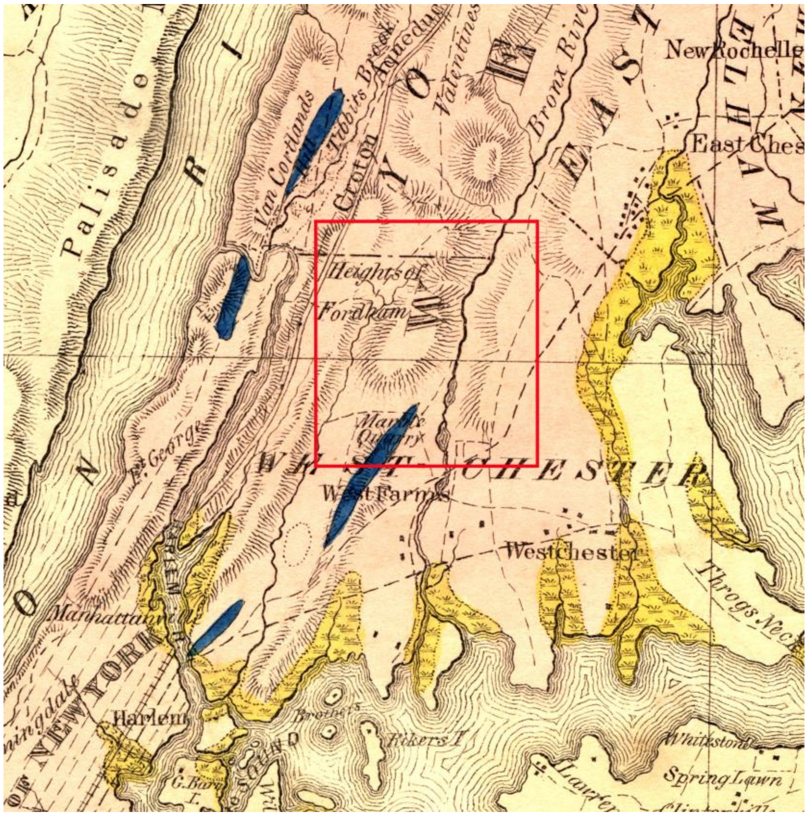



**Figure 4** – Mather's (1843) USGS Folio geological map showing the crystalline rocks of New York City (light pink), all considered a part of the Primitive series (Proterozoic of modern usage). Lenticular blue areas identify Inwood Limestone (marble). General position of the NYBG shown as a red rectangle.

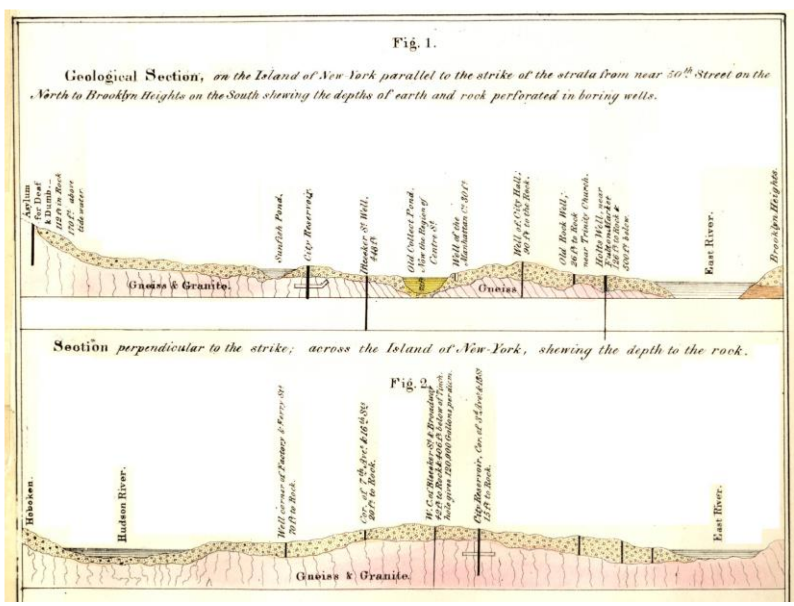



**Figure 5** - Profile-sections of Manhattan and Brooklyn showing depth to bedrock based on borings. The upper section is parallel to the strike of the rocks and extends from 50th Street, Manhattan (at L) across the East River to Brooklyn Heights. Lower section crosses lower Manhattan through old City reservoir (3rd Ave. and 13th St.) from Hoboken on the west (L) to the East River (R). (Mather, 1943, pl. 3, figs. 1 and 2.)

removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiogenic dating techniques and detailed mapping of lithologies by the 1960s and beyond. Formal "de-Grouping" of the "Manhattan Group" took place after spirited debate at a Symposium on the New York City Group of Formations at the 1968 meeting of the New York State Geological Association at Queens College in Queens, New York (Alexandrov, ed., 1969).

F. J. H. Merrill (1890, 1902), in concert with other geologists published the first comprehensive geologic map of New York City in the United States Geological Survey New York City Folio (Merrill, Darton, Hollick, Salisbury, Dodge, Willis, and Pressey, 1902). In this compilation Merrill outlined in map form the basic stratigraphic- and structural framework that modern geologists would test, promote, and amplify upon (Figure 6). Merrill's major contribution was subdivision of Mather's (1843) Primitive Series into mappable units. He first defined the correct relative chronology of the basal Proterozoic Fordham Gneiss ([fgn] = brown with white stippled pattern in Figure 6), the overlying Cambrian to Silurian (sic) Stockbridge dolomite ([ⱾSs] = light pink-colored areas with block pattern in section of Figure 6) and the Silurian (sic) Hudson Schist ([Sh] = pink areas in Figure 6 now known as the Manhattan Schist and associated older Paleozoic schistose rocks).

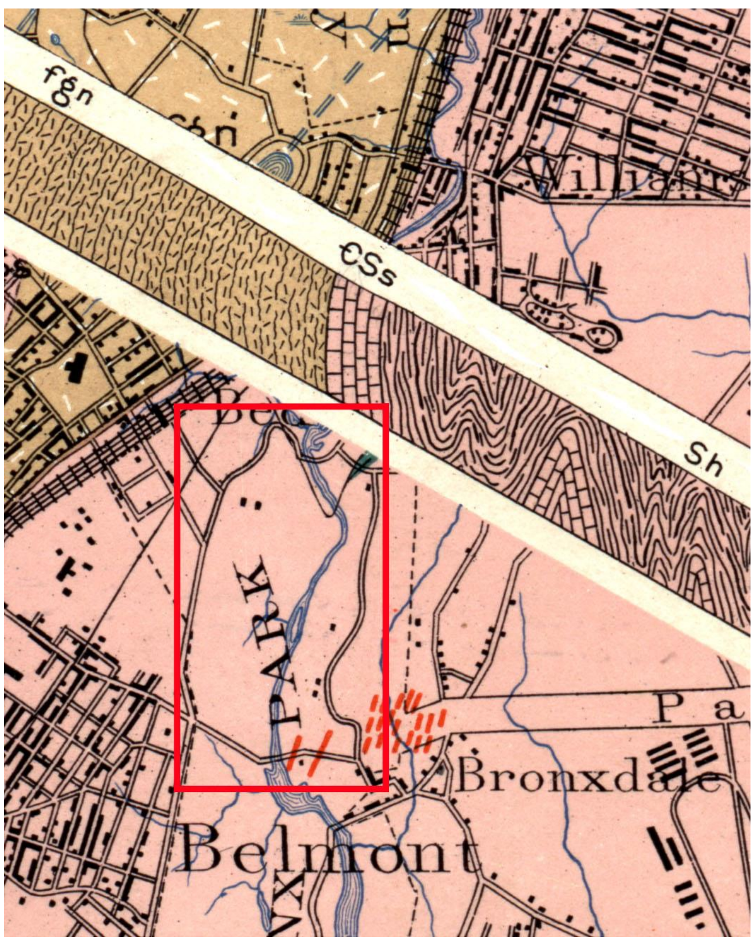



**Figure 6** – Map and diagonal section of Merrill et al (1902) USGS folio map of the region of the Bronx that includes the NYBG (red rectangle) and shows a simplified view of the folded structure of NYC bedrock.

Following major revisions in thinking about the stratigraphy and structure of NYC (Merguerian, 1981a, 1983a; Merguerian, Baskerville and Okulewicz, 1982; Baskerville and Merguerian, 1982, 1983; Mose and Merguerian, 1985, and Merguerian and Sanders 1991b), Baskerville's (1992) USGS map of the Bronx showed a more complex geological interpretation of NYC that embraced some of the stratigraphic and structural ideas proposed by many in the 1980s. His map of the region surrounding the NYBG is shown below as Figure 7.

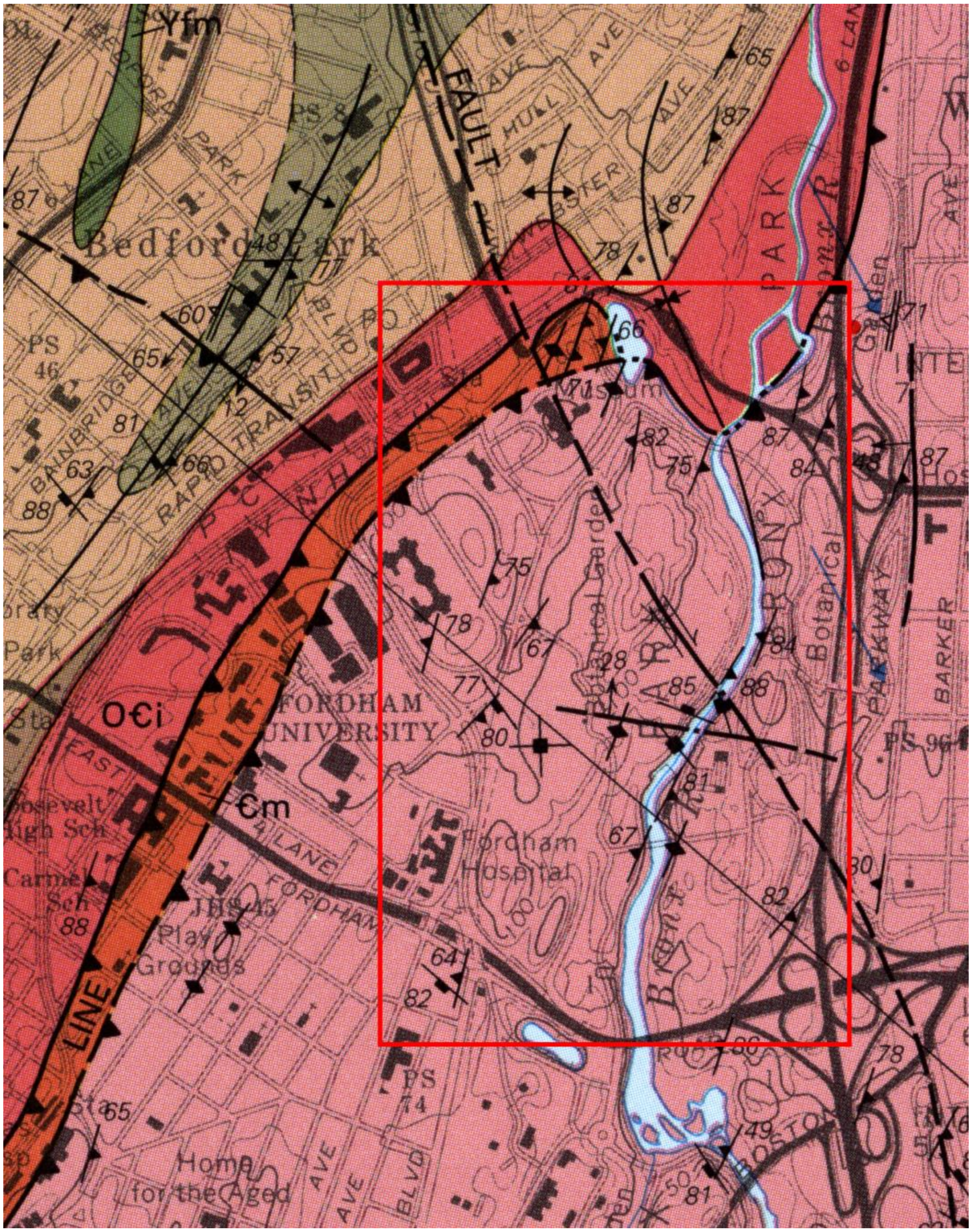



**Figure 7** – Geological map of the NYBG showing the position of Fordham Gneiss (Yfd and Yfm - brown and green units, the Inwood Marble (OЄi – reddish unit), Manhattan Schist (Єm), and the Hartland Formation (OЄh - pink unit) and the trace of the right-lateral Mosholu fault and Cameron's Line. The area of our revised NYBG geological sketch map (See Figure 22, below) shown in red rectangle. (From Baskerville 1992).

Field- and laboratory investigations of the bedrock geology in the NYC area by Merguerian which have been published since 1979 have drawn heavily from earlier- and contemporary studies and suggest that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, structurally complex, roughly coeval, tectonostratigraphic units. Merguerian's investigations agreed, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-not-recognized, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian 1983b, 1984). CM's renegade interpretations on the stratigraphy and subdivision of the Manhattan Schist were presented during a lecture at the New York Academy of Sciences on the evening of 17 December 1984 entitled *"Will the Real Manhattan Schist Please Stand Up!"*

A detailed history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991b). CM's involvement in NYC bedrock studies began in the late 1960s as a City College student in NYC have continued my investigations both academically and as a geotechnical consultant, logging close to five decades of geological study. The major findings from this period have been presented elsewhere (Merguerian 1983b, 1984, 1994a, 1996c, 2002b, 2015b; Merguerian and Baskerville 1987; Merguerian and Merguerian 2004, 2012, 2014a, b, 2016a, b; and Merguerian and Moss 2005, 2006a, 2007, 2015) and in unpublished client reports.

**Bedrock Stratigraphy of New York City and the Bronx**

Drawing heavily from a symposium paper written for the Geological Association of New Jersey (Merguerian 2015b) the following section outlines our new views on the stratigraphy and ductile- and brittle structure of New York City which includes the Garden grounds. Two basic subdivisions of NYC crystalline bedrock (Figures 8, 9) include a substrate of:

**1) Paleozoic Cover Rocks.** Schist, granofels, marble, amphibolite and associated lithotypes, and,
**2) Proterozoic Y Basement Rocks.** Granulite facies gneiss and cross-cutting igneous rocks

Both rock sequences, described below, were internally folded and sheared during Paleozoic orogenesis and cut by younger brittle fracturing (faults and joint discontinuities).

**Layers IIA and IIB: Paleozoic Cover Rocks**

**Hartland Formation (Ꞓ-Oh)**

Gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase± kyanite±garnet schist, gneiss, and migmatite with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite± biotite± garnet. Known for relatively easy excavation because of pervasive jointing parallel to layering the unit has been encountered in the East Side Access, Second Avenue Subway, Manhattan Water Tunnel, #7 Line IRT Extension and Con Edison Steam Tunnel projects and crops out mostly east of the Bronx River at the NYBG. It has been extended into NYC from western Connecticut and Massachusetts based on lithostratigraphic correlation (Merguerian 1983a, b) and it is considered a more metamorphosed part of the slates and interlayered lithic sandstones of the Taconic allochthon (Merguerian and Sanders 1996b). Hartland rocks are exposed in a vertically plunging structure in Garden.

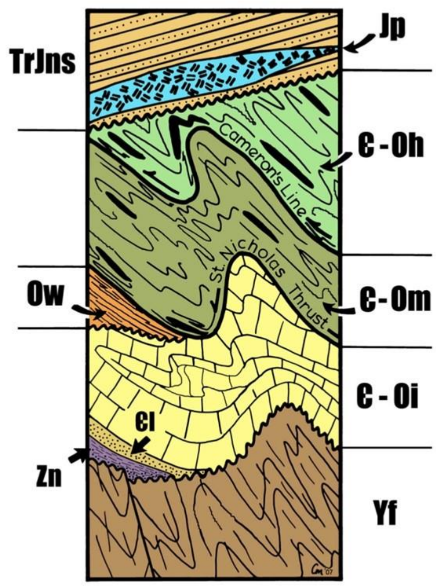



**Figure 8** – Bedrock stratigraphy of New York City as described in text. The polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).

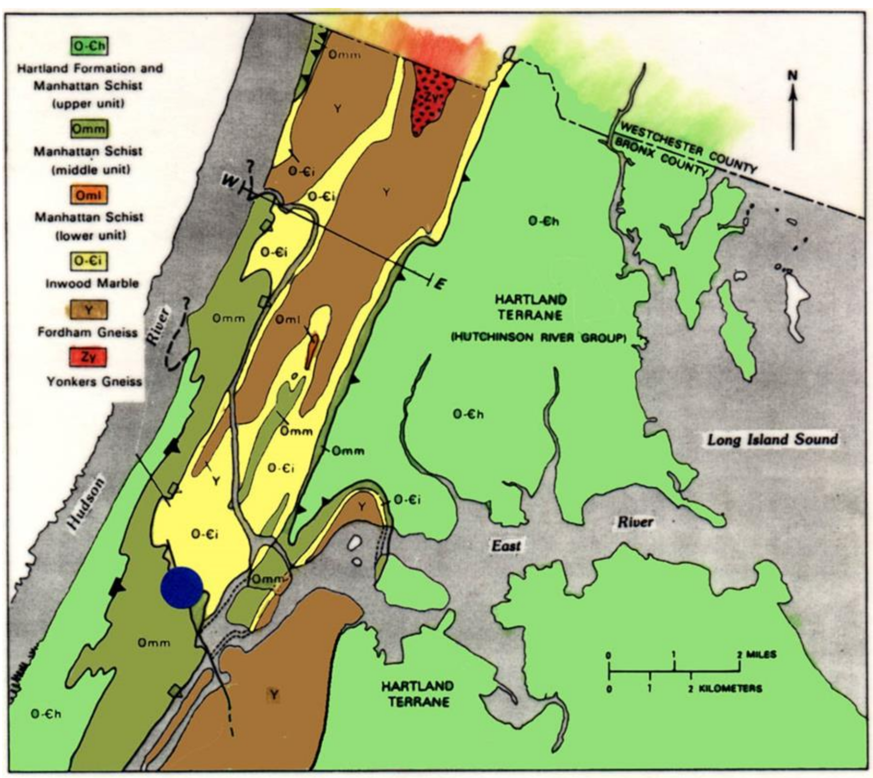



**Figure 9** – New York City generalized geological map and cross sections adapted from Merguerian and Baskerville (1987). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most brittle faults and intrusive rocks have been omitted. Blue dot shows earthquake epicenter of magnitude 2.4 (21 January 2001) that projects above the NW-SE trace of the Manhattanville fault. The generalized map depicts the ductile style of folding and faulting involving Cameron's Line and the St. Nicholas thrust and shows major cross-cutting brittle faults. Note that the unit Omm is equivalent to Ꞓ-Om in this guidebook.

**Manhattan Formation (Ꞓ-Om)**

Massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz±garnet±kyanite±sillimanite±magnetite±tourmaline gneiss, migmatite, and schist. Characterized by the lack of internal layering except for kyanite± sillimanite+quartz+magnetite interlayers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite and scarce quartzose granofels. It forms the bulk of exposed Paleozoic metamorphic rocks of northern Manhattan including the central NYBG exposures. These allochthonous rocks are grouped with the Hartland formation as part of a Taconic Sequence.

**Walloomsac Formation (Ow)**

A discontinuous unit composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase±kyanite± sillimanite±garnet±pyrite±graphite schist, granofels and migmatite containing interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of diopside±tremolite±phlogopite calcite- and dolomitic marble, greenish calc-silicate rock. **Amphibolite is absent** although green amphibole-bearing rocks are locally found. Strongly pleochroic reddish biotite, pinkish garnet as scattered small crystals and porphyroblasts up to 1 cm, graphite and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels invites the interpretation that the unit is metamorphosed middle Ordovician carbonaceous shale + greywacke strata of the autochthonous Annsville, Normanskill and Austin Glen formations of SE New York and correlative Martinsburg Formation to the southwest. Ow is exposed in the SE and NW edges of the Garden.

**Inwood Marble (Ꞓ-Oi)**

Occurring west of the NYBG, white to bluish-gray fine- to coarse-textured dolomitic and lesser calcitic marble locally with siliceous interlayers containing diopside, tremolite, phlogopite, muscovite (white mica), and quartz together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite (Merguerian, Merguerian and Cherukupalli 2011). Layers of fine-textured gray quartzite with a cherty appearance are locally present. The Inwood is correlative with the Cambro-Ordovician carbonate platform or “Sauk” Sequence of the Appalachians.

**Layer I: Fordham - Queens Tunnel Gneiss (Yf)**

The oldest rocks in NYC are a complex assemblage of Proterozoic Y ortho- and paragneiss, metavolcanic and granitoid rocks. Based on detailed studies and U-Pb age dating in the Queens and Brooklyn portions of NYC Water Tunnel #3 (Merguerian, 1999a, 2000a; Brock, Brock, and Merguerian 2001) the Fordham correlative is there known as the Queens Tunnel Complex (QTC) which consists of predominately massive mesocratic, melanocratic and leucocratic, orthogneiss with subordinate schist, granofels, and calc-silicate rocks. Grenvillian high pressure granulite facies metamorphism produced a tough, anhydrous interlocking texture consisting of clino- and orthopyroxene, plagioclase, and garnet that has resisted hornblende and biotite grade Paleozoic retrograde regional metamorphism. No Fordham rocks are found in the Garden in situ except for a few scattered glacial erratics but they underlie the Fordham Ridge immediately west of the park.

**Paleozoic Orogenesis**

The venerable Manhattan Schist of NYC is exposed in Manhattan and Bronx and consists of three separable map units including the Hartland, Manhattan, and Walloomsac formations. (See Figures 8 and 9.) These subdivisions agree, in part, with designations proposed by Hall (1968a, b, c, 1976, and 1980) but recognize a structurally higher unit that is a direct correlative of the Hartland Formation of western Connecticut (Merguerian 1981a, 1983b and 1987). The three schistose tectonostratigraphic units are imbricated along regional ductile faults known as the St. Nicholas thrust and Cameron's Line (Merguerian 1981a, 1983a, 1994a, 1996c).

Now metamorphosed to amphibolite facies grade, the exposed Paleozoic metamorphic cover rocks of NYC were originally deposited as sediment and intercalated volcanic and volcaniclastic materials, though in vastly different environments (Figure 10). Protoliths of the Hartland were originally deposited in a deep ocean basin fringed by offshore volcanic islands. Protoliths of the Manhattan originated along the edge of the Laurentian continental margin as slope-rise strata including thick clay-rich sediment with occasional sand interlayers and mafic dikes or flows.

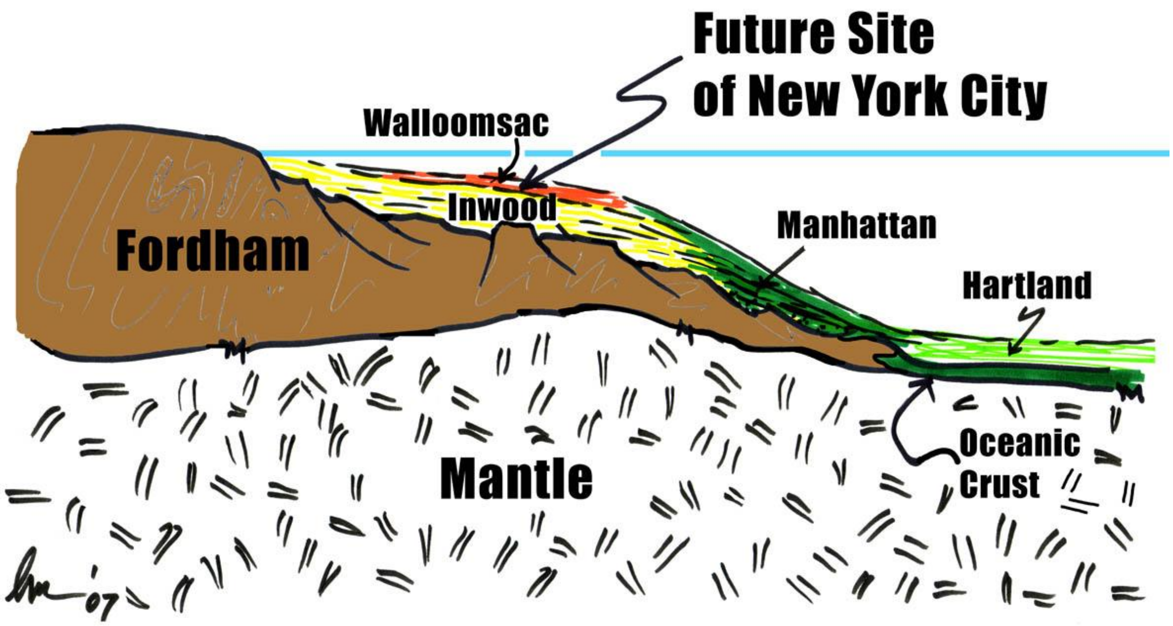



**Figure 10** – Reconstruction of proposed depositional realms at Laurentian margin of protoliths of the Inwood, Walloomsac, Manhattan and Hartland strata before the Taconian arc-continent collision deformed them in mid-Ordovician time (~450 Ma). (CM drawing.)

Formed in the back-arc environment and being closed off from open-ocean conditions with the encroachment of the Taconic arc, protoliths of the Walloomsac were compositionally unique since they originated under restricted oceanic conditions (reducing environment) which formed thick accumulations of carbonaceous and sulphidic clay-rich sediment with occasional sandy and calcareous interlayers in a subsiding intracontinental basin. Loading of the continental shelf edge by the Taconic arc may have triggered the deepening of the Walloomsac back-arc basin and allowed for thick accumulations of black shale and turbidites as seen farther north in the Hudson Valley (Martinsburg, Normanskill, Austin Glen and correlatives – See Table 2).

Underthrusting within the accretionary prism associated with the Taconian arc-continent collision produced the internal shearing, imbrication, deep-seated deformation, and amphibolite facies regional metamorphism of the Paleozoic cover rocks with some basement involvement and the development of Cameron's Line and the Saint Nicholas thrust zones. The underlying Fordham-Queens Tunnel Complex basement rocks experienced localized retrograde metamorphism of Grenville granulite facies fabrics during Taconian and younger events. The Taconian arc-continent collision is depicted in a series of time slices in Figure 11.

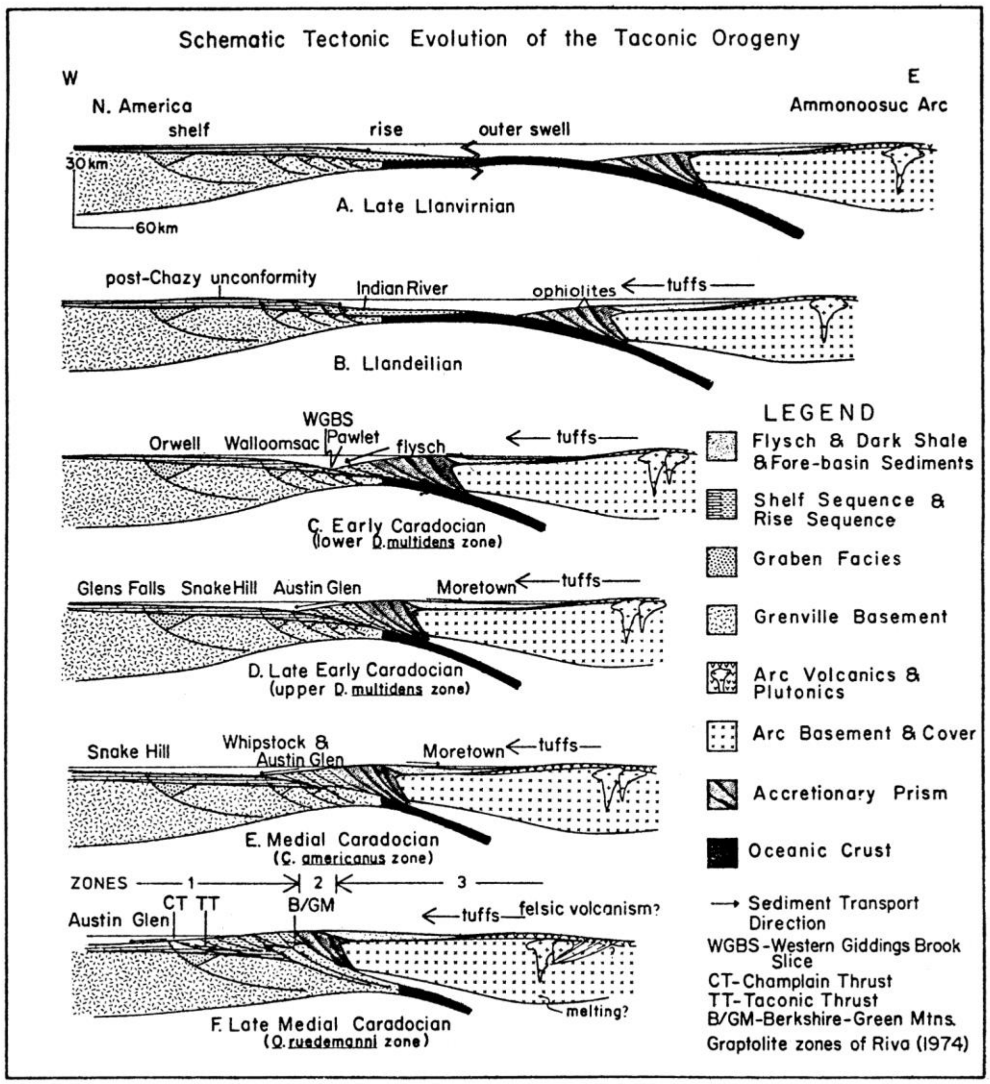



**Figure 11** - Sequential tectonic cross sections for the Taconic orogeny in New England that show from the top down development of the Taconic suture zone. From Rowley and Kidd (1981).

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval shelf- (Ow), transitional slope/rise- (Ꞓ-Om), and deep-water (Ꞓ-Oh) lithotopes that were juxtaposed during telescoping of the ancestral North American shelf edge in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny. (See Figure 11.)

## Tectonostratigraphic units

In metamorphic terranes, tectonostratigraphic units can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile fault zones with mylonites, surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). We use the terms miogeosynclinal and eugeosynclinal, respectively, to designated the products of these contrasting depositional realms.

## Structural Geology of New York City

All Paleozoic cover sequences in NYC have shared a complex structural history which involved three superposed phases of deep-seated Taconian deformation ($D_1$, $D_2$, $D_3$) followed by three or more episodes of open- to crenulate folds ($D_4$, $D_5$, $D_6$) in mid- to late Paleozoic or younger time. Synmetamorphic juxtaposition of the bedrock units occurred very early in their structural history, culminating during $D_2$ based upon field relationships. The Fordham-Queens Tunnel basement sequences harbor a more complex history having endured deformation and metamorphism during the Grenville orogeny (~1.1 Ga) in addition to the three Paleozoic orogenies (Taconian, Acadian, and Alleghenian) whose prograde effects are concentrated in the overlying Inwood, Walloomsac, Manhattan, and Hartland rocks.

The obvious map scale $F_3$ folds in NYC are those with steep N- to NE-trending axial surfaces ($S_3$) and variable but typically shallow plunges toward the S and SW. (See Figure 9.) The $F_3$ folds are typically overturned to the NW with a steep SE-dipping foliation (Figure 12). Shearing in fold limbs and along $S_3$ axial surfaces typically creates a transposition foliation of $S_1$, $S_2$, and $S_3$ that is commonly invaded by granitoids to produce migmatite during both the $D_2$ and subsequent $D_3$ events. These third-generation structures deform two earlier penetrative structural fabrics ($S_1$ and $S_2$). The older penetrative fabrics trend roughly N50°W and dip gently toward the SW except along the limbs of $F_3$ folds. We suspect that all of these structures ($D_1$, $D_2$, and $D_3$) are all products of protracted Taconian orogenesis.

During $D_2$, the rocks acquired a penetrative $S_2$ foliation consisting of oriented mica and intergrown sillimanite and kyanite with flattened quartz together with staurolite and garnet porphyroblasts. Distinctive layers and lenses of kyanite + quartz + magnetite developed in the Manhattan formation and very locally in the Hartland during $D_2$. Near ductile fault contacts the $S_2$ fabric is highly laminated with frayed and rotated mica and feldspar porphyroclasts, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins all developed parallel to the axial surfaces of $F_2$ folds. The $D_3$ folding event, a period of L-tectonism, smeared the previously flattened kyanite + quartz layers and lenses into elongate shapes parallel to $F_3$ axes in schistose rocks. Large porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to $F_3$ hingelines in the Inwood Marble of northern Manhattan. Metamorphism associated with $D_3$ annealed and recrystallized the older $D_2$ mylonites.

Although the regional $S_2$ metamorphic grain of the NYC bedrock trends N50°W and dips gently SW 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° (Figure 12). $S_3$ 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. Metamorphism was of similar grade with $D_2$ which resulted in kyanite overgrowths and annealing of former mylonitic textures (Merguerian 1988).

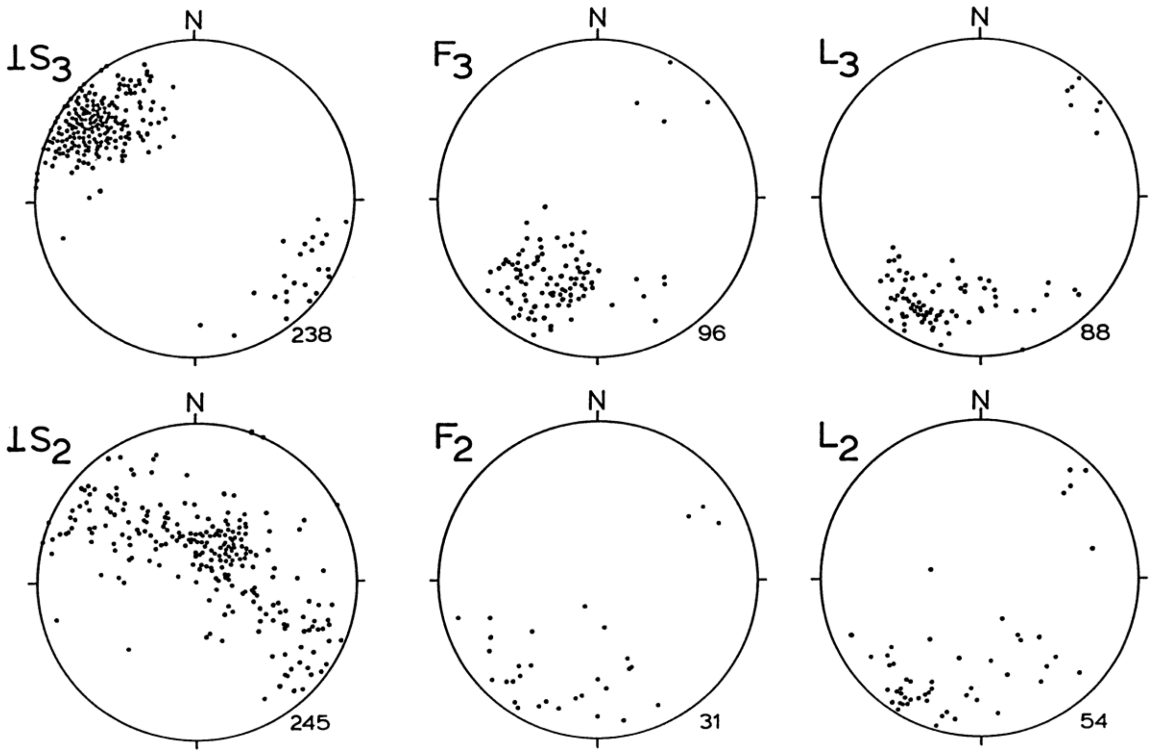



**Figure 12** - Equal area stereograms showing the distribution of poles to $S_2$ and $S_3$, the orientation of $F_2$ and $F_3$ fold hinge lines, and the orientation of $L_2$ and $L_3$ lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, Figure 26, p. 113.)

Originating within the convergent walls of an active subduction zone formerly situated offshore from proto-North America, the $D_1$ to $D_3$ folds and crosscutting fabrics that formed during the Taconic orogeny are overprinted by two- and possibly three- fold phases that, based on their style and general lack of attendant foliation, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics. Presumably, the younger fold phases $D_4$ to $D_6$ record the effects of the Acadian- and terminal-stage Appalachian orogenies.

## Layer VII: NYC Quaternary Sediments and Glaciation

### Previous Interpretations of Glacial-flow-direction Indicators

Almost without exception, geologists who have studied the Pleistocene deposits in the New York metropolitan area concur that a single ice sheet of Late Wisconsinan age created all the flow indicators observed. The following review includes what we consider to be critical papers dealing with this topic. We make no claim that this review is comprehensive or complete.

The idea that only one Late Pleistocene ice sheet invaded the New York City region was proposed by T. C. Chamberlin (1895a, b), reinforced by R. D. Salisbury and assistants (1902), and is implicit in all recent papers where the term "lobe" is used with respect to the margin of the ice sheet (for example, Connally and Sirkin, 1970, 1973).

Salisbury and assistants (1902) found that the predominance of ice-flow indicators showed glacial flow from the NNW to the SSE over the Palisades whereas by contrast, such indicators demonstrated that glacial flow over the Watchung ridges had been predominantly from the NNE to the SSW. Salisbury admitted that the southeastward regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from northwestern New Jersey constituted an anomaly to this explanation of marginal-flow divergence within a single glacier as the cause of the divergent orientations of the glacial grooves and -scratches, but he merely mentioned the possibility of two contrasting glaciers.

Another version of how a single glacier could create flow indicators having several directions is based on the behavior of ice lobes. Such lobes characterize the terminus of a valley glacier that has spread beyond the confining bedrock valley walls. Although the main flow direction of ice in a valley glacier is parallel to the trend of the valley, within the terminal lobe, the spreading ice creates divergent flow paths. Figure 13 shows a map of NYC with what was for a long time the standard view of how the Pleistocene ice descended from Canada and the northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Given the concept that ice from the Labrador center should have been present in NYC, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction.

Interpretations of the Pleistocene glacial history of New York City and vicinity have been powerfully influenced by two factors: (1) the two prominent terminal-moraine ridges on Long Island (the older Ronkonkama moraine to the south and younger Harbor Hill moraine); and (2) the subsurface stratigraphic relationships in major valleys that trend NNE-SSW, most notably the Hudson Valley. Both the terminal-moraine ridges and the subsurface stratigraphic units have been ascribed to the latest glaciation, of latest Wisconsinan age, an interval known as the Woodfordian.

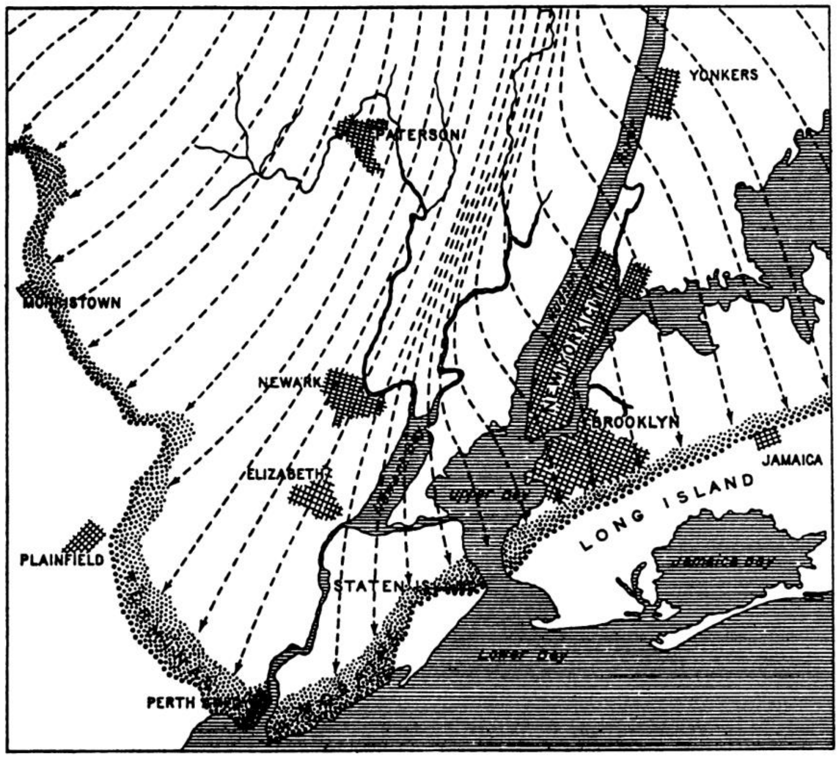



**Figure 13** - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

Proponents of multiple glaciers with contrasting flow directions are not numerous and for the most part, their interpretations have been ignored. They have been crushed in the "one-glacier-did-it-all" stampede. One of the earliest advocates of the multiple-glaciers possibility was Woodworth (1901a), who found in Long Island City that red-brown till, resting on a striated pavement displaying striae oriented NNW to SSE, composes the Harbor Hill Moraine. Fuller (1914) demonstrated the stratigraphic relationships involved in pre-Wisconsinan glaciations. Our only significant difference from Fuller's work is that he assigned Long Island's two major moraine ridges (older and southern Ronkonkama and younger and northern Harbor Hill) to the Wisconsinan. Based on Woodworth's work in Long Island City and out own results on relative ages of the various glacial features, we assign the Harbor Hill Moraine a pre-Wisconsinan (possibly Illinoian, an age likewise advocated by C. A. Kaye, 1964b) age and the Ronkonkama Moraine to a still-older glaciation.

We conclude that more than one glacier flowed across the New York region; flow indicators prove that the ice came from not one but rather from several directions. Years ago, JES prepared Figures 14 and 15 to show how we interpret the flow patterns of glaciers in the same area of Figure 13. In Figure 14, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 15 shows the flow from NNE to SSE as resulting from a later glacier. In our view, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 14. The latest glacier, shown in Figure 15, did not reach much of Long Island. Rather, it covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known.

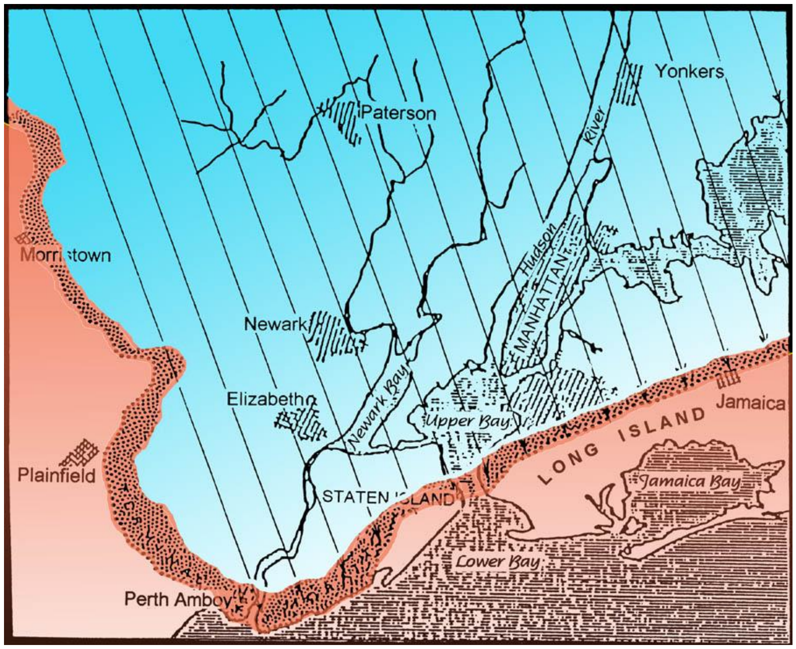



**Figure 14** - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. Drawn by JES; colorized by CM.

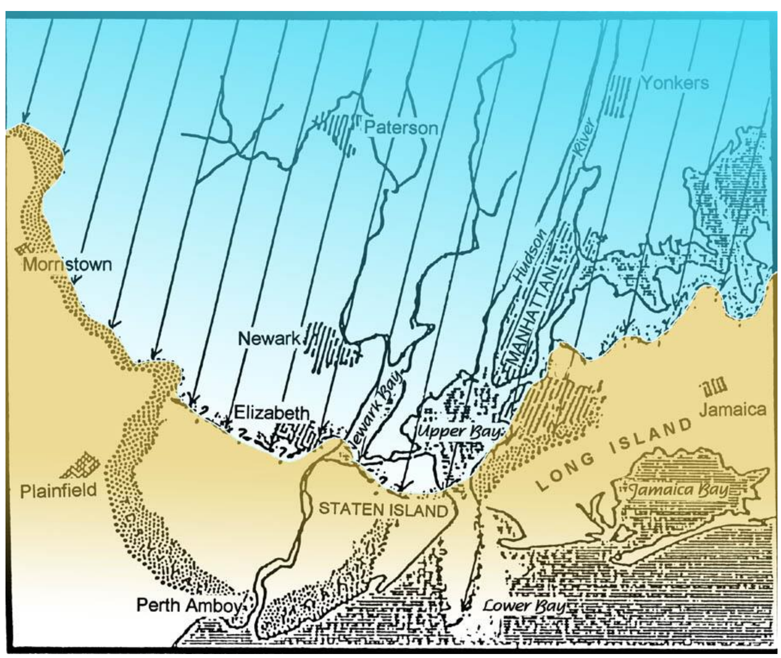



**Figure 15** - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. Drawn by JES; colorized by CM.

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City.  Figure 16 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.

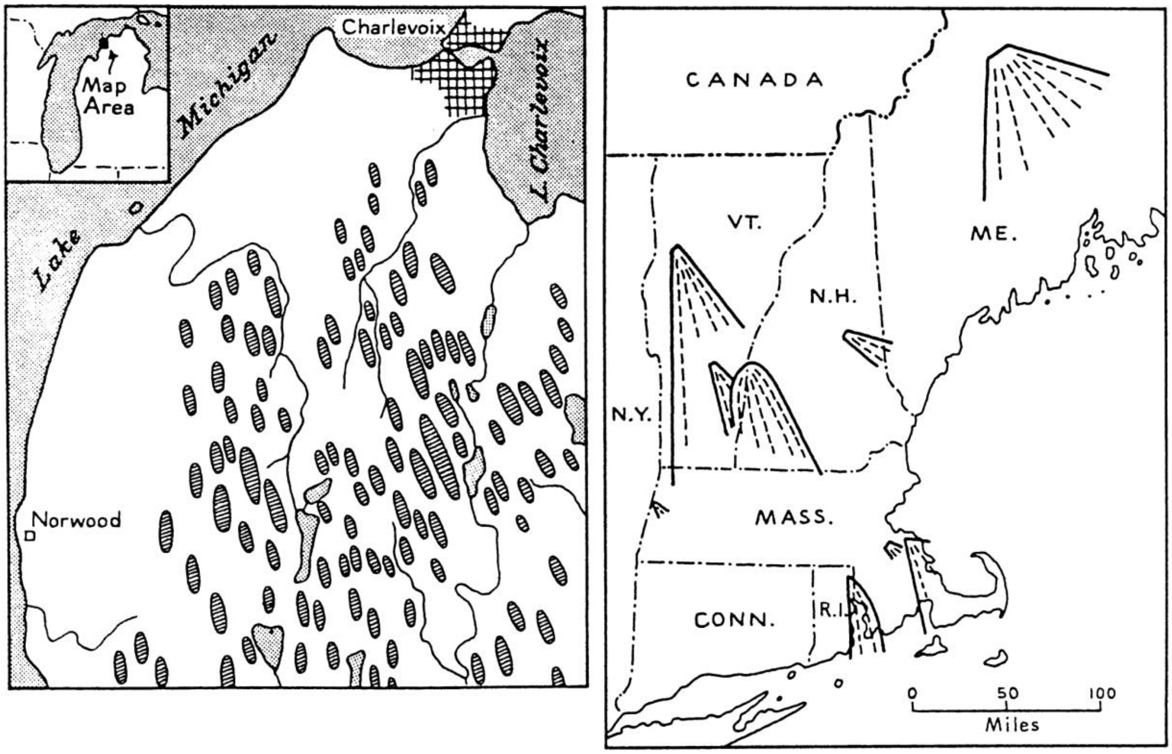



**Figure 16** - Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A.  Swarm of drumlins south of Charlevoix, Michigan.  (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B.  Boulder trains in New England, all products of regional glacier flow from NW to SE.  (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p.

Our view of the glacial history of NYC is summarized in three papers (Sanders and Merguerian 1994b, 1997a, 1998) and we direct the interested reader to them for all the gory details.  Our glacial flow sequence is summarized on Table 3 at the end of this guidebook.

## Faults and Seismicity

It is generally agreed by all geologists and seismologists that abrupt movement on dislocations known as faults produces earthquakes; thus preexisting faults tend to localize new earthquakes.  The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of ductile- and brittle faults.  In addition to the ductile Cameron's Line and the St. Nicholas thrusts, CM's geologic map of Manhattan north of 125th Street shows five northwest-trending brittle faults.  Lobeck (1939) showed two of the major faults of Manhattan south of the 125th Street fault.  One of these, the famous 14th Street fault, controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan south of 23rd Street and north of Canal Street.

During mapping in the water tunnels beneath Manhattan and the East River in the period from 1983-1985 and in the Queens Water Tunnel in the period 1997-2000 (Merguerian 2002b) we identified 5 sets of superposed brittle faults that fall into two broad categories: (a) those that trend northeasterly (parallel to the length of Manhattan and strike of the $S_3$ regional foliation), and (b) those that trend NW and transect the island of Manhattan at a high angle. Invariably, where the ductile faults are oriented northeasterly, they have been reactivated by brittle faults marked by fresh clay-rich gouge up to 5 cm thick. In addition, NW-trending, steeply dipping faults and joints are lined with calcite, pyrite, and zeolite minerals. Thus, the intersections of these two important fault sets has cut New York City into discrete blocks.

According to Baskerville's (1992) geologic map, the Mosholu Parkway fault trends northwest-southeast parallel to the Mosholu Parkway. (See Figure 7.) Baskerville has mapped this fault as being roughly 5.5 km long; his map shows it cutting across the Fordham Ridge toward Van Cortlandt Park. The map symbols indicate Baskerville regards the Mosholu Parkway fault as being a right-lateral strike-slip fault. We do not agree with the trace of the Mosholu fault as depicted by Baskerville and offer an alternative interpretation below.

On 19 October 1985 a Richter-magnitude 4.0 earthquake in Ardsley, Westchester County, woke light sleepers early on a Saturday morning and shook up the scientific community and the engineering community as well. The initial shaking was followed by roughly a dozen, smaller aftershocks. The quake rekindled seismic memories of a magnitude-5.0 earthquake that shook New York City, offshore to the south of Brooklyn in 1884. According to "felt" reports, that quake caused damage to structures and was felt as far south as Philadelphia and as far north as Hartford, Connecticut. Analysis by Leonardo Seeber and coworkers at Lamont-Doherty Geological Observatory indicated that the Ardsley quake was related to a few centimeters of slip along a NW-trending fault. Clearly modern seismicity seems associated with focii on NW-trending faults in NYC.

## Hypotheses on the Origin of the Snuff Mill Gorge and Diversion of the Bronx River

Notice that on the north side of the block diagram of the Botanical Gardens (Figure 17), the Bronx River occupies a mature, U-shaped valley underlain by the Inwood Marble. This represents the typical upstream situation. (See Figure 4.) Indeed, northeast of the NW-SE-trending Mosholu fault, the Bronx River flows SW in a wide NNE-SSW-trending strike-valley lowland underlain by Inwood Marble, a venerable valley former in the humid northeast (Figure 18). Southwest of the fault is the NNE-SSW-trending Webster Avenue lowland, another equally wide valley underlain by the Inwood Marble, is offset to the west from the former and lacking a modern-day river but in which the Bronx River undoubtedly flowed in the past. Just at the point where the NNE-SSW-trending marble lowland has been offset, the Bronx River leaves it and flows southward across resistant gneiss and schist of the Hartland formation in the narrow N-S-trending Snuff Mill gorge. This condition marks a first-order drainage anomaly. Why does not the Bronx River continue to flow southwestward along the Webster Avenue valley which is underlain by the readily weathered and eroded Inwood Marble?

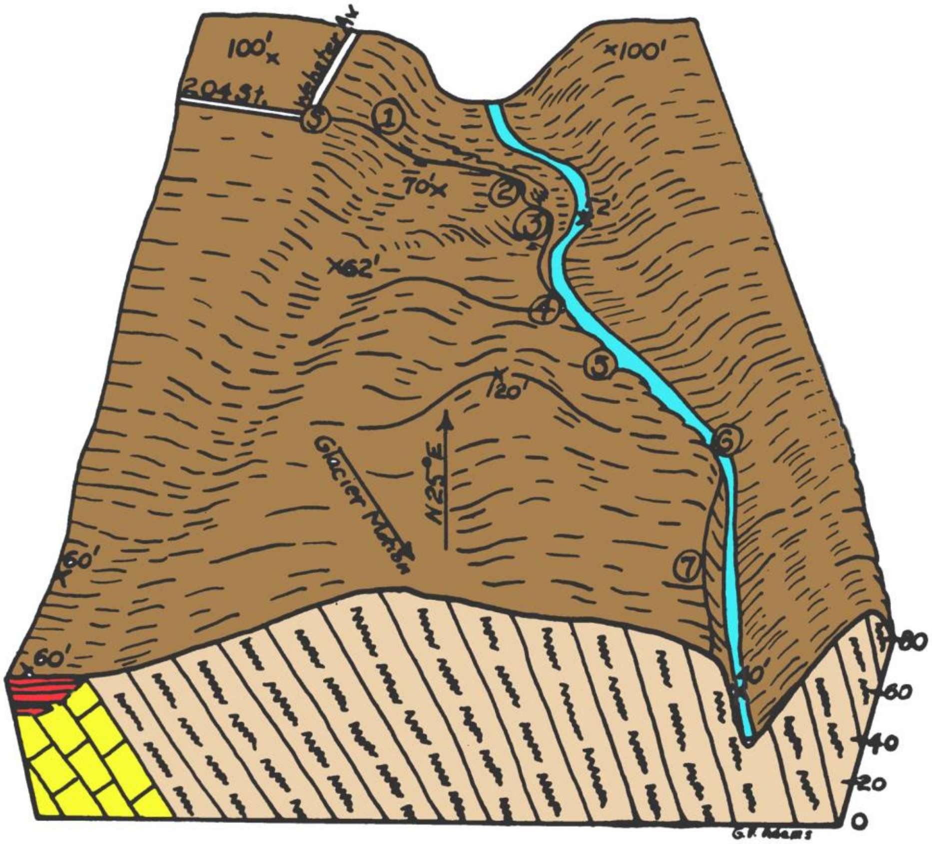



**Figure 17** - Block diagram of the New York Botanical Gardens (drawn by G. F. Adams [formerly from the City College of New York]) showing the generalized structure of the Inwood Marble and the Hartland Formation and transverse profiles of the Bronx River valley. Note that the valley is broad where the Bronx River flows on the Inwood and narrow where it flows on the Hartland.

About at the Mosholu Parkway, the outcrop belt of the marble, and with it, the usual lowland, may have been displaced to the northwest (an effect of Baskerville's Mosholu Parkway right-lateral strike-slip fault?) None of the previously published geologic maps shows such an inferred fault offset in the outcrop of the Inwood Marble. Rather, they all show a shift resulting from a fold. Where the Bronx River turns to its left (east), it has eroded a V-shaped valley that is underlain by metasedimentary- and metavolcanic rocks of the Hartland Formation.

Notice the narrow, V-shaped profile of this valley in the lower right corner of the block diagram (Figure 17). Whether or not a previous Bronx River was able to follow the offset lowland (Webster Avenue Valley) to the SSW as Schuberth (1968) so positively asserts that it did), we do not know. As for the geologic timing of this change, we do not follow Schuberth's suggestion that it took place as long ago as 20 million years to 30 million years. Rather, we agree with Kemp (1897), and think that in postglacial time, the river found a cul-de-sac at the Mosholu Parkway (Merguerian and Sanders 1996a, 1997).

Further flow to the SSW was not possible, perhaps because sediments related to the glacier filled in part of the former valley. Had this NS-trending segment of the Bronx River valley been eroded before the latest glacier arrived in the New York City region, then the ice would surely have changed the valley's transverse profile from a narrow V-shape to a broader U-shape and produced features of glacial erosion which are absent in the Snuff Mill gorge. Therefore, we think that the narrow V-profile of the Bronx River is a powerful argument in favor of a postglacial age for the river's shift into its present course as summarized in Figure 18. In years, this would mean no older than about 12,000 ybp.

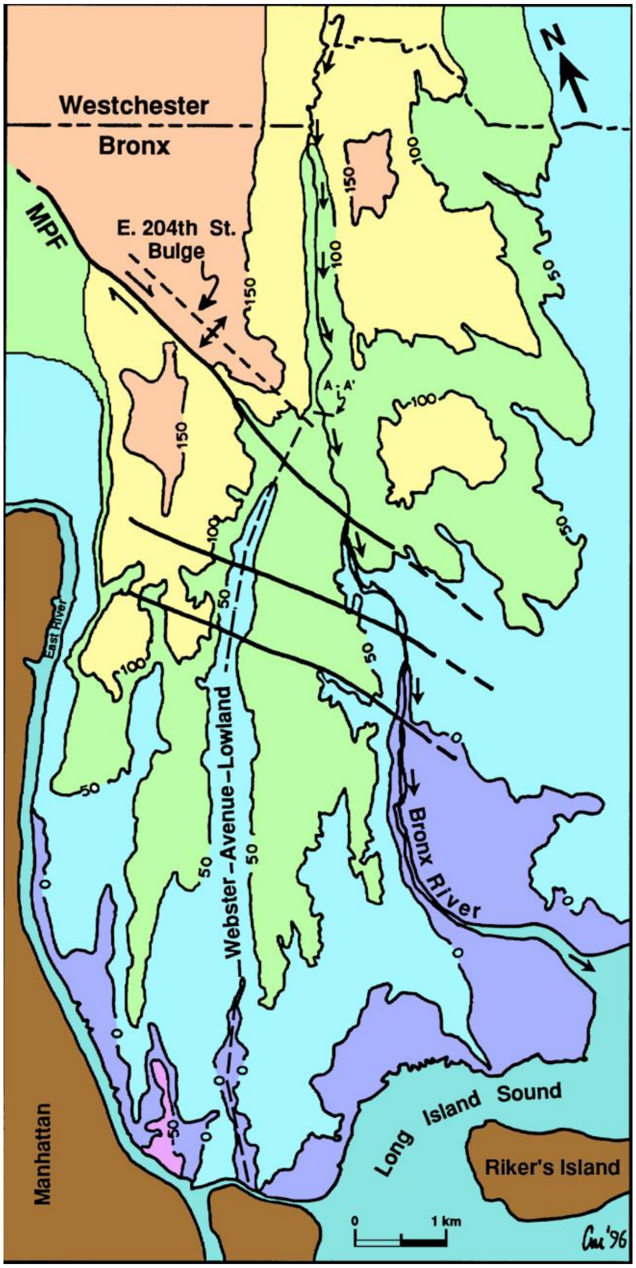



**Figure 18 -** Index- and bedrock-contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including from north to south the Mosholu fault (MF), the Bedford Park fault and the Fordham fault. Map identifies the 204th Street Bulge, the area of the Snuff Mill gorge, and section A-A' of Figure 19. The Webster Avenue Lowland marks the previous course of the Bronx River. Subsurface- and fault data from Baskerville (1992), and engineering records of the New York City Subsurface Exploration Section. (Colorized by CM from Merguerian and Sanders 1996a, fig 4; 1997.)

If the river did indeed follow the marble lowland SW of the Mosholu fault, then some kind of blockage must have prevented it from continuing to do so. During the time when the river's course to the SW down the Webster Avenue lowland was blocked, the water would have been backed up to form a lake. In such a lake, one would expect that some fine lacustrine sediment would have been deposited. After a new course to the south through the Snuff Mill gorge had been established, outfall water from the lake would have been locked into this new course across the Hartland, so that even if the blocked Webster Avenue lowland became available, the river would not re-occupy it.

Several geologic consequences would be associated with diversion of the Bronx River out of the presumably ready-made course underlain by the Inwood Marble along the wide Webster Avenue strike-valley lowland. (See Figures 17, 18.) The records archived in the New York City Office of General Services, Subsurface Branch, contain evidence bearing on the diversion of the Bronx River. Figure 19 shows a stratigraphic profile section culled from borings taken across the Bronx River valley from E. 205th Street across to Burke Avenue, at a point upstream from the inferred blockage/diversion.

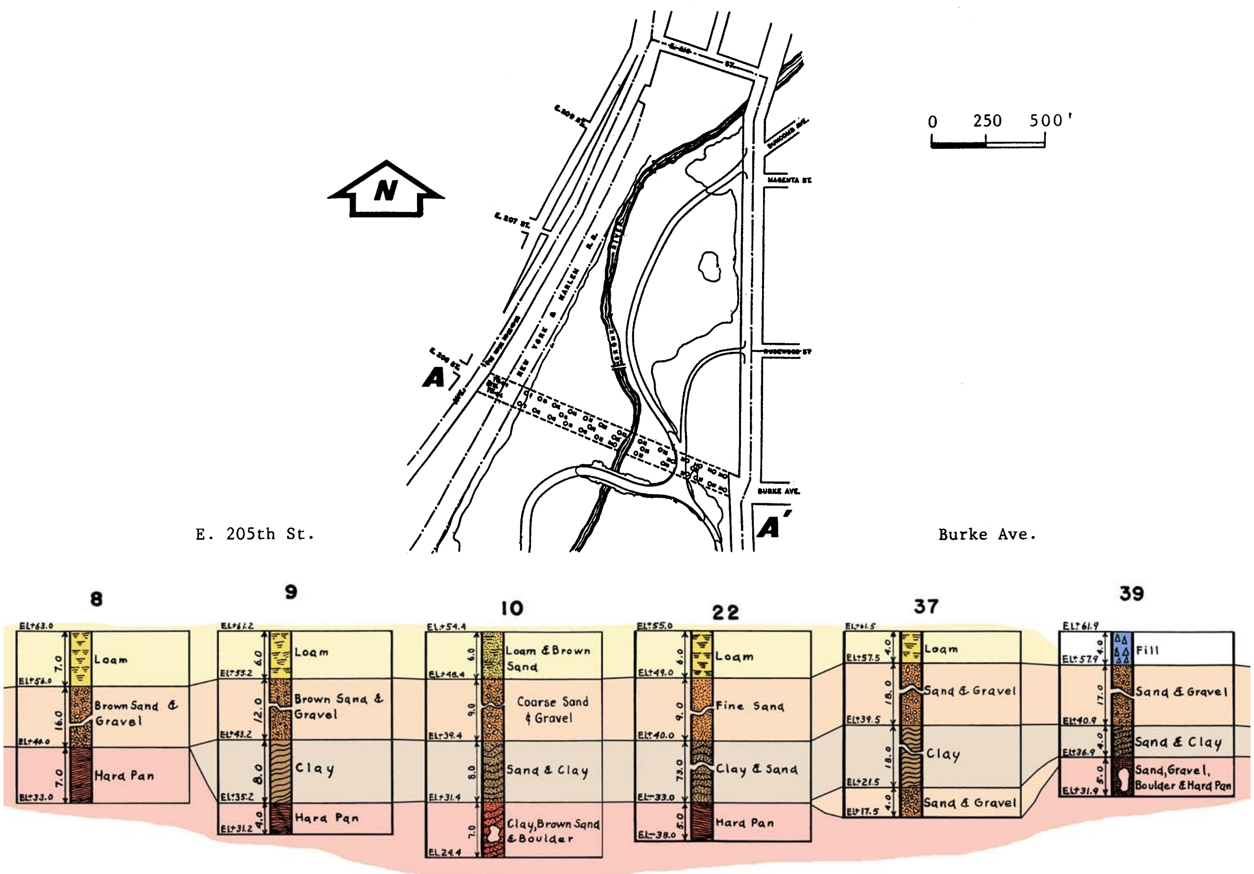



**Figure 19 -** Index map and subsurface stratigraphy from E. 205th Street east-south-eastward to Burke Avenue in the Bronx, upstream of point of diversion of Bronx River based on records of borings assembled in the 1930s by the WPA rock-line map of the Bronx. Line of NW-SE section (A-A') also shown on Figure 18. Index map shows locations of borings and section A-A'. Stratigraphic correlation diagram using original WPA lithologic symbols for individual boring logs. Drawn at 10X vertical exaggeration by JES. Elevations are Bronx Highway Datum. (Colorized by CM from Merguerian and Sanders 1996a, fig 5.)

Several noteworthy features of these boring records stand out. First of all, at the bottoms of several borings are what probably should be classified as till ("hardpan," "boulders"). Overlying the putative till is pebbly coarse sand. Next above is a thick clay. We infer that this clay was deposited from a lake that formed in connection with the diversion. The clay is both underlain and overlain by coarse +/- pebbly brown sand. Not shown on this section is the deposit of cobbles having an exposed thickness 20 feet in the excavations for the new Bronx River sewer mentioned by Kemp (1897, p. 19).

No clay unit comparable to that found north of the Mosholu fault is present in any of the boring records we have examined along the Webster Avenue lowland, where a capping of artificial fill was emplaced before the railroad and streets were built. The records of sediment in the fill of the Webster Avenue valley contain gray sand below, which is overlain by brown sand. Notably absent are any reddish-brown sediment, key indicators of one- or more pre-Woodfordian glacial episodes. As mentioned above, Figure 18 shows contours on the bedrock surface. Note that the Webster Avenue valley is youthful with a narrow, V-shaped profile.

Kemp (1897) inferred that the diversion of the Bronx River was a byproduct of Pleistocene glaciation. Merguerian and Sanders (1996a, 1997) accepted Kemp's post-glacial age assignment but did so for a reason Kemp did not mention. Namely, had the Snuff Mill gorge been in existence **before** the latest glacier arrived in the NYC region, then the ice would surely have changed the profile from its present narrow V-shape (Figure 20) to a broader U-shaped valley. The narrow V-shaped profile of the Snuff Mill gorge and absence of glacial polish or striae on the jagged fresh bedrock exposed in the valley walls by contrast to glacially polished and striated rock on the upland surfaces away from the gorge were powerful arguments in favor of a **post-glacial age** for the downcutting and erosion of the Snuff Mill gorge.

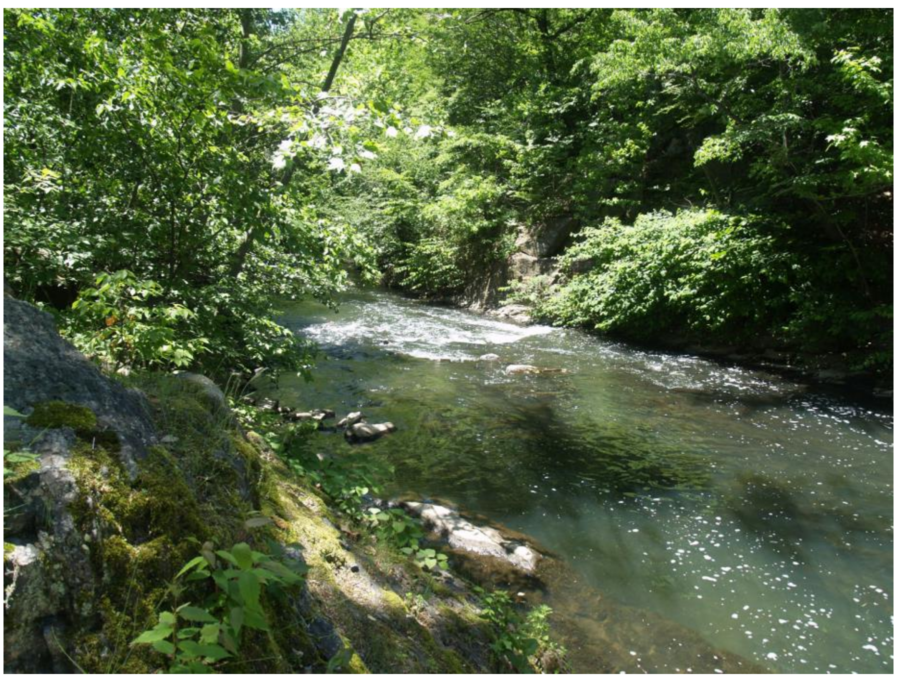


**Figure 20** - View of Snuff Mill gorge showing non-glaciated bedrock exposures along V-shaped course of Bronx River through Hartland rocks. (CM digital image taken 02 June 2011.)

Merguerian and Sanders (1997) suggested that post-glacial development of a bedrock high (E. 204th Street Bulge of Figure 18.) along the NW-SE-trending Mosholu fault blocked the offset marble lowland, dammed the Bronx River, and thus caused a lake to form upstream from the present site of the Mosholu Parkway. Water spilling out of this lake to the south, possibly reoccupying the beginnings of a valley that had been eroded during earlier ice blockage of the Webster Avenue lowland, eroded the N-S-trending Snuff Mill gorge in the New York Botanical Garden, the route the Bronx River takes where it crosses the Hartland and empties into Long Island Sound.

A post-glacial age of diversion is further demonstrated by the absence on the jagged walls of the Snuff Mill gorge of evidence of glacial erosion (for example, smoothed-, polished- and striated rock surfaces). Merguerian and Sanders considered the NW-trending faults of NYC, along with the Dobbs Ferry fault in Westchester, to be seismically capable faults with a history of offset of geological and geomorphic features.

So much for our long-winded geologic background. We now turn to the specifics of the trip, starting with our field trip objectives.

## OBJECTIVES

1) To study the effects of extreme folding, faulting and metamorphism of the Lower Paleozoic strata of the Bronx.

2) To examine lithologic variations in the three schist units of the Bronx formerly "lumped" together into the Manhattan Formation.

3) To examine the evidence for Cameron's Line.

4) To get up close and personal with mylonitic rocks.

5) To examine the effects of multiple glaciations.

6) To get in the groove, glacial-, that is!

7) To find sufficient restrooms to keep field trip participants happy, and,

8) To try to visit all of our planned stops.

## DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

The following twelve stops (Figure 21) illustrate the evidence for changes in the interpretation of the stratigraphy, structure, and presence of ductile shear zones between the schistose rocks in the Garden. It is not known at present whether significant displacement has occurred along the ductile contacts. However, based on regional stratigraphic relationships, the three schist units of the "Manhattan Schist" are interpreted as coeval miogeosynclinal, transitional slope-rise and eugeosynclinal depositional sequences that were juxtaposed at depth during Middle Ordovician deformation of the North American passive continental margin and adjacent oceanic strata during the Taconic orogeny ~ 450 Ma.

The structural geology of the New York Botanical Garden has been the subject of investigations by Langer (1966) and Bowes and Langer (1969) and our independent field studies (Merguerian and Sanders 1993a; Merguerian and Merguerian 2024b). Merguerian and Baskerville (1987) and Baskerville (1992) have mapped the rocks here as belonging to the Hartland Formation but our subsequent work has shown that all three tectonostratigraphic units (Walloomsac, Hartland, and Manhattan) are found in the Garden (Figure 22). The Hartland Formation consists of a vast succession of metasedimentary rocks (that is, metamorphic rocks formed from protoliths that were sedimentary rocks). One of the diagnostic characteristics of the Hartland Formation is well-developed layering and overall aluminous composition. Various kinds of metamorphic rocks are present: muscovite schist and -gneiss with interlayers of mica granofels, quartz-feldspar gneiss, and amphibolite. The schistose- and gneissic members of the Hartland Formation contain minerals rich in aluminum implying that in the sedimentary protolith, clay minerals were abundant.

The Hartland's interlayers of mica granofels and quartz-feldspar gneiss on the one hand, and of amphibolite, on the other, are inferred to have resulted from the metamorphism of turbidites and of basaltic extrusive rocks, respectively. In total, the Hartland Formation is thought to represent the products of metamorphism of a sequence of Lower Paleozoic rocks deposited in deep water adjacent to and east of the early Paleozoic shelf edge of the eastern North American continent (Merguerian, 1983b).

The limbs of the major folds into which the Hartland has been deformed trend roughly N30°E. Dips are steep in both possible directions for fold limbs having such a trend: (1) toward the northwest and (2) toward the southeast. The rocks are well foliated and have been recrystallized. The metamorphic minerals present are products of medium- to high grade regional metamorphic conditions. Such grades of metamorphism imply temperatures such as those found at depths ranging down to 25 km. Rocks formed at such depths typically display folds and small bodies of granitic rocks, the latter implying that locally, the rocks were hot enough to have been partially molten. Altogether, the rocks display numerous features that form as a result of deformation that took place when the rocks were in a ductile condition.

Glacial features noted in the Garden include polished bedrock surfaces, roche-moutonnée structure, glacial grooves and crescentic gouges indicating at least three major glacial episodes: (Glacier I) youngest “Woodfordian” movement from NNE to SSW; (Glacier II) movement from the NW to SE, and older (Glacier IV) movement from NNE to SSW. (See Table 3.)


**Figure 21** – NYBG map locations for parking lot and meeting at Visitor's Center and the twelve trip stops described below (Numbered Stops 1 through 12). (Basemap from https://www.nybg.org/)

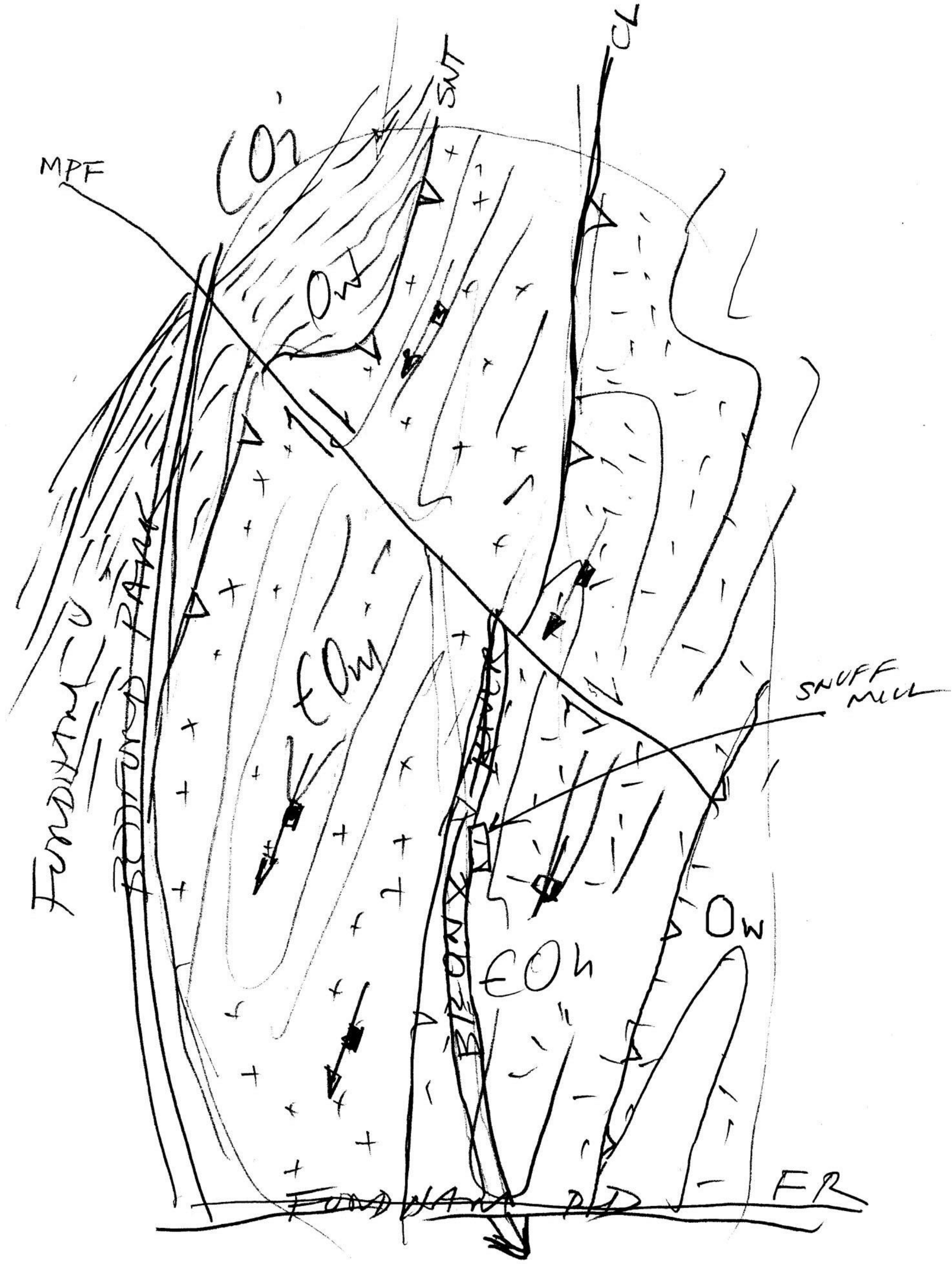



**Figure 22** – Geological sketchmap of the New York Botanical Garden (north to the top) showing a SE-dipping series of thrust slices of Manhattan (Ꞓ-Om), Hartland (Ꞓ-Oh), and Walloomsac (Ow) rocks. The Manhattan is thrust against the Walloomsac and Inwood (Ꞓ-Oi) along the St. Nicholas thrust (SNT) in the NW part of the park. The overall structure is synformal with Manhattan Schist at the center of a SE-plunging $F_3$ synform whose truncated SE-limb is marked by Cameron's Line (CL) near the course of the Bronx River. Farther SE a secondary thrust places an imbricate slice of Walloomsac (Ow) against Hartland rocks (Ꞓ-Oh). The thrust zones are marked by imbricated lithologies and broad zones of mylonite ± migmatite. All of the bedrock units and ductile faults are cut by the NW-trending, right-lateral Mosholu fault. (See Merguerian and Merguerian 2024b for a preliminary map.)

## FIELD TRIP STOPS

*[UTM Coordinates centered on: 594.7E / 4523.6N, Central Park quadrangle.*

The following stops are all within the confines of the New York Botanical Gardens in the Bronx (Figures 21, 22) and are numbered 1 through 12 and are described separately.

**STOP 1** – Walloomsac and Hartland formations, St. Nicholas thrust, granitoids

The SE section of the NYBG is dominated by rocks of the Walloomsac (Ow) and Hartland (Ꞓ-Oh) formations which are in fault contact along the Saint Nicholas thrust (SNT). Remember the Walloomsac consists of rusty-weathering graphitic biotite+muscovite schist with light pink garnet and interlayers of granofels and calc-silicate rocks. The Hartland is lustrous, dominantly muscovitic schist, gneiss granofels and amphibolite so we should be able to see the distinctions in this area. Outcrops show the steeply inclined regional foliation ($S_1xS_2$) and the effects of $F_2$ and $F_3$ folds and folding. Our mapping in 2011 showed the regional foliation ranging from N17°E -N25°E with steep dips into the SE and NW of 78°-90°.

Near the Bourke-Sullivan and Nolan Greenhouse structures, late syn-tectonic foliated pegmatites and granitoids contain abundant xenoliths and screens of country rock occurs as a large mass. It appears more deformed than the Bear's Den granite described by Jaret et al (2022) from the Bronx Zoo property to the south of the Garden which yielded a 400 +/- 15Ma U-Pb age. We are afraid of denned bears so we have not seen it to compare. Since large K-feldspar phenocrysts here are sheared into porphyroclasts flattened into the $S_3$ foliation to produce a flaser structure (Figure 23) we view the intrusive at the Garden as late-syn tectonic with $D_3$.

**Figure 23** – View of flaser structure produced by former megacrystic K-feldspar phenocrysts shredded, sheared, deformed and rolled into stretched porphyroclasts, a texture indicative of excessive ductile shearing. (CM digital image EV032808.)

Farther south along the building outcrops of Walloomsac dominate. Skirting through this area is the St. Nicholas thrust (SNT) which places Hartland rocks to the west against those of the Walloomsac The contact is exposed on the park loop road north of Stop 1.

**STOP 2** - Roche-moutonnée structure in the Hartland Formation.

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roche moutonnée (Figure 24). These are smoothed, broadly rounded and gently inclined on the side from which the ice flowed (a result of the glacier's grinding on a rock obstruction to flow); but jagged, irregular, and steep on the side toward which the ice passed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction.

At Stop 2 the steeply inclined Hartland Formation is here sculpted into a classic roche-moutonée structure with a gentle up-glacier side and a steep down-glacier side. As such, this asymmetrical erosional indicator mandates glacial flow from roughly N15°E toward S15°W (Our Glacier I or IV in Table 3). The development of the steep, down-glacier side of the roche moutonnée was undoubtedly facilitated by the subvertical A-C joints which formed perpendicular to the local $F_3$ folds in the Hartland.

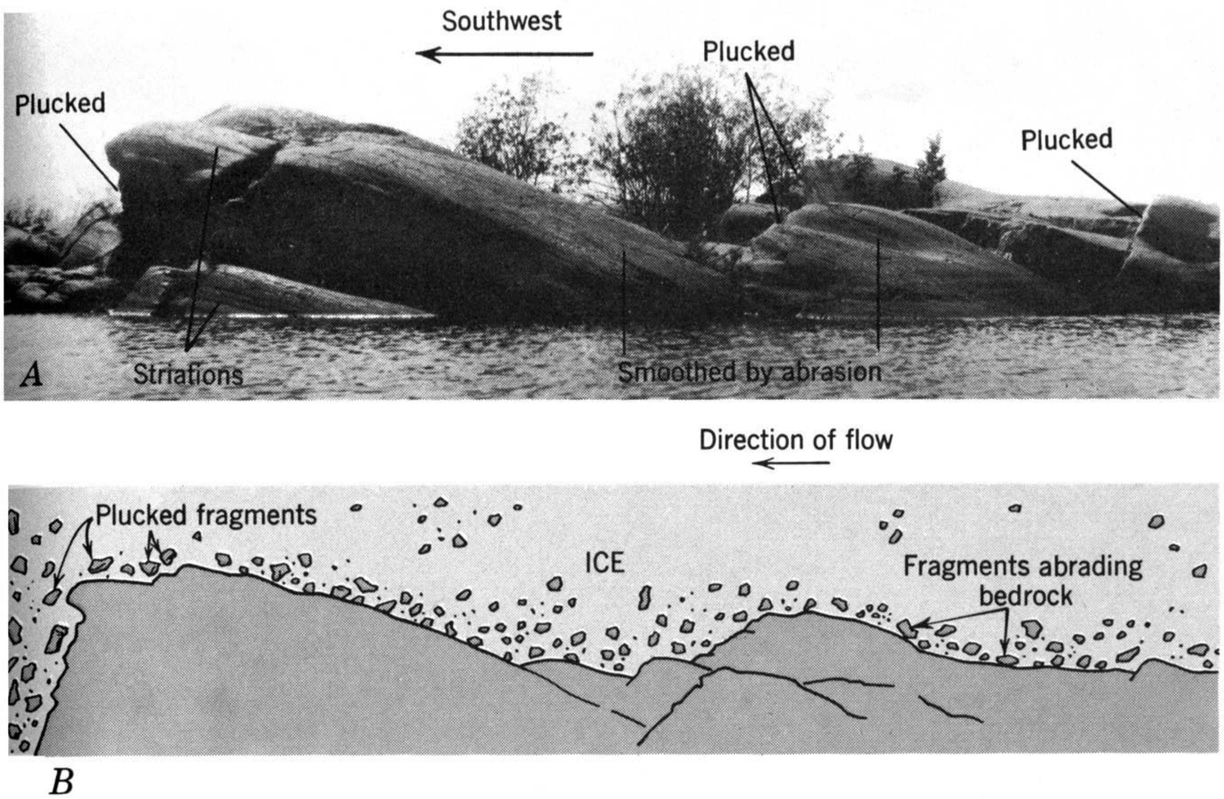



**Figure 24** - Roche moutonnée in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Precambrian granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

**Figure 25** – Southeastward view of roche-moutonée structure developed in Hartland schist and granofels at Stop 2. Note the asymmetry of the exposure with a smooth up-glacier side and an angular "plucked" down-glacier edge produced by ice flowing NNE to SSW. (CM digital image EV022771).

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, JES and CM have found many features displaying doubling of the morphologic expression of a classic roche moutonnée. The view of Figure 25 shows an older rounded, gently dipping part facing the viewer, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by an older glacier flowing from the NW (Glacier II or III in Table 3) has been modified by flow across and over it of a glacier (Glacier I) flowing from a NNE to SSW direction.

Of additional interest here to students of geology is the structure of the Hartland which is deformed by south-plunging $F_3$ folds. Here, by contrast to Stop 3, the metamorphic rocks are well layered and are more typical of the Hartland Formation throughout New York City and New England. The Hartland is vertically foliated in a direction N16°E with the $S_2$ and $S_3$ fabrics transposed and subparallel. On the east side of the outcrop a 2-m-thick pegmatite sill with a quartz core has intruded parallel to the coplanar $S_3$ foliation and the primary layering ($S_0$ through $S_2$) in the Hartland. At the south end of the exposure the pegmatite crosscuts the metamorphic fabric at a high angle and locally, at the north end, includes a 30-cm-long foliated xenolith of Hartland gneiss with diffuse borders. Unlike the late syn-tectonic granitoid examined at Stop 1, the pegmatite is thus post-tectonic (late Paleozoic?) with respect to the $F_3$ folds and the regional foliation. The diffuse xenolith borders suggests that the temperature of the country rock and intrusive were roughly equivalent which further implies that intrusion took place at depths equivalent to the regional metamorphic depth zone of the country rock. Sillimanite- and kyanite-grade rocks form in the depth range of 20-25 km. They are at the surface now!!! Where you putting all that stuff, Vern?

Locally, the $F_3$ folds deform cm-scale pegmatitic- and quartzose segregations which were sweated out and intruded parallel to the older $S_2$ regional foliation. The $F_3$ fold is tight- to isoclinal in outline with an axial surface oriented parallel to the $S_2$ regional foliation (N16°E, 90°) and a S15°W plunge at 03°. Note the spectacular "textbook" development of Z-, M-, and S-folds around the eastern-, northern-, and western portions of the southward-plunging synformal fold.

**STOP 3** - Migmatitic Manhattan Formation on east side of Bronx River at waterfall area.

Manhattan Formation (Ꞓ-Om) rocks occur here with internal layering on the scale of 4- to 6 cm and 4 mm muscovite pseudomorphs locally scattered on the foliation surface. We suspect that the tabular- to blocky mica booklets may be the result of retrograde metamorphic replacement of the aluminosilicate kyanite as similar relationships were encountered in Manhattan and on the west side of the NYBG in rocks of similar grade. Small K-feldspar-bearing pegmatitic sill-like intrusives are found parallel to the foliation, oriented N25°E, 90°. Two dolerite erratics are also visible suggesting NW- to SE-directed glacial ice motion.

Southward along the trail beneath the footing for the Hester Bridge, steeply foliated biotite-garnet-sillimanite gneiss and migmatitic gneiss of the Manhattan bears a gentle southward-plunging $L_3$ lineation. The foliation is oriented N24°E, 74°NW. Rocks here are not particularly well-layered and do not contain granofels. Beneath the bridge, a spectacular example of rectilinear root wedging follows a prominent joint pattern in the bedrock. The Bronx River is here flowing in a steep post-glacial canyon that may be fault- and/or joint controlled. On the west side of the river, glaciated rocks are exposed in subvertical cliffs that extend upward about 25 m above the water level.

**STOP 4** - Stratigraphy of the Manhattan Formation and evidence for glaciation.

Here, the Manhattan Formation (Ꞓ-Om) contains massive muscovite-biotite-plagioclase-quartz fine-textured foliated granitoid layers 1 to 1.5 m thick intercalated with mica schist bearing conspicuous garnet-kyanite-sillimanite-quartz nodules up to 1 cm in size. Some of the former kyanite porphyroblasts have been retrograded to muscovite which produced pseudomorphs of muscovite after kyanite. Two subparallel foliations are oriented N21°E, 83°NW, the result of transposition of the $S_3$ and older fabrics. Together these lithologies are interpreted as metamorphosed slope-rise strata (now schist) that may have been deposited at the former shelf edge prior to their metamorphism [Layer II(A)E in Table 2].

The evidence for glaciation is here in the form of a huge glacial erratic of the Fordham Gneiss (Yf) perched upon the glacially polished outcrop surface. Because Fordham Gneiss is not found in situ east of the NYBG, we can only surmise that the boulder was derived from the NW. Etched into the surface are prominent glacial grooves oriented from N26°W to S26°E (our Glacier II or III in Table 3). They are parallel to the overall asymmetry of the outcrop with smoothed, gentle NW slopes and jagged, steep SE ledges. The gentle, polished NE-facing slopes suggest that the outcrop may also have been sculpted by Glacier I in a direction parallel to the strike of the foliation (N21°E). The associated jagged SW edge of this suspect roche moutonnée may have been strongly modified by the effects of the younger, SW-directed glaciation.

**STOP 5** - Shallow early structures in the Manhattan Formation and evidence for two glaciations.

This low-relief outcrop contains superposed structural- and glacial features and offers the most in geology for very little investment in real estate. Bedding and the early foliation in the Manhattan create an enveloping surface oriented N52°W, 20°SW, defined by a contorted sequence of interlayered schist, thin granofels, and their subparallel metamorphic foliation. The $F_2$ folds are reclined (plunge down the dip of the foliation) and are isoclinal in profile with axial surfaces parallel to bedding and the $S_2$ foliation. Flattened into the $S_2$ foliation are kyanite-sillimanite-quartz nodules. The nodules and the enclosing foliation are folded by upright, gently south-plunging $F_3$ folds with axial surfaces oriented N17°E, 90°.

The overall shape of this glacially sculpted outcrop displays the erosional effects of two glaciations from different directions. The prominent N22°W to S22°E glacial grooves (Glacier II or III) here cut across an older roche-moutonnée structure (Glacier IV?) oriented from N26°E to S26°W. Thus, we here have combined evidence suggested from earlier stops indicating glacial flow from two contrasting directions. Of no great surprise to us but of some lament in the scientific community, these field data are in total support of the multi-directional glacial interpretation for the New York area first suggested by Sanders and Merguerian (1991a, b).

**STOP 6** - Elephant Rock--a trunkful of crescentic- and lunate gouges, erratics, and striae in deformed Manhattan rocks.

The most-obvious glacial feature at this stop is the enormous, split erratic boulder of Yonkers Gneiss on the NE part of the exposure near the entrance to the Rock Garden. The presence of the Yonkers here constrains ice-flow direction in that exposures of the Yonkers are limited to areas directly north and east of us. Accordingly, this boulder was NOT transported by ice flow from the NW; it must have been deposited by our Glacier I from the NNE. (See Table 3.) Because subsequent glaciers tend not to leave pre-existing erratics in place, the mere presence of this Yonkers Gneiss boulder mandates the Glacier I interpretation.

Evidence of glacial flow from the NW (Glacier II and/or III) in the form of roche-moutonnée structure and a plethora of photogenic glacial striae oriented N23°W to S23°E is abundant. If one walks toward the western part of the outcrop, one encounters hard evidence for the older, SSW-directed glaciation (Glacier IV). Here, roche-moutonnée structure, crescentic-, as well as lunate gouges (Figure 26) together indicate glacial flow from N22°E to S22°W. These older glacial features are clearly crosscut by striae oriented NW to SE and roche-moutonnée features described above.

In some places, glacial ice created various crescentic marks. Such marks have been subdivided and named according to the relationship between their curvature and the direction of flow (Flint, 1971, p. 95; Gilbert, 1906; Harris, 1943; MacClintock, 1953). Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 26). Crescentic marks can be used to infer the direction of ice flow by means of 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.

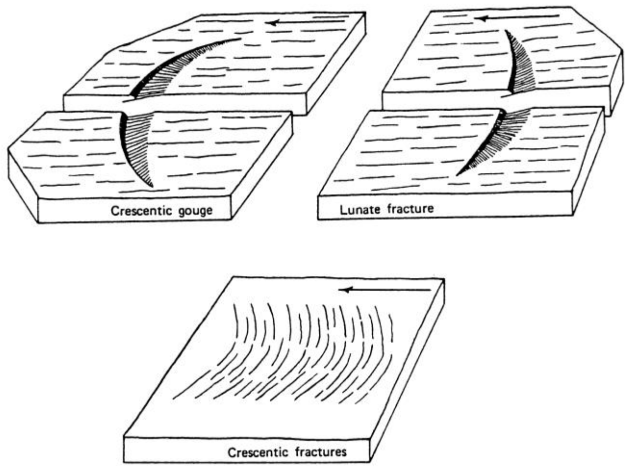



**Figure 26** – Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show the inferred direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

For bedrock enthusiasts, the Manhattan here consists of schist, granofels and thick amphibolite (Figure 27) with the dominant $S_3$ foliation oriented N21°E, 68°SE yet the orientation of the older $S_2$ foliation in the Manhattan is gently inclined here, similar to its orientation at our previous stop. Of structural interest, shallow south-plunging $F_3$ Z-folds plunge 16° into S19°W, deform the older $S_2$ foliation and related subparallel features. The axial surfaces of the $F_3$ folds are oriented N15°E, 90° to N22°E, 85°NW, consistent with measurements made elsewhere in the Gardens. Note the characteristic maroon weathering color in some of the granitoid segregations, the fine laminations defining a mylonitic foliation and the steep NW-trending joints.

**Figure 27** – View of amphibolite contact with massive muscovitic schist and minor granofels of the Manhattan Formation. (CM digital image EV152979.)

**STOP 7** - Lincoln Rock - Two glacial directions and local flow divergence.

Lincoln rock is the highest natural point in the New York Botanical Gardens and consists of highly glaciated rocks of the Manhattan Formation in the form of a steep-walled rock drumlin. The older glacial feature (Glacier IV) is the overall NNE- to SSW-oriented roche-moutonnée structure of this large roche moutonnée with its steep, well-polished NNE side and jagged, glacially plucked SSW side. Glacial striae related to this event are oriented N13°E to S13°W. Superimposed on these features are glacial grooves oriented N32°W, a divergence 6° to 10° from our earlier measurements of the SE-directed flow of Glaciers II and/or III. We suggest that this is a local westward divergence caused by the unusually steep-walled outcrop. The foliation in the Manhattan is oriented N15°E, 80°SE.

**STOP 8** - Well layered Manhattan cut by a prominent joint set.

The most-obvious structural features in this exposure are the well-developed joint set oriented N67°W, 67°SW. The joints are spaced, on average, from 5 to 6 cm and cut the outcrop into an obvious blocky form. Typically, such profuse development of joints in an outcrop alerts the “budding” (an appropriate term for springtime use in the Garden) field geologist to "be on the alert" for a fault having an orientation parallel to one set of joints. Commonly, however, faults are easily eroded and do not show up in outcrop. Rather, they are found by duplication- or omission of geologic units and/or geomorphic expression. Here, we argue that the change in flow orientation of the adjacent Bronx River to the southeast may be the result of offset by a northwest-trending fault (presumably the Mosholu) that parallels one of the joint sets.

Foliation in the Manhattan Formation (N13°E, 77°NW) is quite penetrative compared to exposures observed thus far. Such highly laminated metamorphic textures are typical of mylonites, ductile-fault rocks produced at significant depths around fault zones. As such, we may be dangerously close to Cameron's Line, a ductile fault that separates the Hartland Formation on the east and southeast from rocks of the Manhattan Formation on the west and northwest. Clearly, the evidence at this outcrop is not sufficiently overwhelming to enable us to be absolutely certain of this but it is time to start looking for supporting evidence.

We are clearly in the vicinity of Cameron’s Line based on the confusion in identifying lithologies. Exposures of massive granofels a few hundred feet to the north are definite Manhattan consisting of mylonitic migmatitic muscovite-biotite-quartz-plagioclase schist and 0.75 m thick foliated granitoids. Foliations here trend N15°E-N20°E, 73°-86°NW and the rocks have the typical weathering color of Manhattan.

**STOP 9** - Dolerite erratics.

Just a quick stop to see a few dolerite erratics. Remember that dolerites are medium-textured mafic rocks far-travelled from the Palisades intrusive sheet of New Jersey. As such they indicate NW- to SE-directed glacial flow across the New York City area. We have today seen ample erosional evidence of glacial flow (Glaciers II and/or III) from this direction. In this instance we see the effects of glacial deposition.

**STOP 10** - Manhattan Schist Formation.

Adjacent to the parking lot are rocks that we argue do not fit the Hartland but are dead ringers for a vast sequence of Cambrian to Ordovician metamorphosed strata known as the Hoosac and Waramaug formations farther north in Connecticut and Massachusetts and as the Manhattan Schist (Ꞓ-Om) here in NYC. In contrast to the Hartland, which is typically gray-weathering, well layered and rich in muscovite with abundant quartzose granofels and greenish amphibolite layers, the Manhattan found here is brown- to maroon in weathered color, tends to be massive and richer in biotite, contains little to no granofels, and includes thin layers of blackish amphibolite. Here, the Manhattan consists of magnetite-bearing kyanite-biotite-garnet-quartz-plagioclase-tourmaline schist with typical "nubby" weathering appearance the result of weathering-resistant kyanite lenses, layers, and nodules (Figure 28). What is more abundant highly flatted injections of foliated granitoid and quartz veining are found parallel to the dominant mylonitic foliation.

The foliation is transposed (a composite of the $S_2$ and $S_3$ foliations), oriented N20°E, 65°NW. North of Stop 10 and SE of the Pfizer Building, thinly laminated biotite-garnet migmatitic schist contains magnetite and tourmaline – two key mineral indicators of the Manhattan Formation. The contact between the Manhattan and Walloomsac (Saint Nicholas thrust) occurs beneath the Pfizer Plant Building (Merguerian and Sander 1998).

**Figure 28** – View of Manhattan Schist at Stop 10 showing typical "nubby" weathering style produced by resistant kyanite lenses and nodules. (CM digital image EV022749.)

**STOP 11** - Manhattan Formation and amphibolite float.

Just across from Stop 10, on the south side of Magnolia Road, occurs an outcrop atypical of the Hartland Formation with a 40-cm-thick layer of biotite-quartz granofels. The $S_3$ foliation is here oriented N23°E, 90° and is parallel to the layering (bedding) in the granofels unit. Of additional interest here is a float block of amphibolite meaning that the rock is not connected bedrock but "floating" in the regolith. The angular nature of the block suggests that it has not been "floated" very far – perhaps by the grounds personnel of the NYBG!

**STOP 12** - Mylonitic Manhattan Formation and the elusive Inwood Marble.

The foundation analysis for the Pfizer building allowed for mapping and petrographic analysis of the exposed rock in 1997-98. Here we found annealed mylonites of the Saint Nicholas thrust which separates Manhattan and Walloomsac rock sequences. Merguerian and Sanders (1998) contains all of the details. Within a zone about a 6m wide surrounding the SNT, all rock exposures displayed the megascopic effects of ductile faulting in the form of highly laminated mylonitic textures and an overall reduction of crystal size resulting in predominately dark-colored, fine-textured rocks. Yet, away from the SNT, the rocks showed little obvious textural evidence for mylonitization, an observation borne out by our petrographic studies.

Within the SNT zone, the rocks are highly laminated, and splintery in appearance; many thin intercalated slices of schistose units Ow and Ꞓ-Om, scraps of serpentinized calc-silicate marble, and hornblende+biotite granofels are present. Rocks of unit Ꞓ -Om retain their distinctive massive appearance and exhibit telltale aluminosilicate nodules together with biotite, quartz, magnetite, and large garnet augen and are locally migmatitic, exhibiting the effects of lit-par-lit granitization. By contrast, the rocks of unit Ow are slabby in appearance with reddish biotite, plagioclase, and quartz the predominant minerals. Garnet is locally abundant. Local layers and lenses, up to 1 m thick, of pyritiferous calc-silicate calcite marble (= “Balmville”) characterize the unit Ow.

In outcrops away from the Pfizer Building the attitude of the Manhattan Schist observed at Stop 10 is repeated here; the brown- to maroon-weathering Manhattan displays a massive but hackly appearance. Unlike other outcrops in the park (with the exception of the outcrop of Hartland at Stop 8), these rocks possess a penetrative mylonitic foliation with elliptical quartzose augen (flaser structure) and sheared-out $F_2$ folds defining the $S_2$ foliation. Some of the shearing may have resulted from deformation during the $F_3$-folding episode but the penetrative mylonitic texture is quite distinctive. We agree with Baskerville (1992) that the appearance of the lowland immediately north of us (Twin Lakes and ponds east of Picnic Area) is underlain by the less-resistant Inwood Marble. The lack of exposed carbonate is typical for our humid-temperate climate and therefore we must resort here, in the absence of drill-core data, to negative outcrop evidence (the valley) to exhalt the existence of the marble.

**ACKNOWLEDGEMENTS**

This field guide was prepared utilizing data gathered from outcrops, tunnels, and construction excavations in Manhattan together with some additional data from the Bronx provided by the late Dr. Charles A. Baskerville formerly of the U. S. Geological Survey. We thank the late Dr. Leo M. Hall for helpful discussions in developing the lithostratigraphic views presented here on the schists of Manhattan. We thank Drs. Patrick W. G. Brock and Pamela Brock formerly of Queens College for their critical comments on an older version of this guidebook. CM, JMM and JES were assisted in the field by Diane Dennis, James Harris, Norma Iturrino, P. LaJuke, and H. Manne and received abundant subsurface data from local municipal agencies and engineering firms too numerous to mention here individually. We dedicate this guide to our dear friend and mentor, Dr. John E. Sanders.

We sincerely hope that you've enjoyed today's field trip!

## 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.<br>Drainage from Great Lakes overflows into Hudson Valley.<br>Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley.<br>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.<br>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.<br>Newark basins deformed, arched, eroded. |
| (Triassic) | 190 | Continued filling of subsiding Newark basins and mafic igneous activity both extrusive and intrusive.<br>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 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 | (Є-Oh) Hartland Fm. |
| Pine Plains Fm. | (Є-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** |
| | **IIIC** | | **Island dammed in on S by pre-Ronkonkoma terminal moraine.** |
| ***Yarmouthian*** | | | **Jacob Sand, Gardiners Clay.** |
| **Kansan(?)** | **IV** | **NNE to SSW** | **Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.** |
| ***Aftonian(?)*** | | | **No deposits; deep chemical decay of Till V.** |
| **Nebraskan (?)** | **V** | **NW to SE** | **Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.** |
| | | | **Pre-glacial (?) Mannetto Gravel fills subsurface valleys.** |

## REFERENCES CITED


Alexandrov, E. A., ed., 1969, Symposium on the New York City Group of Formations: New York State Geological Association Annual Meeting, 40th, Flushing, New York: Flushing, NY, Department of Geology Geological Bulletin 3, Queens College Press, 83 p.

Baskerville, C. A., 1992, Bedrock and engineering geological maps of Bronx County and parts of New York and Queens counties, New York: United States Geological Survey Miscellaneous Investigations Map I-2003, scale 1:24,000.

Baskerville, C. A.; and Merguerian, Charles, 1982, Tectonic history of the New York Metropolitan area (abs.): Empire State Geogram, Albany, N.Y., v. 18, p. 19, 43.

Baskerville, C. A.; and Merguerian, Charles, 1983, Stratigraphic differentiation in the Manhattan Schist, New York City (abs.): Geological Society of America Abstracts with Programs, v. 15, no. 3, p. 169.

Bennington, J Bret, and Merguerian, Charles, 2007, Geology of New York and New Jersey: Physical Geology Textbook Supplement: Thomson Brooks/Cole Company, 24 p.

Berkey, C. P., 1948, Engineering geology in and around New York, p. 51-66 in Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America Annual Meeting, 61st, New York City, 135 p.

Bowes, D.; and Langer, A. M., 1969, Polyphase deformation in the schists of the Bronx, New York City, p. 17-31 in Alexandrov, E. A., ed., Symposium on the New York City Group of Formations: New York State Geological Association Annual Meeting, 40th, Flushing, New York: Flushing, NY, Department of Geology Geological Bulletin 3, Queens College Press, 83 p.

Brock, Pamela Chase; Brock, Patrick W. G.; and Merguerian, Charles, 2001, The Queens Tunnel Complex: a newly discovered granulite facies Fordham orthogneiss complex that dominates the subsurface of western Queens: p. 1-8 in Hanson, G. N., chm., Eighth Annual Conference on Geology of Long Island and Metropolitan New York, 21 April 2001, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 128 p.

Chamberlin, T. C., 1895a, Glacial phenomena of North America, p. 724-775 in Geikie, James, The great ice age: New York, D. Appleton and Company, 545 p.

Chamberlin, T. C., 1895b, The classification of American glacial deposits: Journal of Geology, v. 3, p. 270-277.

Connally, C. G., and Sirkin, L. A., 1970, Late glacial history of the upper Wallkill Valley, New York: Geological Society of America Bulletin, v. 81, no. 11, p. 3297-3305.

Connally, C. G., and Sirkin, L. A., 1973, The Wisconsinan history of the Hudson-Champlain lobe, p. 47-69 in Black, R. F., Goldthwait, R. P., and Willman, H. B., eds., The Wisconsinan Stage: Geological Society of America, Memoir 136, 334 p.

Dana, J. D., 1880, On the geological relations (sic) of the limestone belts of Westchester County, New York: American Journal of Science, 3rd series, v. 20, p. 21-32, 194-220, 359-375, 450-456; v. 21, p. 425-443; 1881, v. 22, p. 103-119, 313-315, 327-335.

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

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

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

Fuller, M. L., 1914, The geology of Long Island, New York: United States Geological Survey Professional Paper 82, 231 p.

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

Hall, L. M., 1968a, Times of origin and deformation of bedrock in the Manhattan Prong, p. 117-127 in Zen, Ean; White, W. S.; Hadley, J. B.; and Thompson, J. B., Jr., eds., Studies of Appalachian geology, northern and maritime: New York, Wiley-Interscience Publishers, 475 p.

Hall, L. M., 1968b, Geology in the Glenville area, southwesternmost Connecticut and southeastern New York, Section D-6, p. 1-12 in Orville, P. M., ed., Guidebook for field trips in Connecticut: New England Intercollegiate Geological Conference, Annual Meeting, 60th, New Haven, Connecticut, October 1968: Connecticut Geological and Natural History Survey Guidebook 2, not consecutively paginated.

Hall, L. M., 1968c, Trip A: Bedrock geology in the vicinity of White Plains, New York, p. 7-31 in Finks, R. M., ed., Guidebook to Field Excursions: New York State Geological Association Annual Meeting, 40th, Queens College, Flushing, New York, October 1968: Flushing, NY, Queens College Department of Geology, 253 p.

Hall, L. M., 1976, Preliminary correlation of rocks in southwestern Connecticut, p. 337-349 in Page, L. R., ed., Contributions to the stratigraphy of New England: Boulder, CO, Geological Society of America Memoir 148, 445 p.

Hall, L. M., 1980, Basement-cover relations (sic) in western Connecticut and southeastern New York, p. 299-306 in Wones, D. R., ed., International Geological Correlation Project, Proceedings, Project 27: The Caledonides in the U. S. A.: Blacksburg, VA, Virginia Polytechnic Institute and State University Department of Geological Sciences, Memoir 2, 329 p.

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

Jaret, S. J., Tailby, N., DiPadova, E., Rasbury, E.T., and Wooten, K., The Bear's Den Granite, Bronx Zoo, NY (abs.), in Hanson, G. N., chm., Twenty-ninth Annual Conference on Geology of Long Island and Metropolitan New York, 09 April 2022, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 1p.

Kaye, C. A., 1964b, Outline of Pleistocene geology of Martha's Vineyard, Massachusetts: United States Geological Survey Professional Paper 501-C, p. C134-C139.

Kemp, J. F., 1887, The geology of Manhattan Island [N. Y.]: Transactions of the New York Academy of Sciences, v. 7, p. 49-64.

Kemp, J. F., 1895, The geological section of the East River, at Seventieth Street, New York: New York Academy of Sciences Transactions, v. 14, p. 273-276.

Kemp, J. F., 1897, The glacial (sic) or postglacial diversion of the Bronx River from its old channel: New York Academy of Sciences Transactions, v. 16 (1896), p. 18-24, map.

Langer, A. M., 1966, Older Paleozoic metamorphism and pegmatization (sic) in the Bronx, New York: New York Academy of Sciences Annals, v. 26, p. 812-829.

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

Leverett, Frank; and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: United States Geological Survey Monograph 53, 529 p.

Lobeck, A. K., 1939, Geomorphology. An introduction to the study of landscapes: New York and London, McGraw-Hill Book Company, Inc., 731 p.

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

MacClintock, Paul, 1953, Crescentic crack, crescentic gouge, friction crack, and glacier movement: Journal of Geology, v. 61, p. 186.

Mather, W. W., 1843, Geology of New York. Part I. Comprising (sic) the geology of the First Geological District: Albany, Carroll & Cook, Printers to the Assembly, 653 p., 46 pl. (Includes report of Prof. L. D. Gale on New York Island based on survey of 1828 and 1829.)

Merguerian, Charles, 1981a, Tectonic history of the New York City area (abstract): Empire State Geogram, v. 17, p. 28 (only).

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

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

Merguerian, Charles, 1984, Revised stratigraphy of the Manhattan Schist, New York City (abstract): Empire State Geogram, v. 20, p. 28-29.

Merguerian, Charles, 1987, The geology of Cameron's Line, West Torrington, Connecticut, p. 159-164 in Roy, D. C., ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, Volume 5, 481 p.

Merguerian, Charles, 1988, Annealed mylonitic textures in polyphase deformed metamorphic terrains (abstract): Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A214 (only).

Merguerian, Charles, 1994a, Stratigraphy, structural geology, and ductile- and brittle faults of the New York City area, p. 49-56 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Merguerian, Charles, 1996c, Stratigraphy, structural geology, and ductile- and brittle faults of New York City, p. 53-77 in Benimoff, A. I. and Ohan A. A., chm., The Geology of New York City and Vicinity, Field guide and Proceedings, New York State Geological Association, 68th Annual Meeting, Staten Island, NY, 178 p.

Merguerian, Charles, 1999a, Techniques of TBM tunnel mapping - the Queens Tunnel, NYC, p. 8-12 in Hanson, G. N., chm., Sixth Annual Conference on Geology of Long Island and Metropolitan New York, 24 April 1999, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 143 p.

Merguerian, Charles, 2000a ms., Rock mass properties of the Queens Tunnel Complex: Duke Geological Laboratory Report QT0010, 257 p. + Geological Field Map Album, Scale 1"=10' (Stations 3+65 to 254+00).

Merguerian, Charles, 2002b, Brittle Faults of the Queens Tunnel Complex, NYC Water Tunnel #3: p. 63-73 in Hanson, G. N., chm., Ninth Annual Conference on Geology of Long Island and metropolitan New York, 20 April 2002, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 116 p.

Merguerian, Charles, 2015b, Review of New York City bedrock with a focus on brittle structures; p. 17-67 in Herman, G. C. and Macaoay Ferguson, S., eds., Geological Association of New Jersey Guidebook, Neotectonics of the New York Recess, 32nd Annual Conference and Field Trip, Lafayette College, Easton, PA, 214 p.

Merguerian, Charles; and Baskerville, C. A., 1987, The geology of Manhattan Island and the Bronx, New York City, New York, p. 137-140 in Roy, D. C., ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, v. 5, 481 p.

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

Merguerian, Charles; and Merguerian, Mickey, 2004, Geology of Central Park – From rocks to ice: in Hanson, G. N., chm., Eleventh Annual Conference on Geology of Long Island and Metropolitan New York, 17 April 2004, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 24 p.

Merguerian, Charles; and Merguerian, J. Mickey, 2012, Structural geology and metamorphism of the Inwood Marble, NYC, NY: Geological Society of America Abstract # 199974, Abstracts with Programs, v. 44, no. 2, p. 73.

Merguerian, Charles; and Merguerian, J. Mickey, 2014a, Stratigraphy, structural geology and rock mass properties of the Hartland Formation, Second Avenue Subway, NYC, NY: Geological Society of America Abstract # 235972, Abstracts with Programs, v. 46, no. 2, p. 90.

Merguerian, Charles; and Merguerian, J. Mickey, 2014b, Field guide for Isham and Inwood Parks: Field trip for First Lamont Doherty Earth Observatory Manhattan Prong Workshop, 06-07 September 2014, 59 p.

Merguerian, Charles; and Merguerian, J. Mickey; 2016a, Stratigraphy, structure and tectonics of New York City as viewed through its parks: p. 142-162 in Alexander A. Gates and J Bret Bennington, eds., Geologic diversity in the New York metropolitan area, New York State Geological Association, 88th Field Conference, 30 September - 02 October 2016; 446 p.

Merguerian, Charles; and Merguerian, J. Mickey; 2016b, Trip A-5 - Field guide to Isham, Inwood, and Central parks, NYC, NY: p. 163-189 in Alexander A. Gates and J Bret Bennington, eds., New York State Geological Association, 88th Field Conference, 30 September - 02 October 2016; 446 p.

Merguerian, Charles and Merguerian, J. Mickey, 2024b, Stratigraphy, structure and tectonic implications of the New York Botanical Garden, Bronx, NY: *in* Jaret, S. L., *chm*., Thirty-first Annual Conference on Geology of Long Island and Metropolitan New York, 13-14 April 2024, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 22 p.

Merguerian, Charles; Merguerian, J. Mickey; and Cherukupalli, Nehru, E., 2011, Stratigraphy, structural geology and metamorphism of the Inwood Marble Formation, northern Manhattan, NYC, NY: in Hanson, G. N., chm., Eighteenth Annual Conference on Geology of Long Island and Metropolitan New York, 09 April 2011, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 19 p.

Merguerian, Charles; and Moss, C. J., 2005, Newly discovered ophiolite scrap in the Hartland Formation of midtown Manhattan: in Hanson, G. N., chm., Twelfth Annual Conference on Geology of Long Island and Metropolitan New York, 16 April 2005, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 8 p.

Merguerian, Charles; and Moss, C. J., 2006a, Structural implications of Walloomsac and Hartland rocks displayed by borings in southern Manhattan: in Hanson, G. N., chm., Thirteenth Annual Conference on Geology of Long Island and Metropolitan New York, 22 April 2006, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 12 p.

Merguerian, Charles; and Moss, C. J., 2007, Newly discovered serpentinite bodies associated with the St. Nicholas thrust zone in northern Manhattan: in Hanson, G. N., chm., Fourteenth Annual Conference on Geology of Long Island and Metropolitan New York, 14 April 2007, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 13 p.

Merguerian, Charles and Moss, C. J., 2015, Structural geology and metamorphism of the World Trade Center Site: in Hanson, G. N., chm., Twenty-second Annual Conference on Geology of Long Island and Metropolitan New York, 11 April 2015, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 12 p.

Merguerian, Charles; and Sanders, J. E., 1991b, Trip 16: Geology of Manhattan and the Bronx, 21 April 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 141 p.

Merguerian, Charles; and Sanders, J. E., 1993a, Geology of Cameron's Line and the Bronx Parks: Guidebook for On-The-Rocks 1993 Fieldtrip Series, Trip 26, 08 May 1993, Section of Geological Sciences, New York Academy of Sciences, 103 p.

Merguerian, Charles; and Sanders, J. E., 1996a, Diversion of the Bronx River in New York City - evidence for postglacial surface faulting?, p. 131-145 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 20 April 1996, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 177 p.

Merguerian, Charles; and Sanders, J. E., 1996b, Contrasting styles of the Taconic orogeny in New York: deep- vs. shallow thrusts, p. 116-130 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 20 April 1996, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 177 p.

Merguerian, Charles; and Sanders, J. E., 1997, Bronx River diversion: neotectonic implications (abs.): Paper No. 198, p. 710 in Hudson, J. A. and Kim, Kunsoo, eds., International Journal of Rock Mechanics and Mining Sciences, Special Issue, 36th U.S. Rock Mechanics Symposium, Columbia University, New York, June 29-July 02, 1997, v. 34, no. 3/4, 714 p. Full version on CD-ROM, 10 p.

Merguerian, Charles; and Sanders, John E., 1998, Annealed mylonites of the Saint Nicholas thrust (SNT) from a new excavation at the New York Botanical Gardens, The Bronx, New York: p. 71-82 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 18 April 1998, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 161 p.

Merrill, F. J. H., 1886a, On the geology of Long Island: New York Academy of Sciences Annals, v. 3, p. 341-364.

Merrill, F. J. H., 1886b, Some dynamic effects of the ice sheets: American Association for the Advancement of Science Proceedings, v. 35, p. 228-229.

Merrill, F. J. H., 1890, On the metamorphic strata of southeastern New York: American Journal of Science, 3rd series, v. 39, p. 383-392.

Merrill, F. J. H., 1891a, On the postglacial history of the Hudson River valley: American Journal of Science, 3rd series, v. 41, p. 460-466.

Merrill, F. J. H., 1891b, Quaternary geology of the Hudson Valley: New York State Geologist, Annual Report, v. 10, p. 103-109.

Merrill, F. J. H., 1898a, The geology of the crystalline rocks of southeastern New York: New York State Museum Annual Report 50, v. 1, p. 21-31.

Merrill, F. J. H., 1898b, The origin of serpentinites in the vicinity of New York: New York State Museum Annual Report 50, v. 1, p. 32-44.

Merrill, F. J. H., 1898c, The geology of greater New York (abs.): Transactions of the New York Academy of Sciences, v. 16, p. 370-371.

Merrill, F. J. H.; Darton, N. H.; Hollick, Arthur; Salisbury, R. D.; Dodge, R. E.; Willis, Bailey; and Pressey, H. A., 1902, Description of the New York City district: United States Geological Survey Geologic Atlas of the United States, New York City Folio, No. 83, 19 p. (Includes colored geologic map on a scale of l:62,500).

Mose, D. G.; and Merguerian, Charles, 1985, Rb-Sr whole-rock age determination on parts of the Manhattan Schist and its bearing on allochthony in the Manhattan Prong, southeastern New York: Northeastern Geology, v. 7, no. 1, p. 20-27.

Ries, Heinrich, 1895, On a granite-diorite near Harrison, Westchester County, N.Y.: New York Academy of Sciences Transactions v. 14, p. 80-86.

Rowley, D. B., and Kidd, W. S. F., 1981, Stratigraphic relationships and detrital composition of the Medial (sic) Ordovician flysch of western New England: Implications for the tectonic evolution of the Taconic orogeny: Journal of Geology, v. 89, p. 199-218.

Salisbury, R. D., 1902, Pleistocene formations, p. 11-17 in Merrill, F. J. H., Darton, N. H., Hollick, Arthur, Salisbury, R. D., Dodge, R. E., Willis, Bailey,, and Pressey, H. A., Description of the New York City district: United States Geological Survey, Geologic Atlas of the United States, New York City Folio, No. 83, 19 p.

Sanders, J. E., and Merguerian, Charles, 1991a, Pleistocene tills in the New York City region: New evidence confirms multiple (three and possibly four) glaciations from two directions (NNE to SSE (sic) and NW to SE) (abstract): Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 123 (only).

Sanders, J. E.; and Merguerian, Charles, 1991b, Pleistocene geology of Long Island's north shore: Sands Point and Garvies Point to Target Rock: Long Island Geologists' Association Field Trip 29 June 1991 Guidebook: Hempstead, NY, Hofstra University Department of Geology, 40 p.

Sanders, J. E., and Merguerian, Charles, 1994b, The glacial geology of New York City and vicinity, p. 93-200 in A. I. Benimoff, ed., The Geology of Staten Island, New York, Field guide and proceedings, The Geological Association of New Jersey, XI Annual Meeting, 296 p.

Sanders, J. E.; and Merguerian, Charles, 1997a, Geologic setting of a cruise from the mouth of the East River to the George Washington bridge, New York Harbor: 36th U.S. Rock Mechanics Symposium, NYRocks '97, Columbia University, NY, June 30, 1997, 148 p.

Sanders, John E., and Merguerian, Charles, 1998, Classification of Pleistocene deposits, New York City and vicinity – Fuller (1914) revived and revised: p. 130-143 in Hanson, G. N., chm., Geology of Long Island and Metropolitan New York, 18 April 1998, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 161 p.

Schuberth, C. J., 1968, The geology of New York City and environs: Natural History Press, Garden City, New York, 304 p.

Woodworth, J. B., 1901a, Pleistocene geology of portions of Nassau County and Borough of Queens (N. Y.): New York State Museum Bulletin 48, p. 618-670 (includes geologic map).

**Filename:** LIAPG_2404.docx