FIELD TRIP GUIDEBOOK
ISHAM AND INWOOD PARKS, NYC

Lamont-Doherty Earth Observatory
Manhattan Prong Workshop
06-07 September 2014
Charles and J. Mickey Merguerian

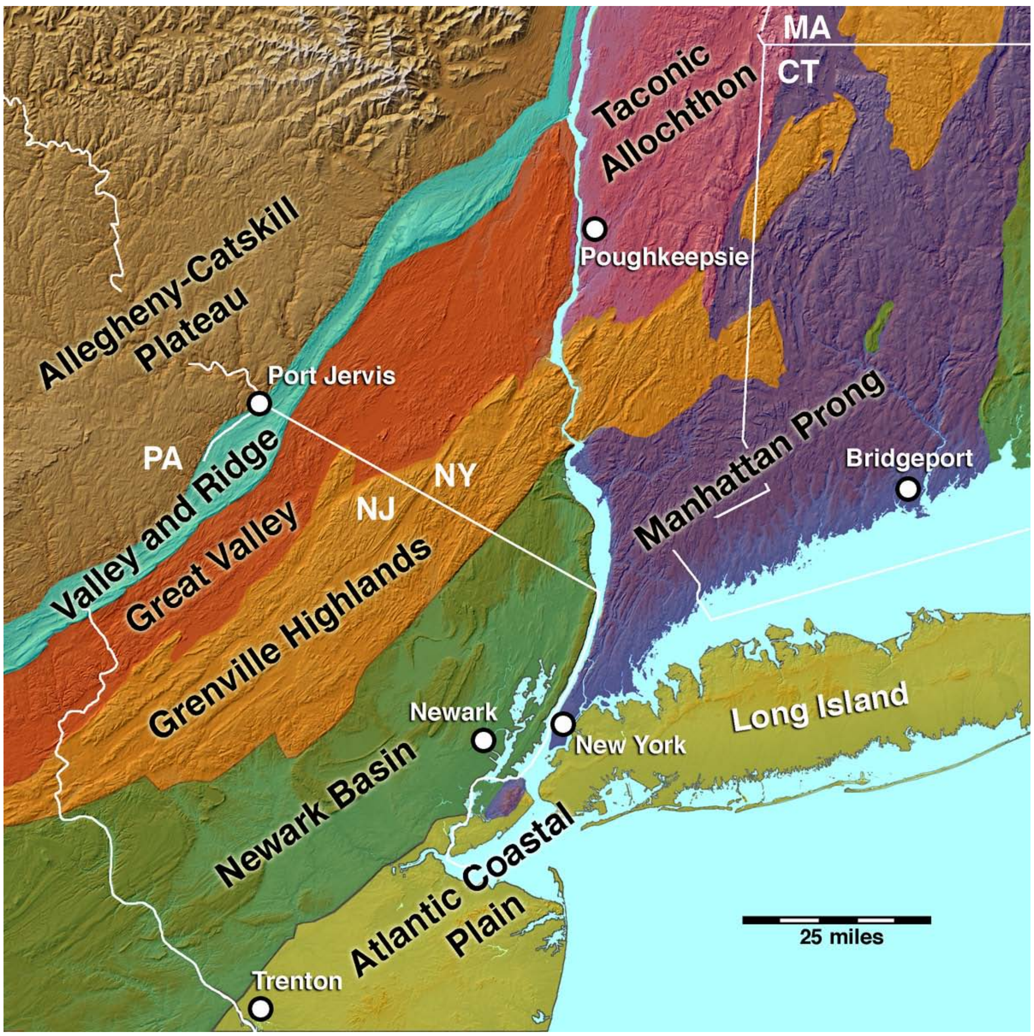

Figure 1 – Physiographic diagram showing the major geological provinces in southern New York, northern New Jersey, and adjoining states. (From Bennington and Merguerian, 2007.)

Field Trip Led by Charles Merguerian
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INTRODUCTION

This guidebook has been provided to discuss some of the field geological background to help participants of the LDEO Manhattan Prong Workshop visualize details of the local bedrock geology in NYC, to help understand the questions that need to be addressed at this former Taconian convergent margin, and to provide a framework to better craft future field and geochemical investigations in the region. As such this guide has been constructed to explain some of the details and problems surrounding Appalachian bedrock geology as exposed in northern Manhattan.

Table 1 (Tables can be found at back of guidebook) is a time chart showing geologic time subdivisions used on the bedrock maps herein and Table 2 summarizes the major local geologic units (stratigraphy) in terms of layers designated by Roman numerals and stratigraphic sequences. Much of this guidebook has been brutally scavenged from a series of guides by Charles Merguerian and the late John E. Sanders written to accompany the On-The-Rocks field trip series conducted under the auspices of the New York Academy of Sciences in the interval 1988-1998 and has incorporated our latest research on the region.

The Manhattan Prong

The Appalachians Highlands province designates the high region in the median part of the Appalachian chain. In the northern Appalachians, this continuous highland region is named the New England uplands province. In western Connecticut and southeastern New York, this highland province has been divided into two "prongs:" the Manhattan Prong on the southeast and the Hudson Highlands-Reading Prong on the northwest (Figure 1, cover). The Manhattan Prong stretches from western Connecticut southwestward across Westchester County to parts of New York City, including all of the Bronx, extreme western Queens, all of Manhattan Island, and the the part of Staten Island around Todt Hill. It also includes a small area in easternmost New Jersey, a narrow strip of land stretching from Hoboken south to Jersey City.

The morphology of the Manhattan Prong is a somewhat subdued valley-and-ridge type in that low, rounded, elongate ridges underlain by schist or gneiss are separated by linear valleys underlain by marble and/or brittle faults. The underlying bedrock consists chiefly of metamorphic rocks of Proterozoic and Early Paleozoic vintage. Within this metamorphic complex are a few bodies of igneous rocks, some of which have also been metamorphosed and some of which have not. Some of these bodies of igneous rock form irregular hills as topographic highs.

According to our most recent interpretation, much of the Manhattan Schist in NYC is nothing but the Taconic allochthon in metamorphosed disguise. One of the key objectives of this workshop and associated field trip is to show you the field relationships and discuss what we think are the protoliths of the metamorphic rocks underlying the Manhattan Prong.

BEDROCK UNITS OF THE REGION

Layer I: Mid- to Late Proterozoic Crystalline Basement Complex

The oldest recognized strata in southeastern New York include the Fordham Gneiss in the Manhattan Prong physiographic province of the New York City area and the Hudson Highlands gneisses of the Reading Prong (Figure 2, Table 2). In the Pound Ridge area (PR in Figure 2) the Proterozoic Y gneiss of the Fordham (a 1.1 Ga U/Pb age on zircons by Grauert and Hall, 1973) is cut by Proterozoic Z granitic gneiss (the Pound Ridge Gneiss and correlative Yonkers Gneiss farther south [Y in Figure 2]). The Pound Ridge gneiss is dated as latest Proterozoic (579+21 Ma Rb-Sr age by Mose and Hayes, 1975) and shows an intrusive, or possibly an unconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. Age dating of the Fordham-correlative Queens Tunnel orthogneiss complex has also yielded a 1.1 Ga U-Pb age (Brock, Brock, and Merguerian 2001; Merguerian, Brock, and Brock 2001)

The Yonkers granitic gneiss has yielded ages of 563+30 Ma (Long, 1969) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or volcanism (Pound Ridge?) in response to rifting of the ancient Gondwanan supercontinent.

The rifting of the Proterozoic Y craton in latest Proterozoic time set the stage for the first of the trailing-edge continental margins of eastern North America. This trailing edge, (or passive margin I) was to receive clastic, then carbonate sediments of the Sauk Sequence of Layer IIA. (See Tables 1 and 2.) Work by Patrick and Pamela Brock (1989) in the vicinity of the Peach Lake quadrangle, NY nad CT, shows the presence of a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation) that rest unconformably on the Fordham basement rocks. As such, the Brock’s have identified an eastern dominantly volcaniclastic facies of the metamorphosed Proterozoic Z igneous activity marked by the Yonkers and Pound Ridge gneisses. In addition, this important work has illuminated and expanded the age, areal importance, and stratigraphic correlation of the Lowerre-Poughquag Cambrian(?) clastics at the base of Layer II. Their work will be highlighted at this conference and a field trip will show some of their work on the Ned Mountain in the Bronx. One of the questions that remains to be answered is whether this is the product of a separate tectonic cycle or simply the rift-facies beginning of the Late Proterozoic-Early Paleozoic trailing edge continental margin sequence that grades upward into the Manhattan Schist(s) as described in this guide.

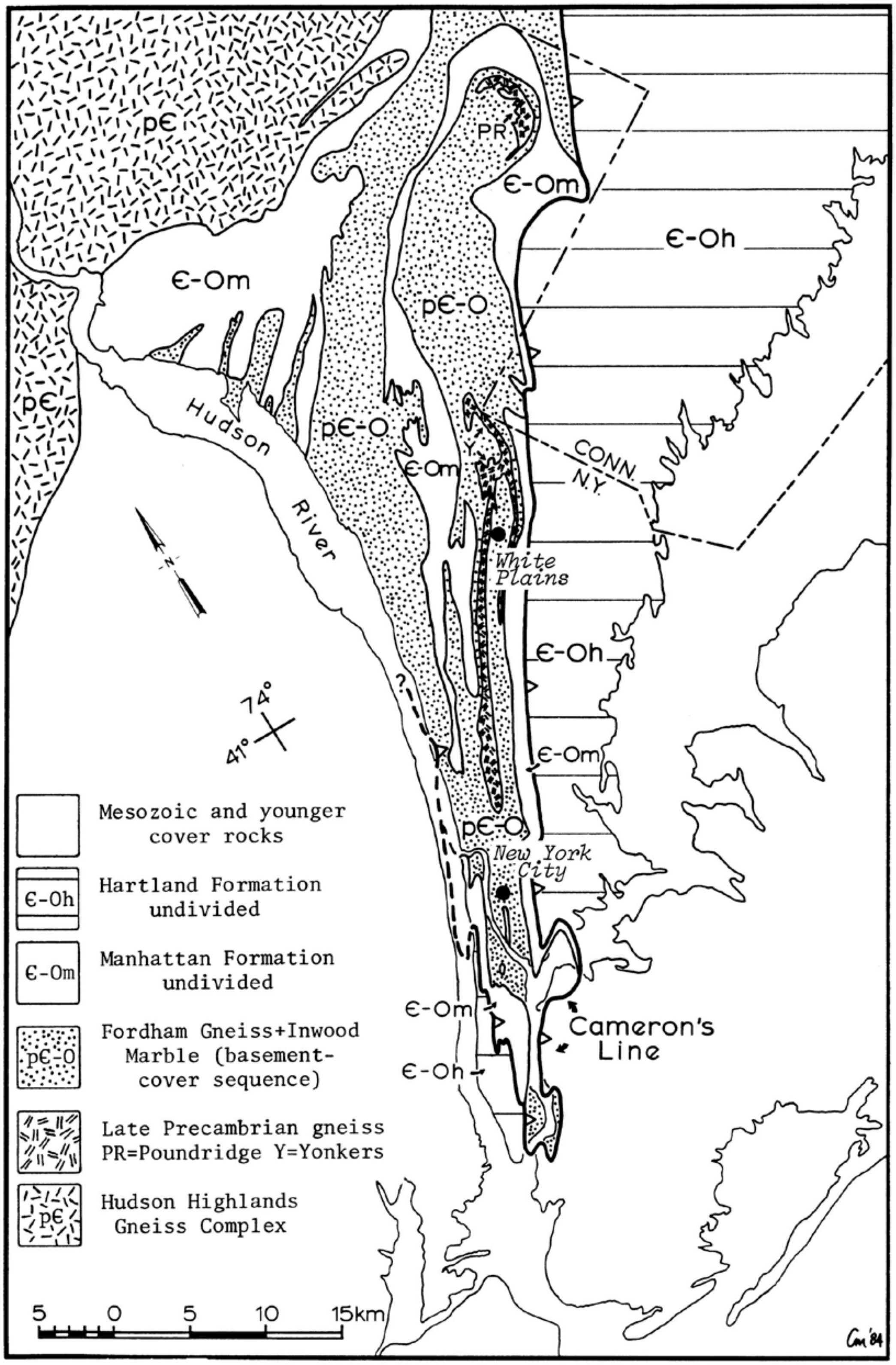

Figure 2 - Geologic sketchmap of the southern end of the Manhattan Prong showing the highly metamorphosed bedrock units. (From Merguerian and Baskerville 1987.)

Layer II: Sequences in Lower Paleozoic Rocks

In the region of our field trip are the depositional products of two contrasting paleogeographic-paleotectonic regimes:

(1) The regime of an ancient passive continental margin, which lasted from early in the Cambrian Period until the middle of the Ordovician Period (Figures 3, 4; Table 2) and which featured on the west a shallow, tropical carbonate shelf that passed eastward into deep water. On the shallow carbonate shelf, the Sauk Sequence [Layer IIA(W)] was deposited. East of the shelf edge, on a former continental rise, was deposited the Taconic Sequence of Layer IIA(E), a vast prism of fine-textured, predominantly terrigenous sediment. Still-farther eastward (oceanward) was a source of volcanogenic material.

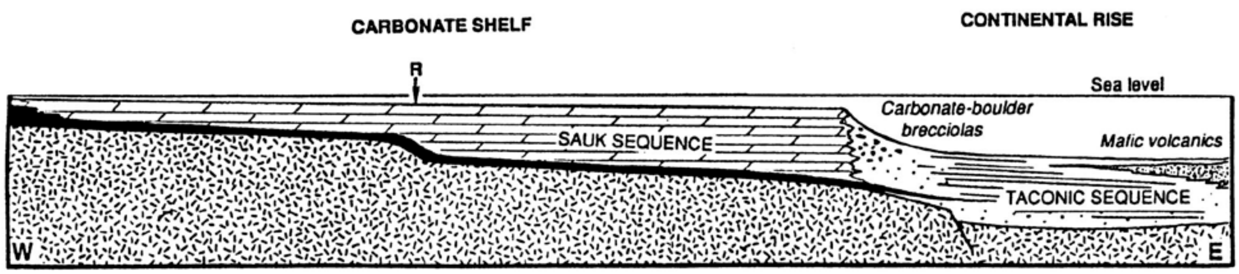

Figure 3 - Cross-sectional view of the Laurentian shelf edge showing the depositional environments of the Sauk and Taconic sequences. (Sketch from J. E. Sanders.)

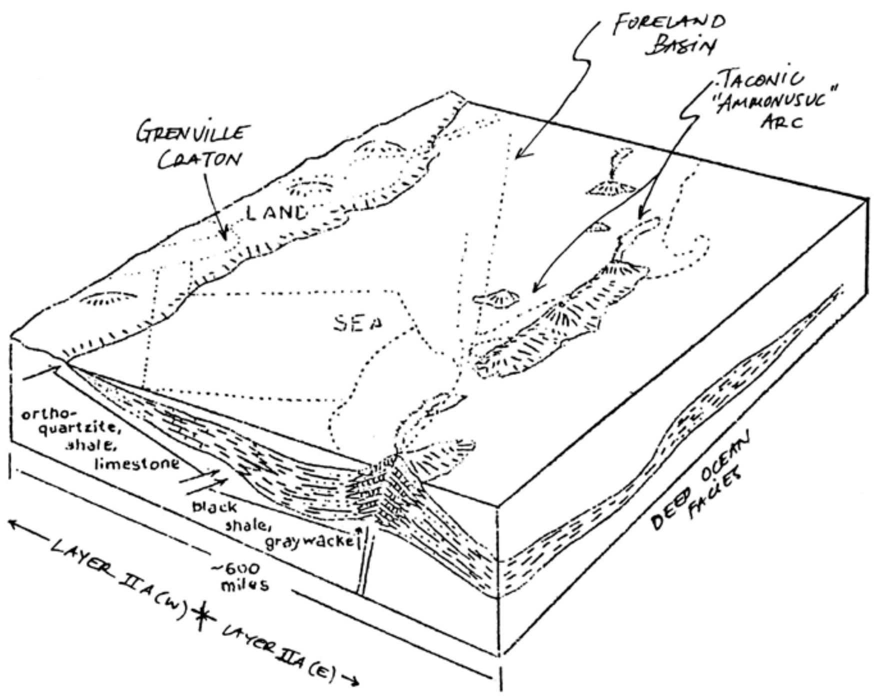

Figure 4 - Block diagram showing the Lower Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.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

(2) The regime of an active convergent continental margin, which commenced later in the Ordovician Period and extended through at least the Silurian Period. (See Figure 4.) The key depositional feature of this regime was a foreland basin, a vast synclinal trough that came into existence as a consequence of the great loads imposed on the lithosphere by an encroaching volcanic arc and continent-vergent overthrusts. This foreland basin subsided quickly and deeply – kind of like the elder Merguerian's career. In its deep marine waters dark-colored shales and graywackes of the Tippecanoe Sequence [Layer IIB] were deposited above the Sauk Sequence dolomitic carbonates of Layer IIA. Farther north, the evidence for this change consists of a karst landscape at the top of the carbonate succession and the covering of this karst surface with graptolite-bearing shales (Figure 5).

Sauk Sequence Carbonates

In the area of our trip, which lies in the central part of the former carbonate shelf, the Sauk Sequence [Cambro-Ordovician carbonates of Layer IIA(W)] is known as the Wappinger Group (local name taken from Wappinger Creek, south of Poughkeepsie or the Kittatinny Group (New Jersey name), and their metamorphosed equivalents (Vermont Marble, Stockbridge Marble, and Woodville Marble to the north and the Inwood Marble in Westchester County and New York City). This vast sheet of Sauk Sequence carbonates is known elsewhere by other names. It is the famous oil-bearing Arbuckle Group of Oklahoma and Kansas; the Ellenburger Group of Texas; and the Knox Group of the southern Appalachians. In general, it consists of dolomitic rocks of Cambrian and Early Ordovician ages (Table 2). The episode of accumulation of the Sauk Sequence ended when virtually the entire North American continent, formerly submerged by a shallow sea, became emergent and a surface of unconformity formed.

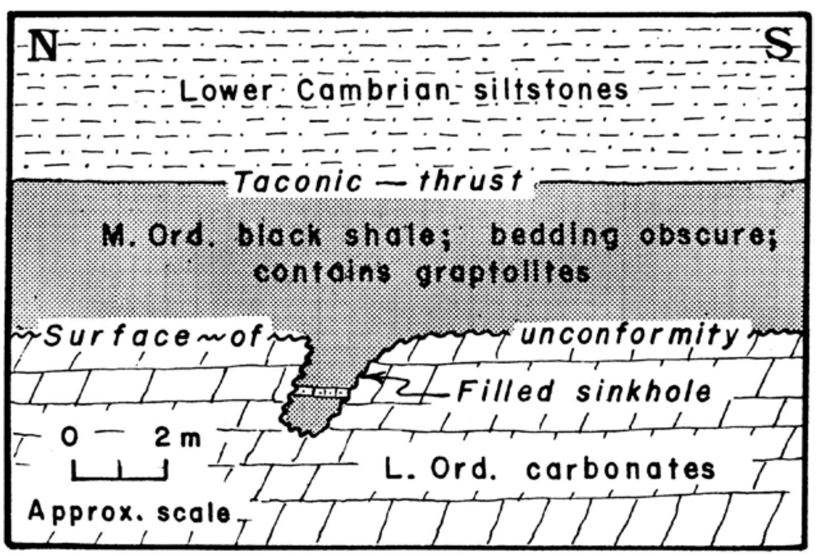

Figure 5 - West face of Bald Mountain, Washington County, New York, showing the three major units of the "Taconic Problem" in contact. The surface of unconformity proves that some terrigenous sediment do not have to be in thrust contact with the Cambro-Ordovician carbonate succession. The Taconic thrust of Cambrian siltstones against Middle Ordovician shales took place along the sea floor. Thus, locally, there is no major indication of thrusting (no mylonite, no contrast in minor structures above and below the thrust - thus nothing to show the presence of a thrust to investigators who do not pay attention to the fossils). Based on Sanders, Platt, and Powers (1961).

Tippecanoe Sequence

During the next episode of marine submergence, starting in the Middle Ordovician Epoch, the Tippecanoe Sequence strata began to accumulate. The initial deposits of the Tippecanoe Sequence consist predominantly of limestones (as contrasted with the generally dolomitic rocks of the underlying Sauk Sequence). These limestones are richly fossiliferous and have been studied extensively and subdivided to the maximum extent possible. A few local names applied to these limestones must be understood. In particular, the subdivisions of the Middle Ordovician limestones used early in the twentieth century were as follow:

Trenton

Middle Ordovician | Black River [Lowville Limestone in Upper Part]

Chazyan

These Middle Ordovician limestones are overlain by a thick body of terrigenous strata, shales at the base, coarse graywackes in the middle, and shales again at the top that are now considered to represent foreland basin sediments which accumulated during and after the emplacement of the great overthrusts (to be discussed subsequently). Before the Sequence terms had been proposed and later applied in New York State, workers in the nineteenth century used the name "Hudson River shales" as a collective term for the shales and other terrigenous strata of the lower part of the Tippecanoe Sequence. The name "Hudson River" for the shales was continued well into this century (for example, in the geologic report on the Newburgh quadrangle, Holzwasser, 1926). Other names that have been applied to the thick terrigenous strata of the lower part of the Tippecanoe Sequence include Normanskill and Martinsburg.

A second complication with the terrigenous strata of the Tippecanoe Sequence is their thickness, a difficult problem compounded by lack of large, continuous exposures. lack of a detailed stratigraphic subdivision and by the complex effects of multiple episodes of tectonic deformation. From time to time, contrasting thickness values have appeared in the literature based on: (1) guesses by those who did not attempt to work out the stratigraphic succession nor geologic structure but whose "sixth geologic sense of how things ought to be" informed them that the number should be small (i.e., no more than a few hundred meters), (2) calculations made after careful mapping, and (3) the results of exploratory borings.

Ruedemann pioneered the category (1) "thick-small" version of the thickness of these shales. Ruedemann based his conclusions on his mapping of the region around Saratoga Springs and study of a well at Mechanicville that cut 1,400 feet of shale where the dip was about 70° and the beds were repeated on overturned folds. He concluded (in Cushing and Ruedemann, 1914, p. 91) that: "the thickness of the shale in the well is clearly no indication of a corresponding thickness of shale beds." Ruedemann arrived at his preferred estimate of 1,000 feet from studying expsoed strata on the west face of Willard Mountain.

Exploratory borings in the Hudson Valley have supported these large thickness determinations. At least three exploratory borings have been drilled in locations where the hole penetrated 8,000 feet or more of shale, probably much more than the operators had imagined would be present. The Senigon boring, Quebec, cut 4,000 feet of shale. The Columbia Gas No. 1 D. J. Finnegan boring in southern Washington Co., NY, penetrated 2,760 feet of Taconic strata and 2,000 feet of mid-Ordovician (presumably Utica) shale. The Crom-Wells No. 1 Fee, SW of Middletown, Orange Co., NY, drilled through 4,700 feet of shale.

Taconic Sequence

In our view, the Taconic Sequence refers to the predominantly fine-textured terrigenous strata (Layer IIA(E) in Table 2) that were deposited seaward of, and in much deeper water than were the Sauk Sequence (Cambro-Ordovician) dolomitic carbonates and continued to be deposited during the time when the Knox unconformity was forming and while the lower parts of the Tippecanoe Sequence were accumulating. The contact is a result of subaerial exposure of the carbonates and subsequent formation and subsidence of a foreland basin along the eastern edge of the former shallow-water carbonate shelf. (See Figure 5.)

Taconic Orogeny

The overthrusts with which the origin of the Tippecanoe foreland basin have been associated were the initial products of a mountain-building event known as the Taconic orogeny. As a result of this orogeny, mountains were elevated where formerly the deep sea stood. From these mountains, coarse sediments were shed westward toward the interior of the continent and restricted oceanic circulation produced anerobic conditions that resulted in black shales of the foreland basin. Subsidence of the basin and the bathymetric reversal that resulted in the thick deposits of Normanskill black shales and intercalated turbidites were the result of loading of the Taconian arc on the former open-ocean passive continental margin of Laurentia and the formation of gravity slides of sediment with a dual polarity – clastic and volcaniclastic sediment from the Taconian arc terrane interfingering with clastic sediment derived from the Laurentian continent.

The first major overthrust event involved duplication of the Sauk Sequence and lower parts of the overlying Tippecanoe Sequence along the Champlain and related thrusts. In northwestern Vermont, the Champlain thrust is overlain by Lower Cambrian quartzites; no underlying Proterozoic basement rocks are involved. Farther south, from Stissing Mountain, Dutchess County, New York, and into northwestern New Jersey, the Lower Cambrian quartzite rests nonconformably on Proterozoic, usually graphitic, rocks that locally at least can be shown to be overthrust against the lower part of the Tippecanoe Sequence. Somewhat later, the Taconic allochthon was emplaced. Within this allochthon, the fine-textured terrigenous sediments of the Taconic Sequence [Layer IIA(E)], the former ancient continental rise deposits, were displaced continentward to positions above the Sauk Sequence carbonates [Layer IIA(W)] and the strata of the lower part of the Tippecanoe Sequence [Layer IIB].

The late Middle Ordovician convergent orogenic events are collectively designated as the Taconic Orogeny. Formed during this orogenic episode were the Champlain family of overthrusts (as noted, from Stissing Mountain southwestward, involving continental-type Proterozoic basement) as well as the Sauk Sequence and part of the Tippecanoe Sequence and

Taconic overthrusts (and, as already mentioned, involving only the Taconic Sequence and never any pre-Taconic basement). At the same time, and somewhat earlier, an extensive fold belt, a zone of regional metamorphism, and various stitching plutons dated at roughly 450 Ma were intruded (Ratcliffe and others 2012).

As mentioned above, while the deep-water turbidites and related sediments of the Tippecanoe Sequence were accumulating in the foreland basin, the great overthrusts may have moved along the former sea floor. To many geologists, subscribing to this older thinking (Zen, 1967; Bird and Dewey, 1975; Ratcliffe and others, 1975), the Taconic orogeny was envisioned as a series of gravity-induced slides (the Low Taconics) and eventually overthrusts (the High Taconics) of the oceanic sequence [Layer IIA(E)] above the Sauk Sequence carbonate-shelf deposits [Layer IIA(W)] and overlying flysch of the Tippecanoe Sequence [Layer IIB]. This episode of continentward displacement was driven by the encroachment of a volcanic arc (the Ammonoosuc-Oliverian Complex in Figure 6) against the passive continental margin of Ordovician North America.

Many workers [including us, Rowley and Kidd (1981), Stanley and Ratcliffe (1985)] do not believe in gravity sliding as a model for the emplacement of the structurally lowest Taconic allochthons. Rather, based on stratigraphic and structural evidence, these workers envision all Taconic displacements resulted from continentward overthrusting of a subduction complex formed between the oceanward-facing continental margin sequence and the encroaching Taconic arc complex (Figure 6).

The main argument for gravity-induced sliding of allochthons, the presence of olistostromes and wildflysch conglomerates on the western, leading edge of the Taconic allochthon are now interpreted as deposits of forethrust olistostromes in front of an overriding accretionary wedge. As far as is now known, the Taconic allochthon itself includes only sedimentary strata; no pre-Taconic continental basement has been found. However, such massive overthrusts of strata over strata undoubtedly are accompanied by thrust slices in which the basement overrides sedimentary strata. In eastern New York State, slivers of Cambro-Ordovician carbonate have been mapped and identified within the base of Taconic sole thrusts by Zen and Ratcliffe (1966) and by Ratcliffe and others (1975).

In Newfoundland, thick slices of oceanic lithosphere (i.e., an ophiolite succession) have been thrust over the Cambro-Ordovician shallow-water carbonate-shelf deposits (of Sauk and basal Tippecanoe Sequences). Detrital chromite, a mantle-derived chromium oxide, probably shed westward during subaerial exposure of ophiolitic slabs, has been found in the flysch deposits associated with the Newfoundland "Taconics".

An important point associated with the concept of the Champlain family of overthrusts where they involved the Proterozoic basement is that post-thrust uplift and erosion probably removed large amounts of such slice(s) of granitic basement and that the only parts remaining are those that have been protected from erosion by being downdropped. This possibility is mentioned here because erosion of an overthrust block composed of granitic basement rocks could have provided a supply of coarse quartz to form the Lower Silurian Green Pond-Shawangunk-Tuscarora-Clinch sheet of sandstones and local conglomerates at the base of Layer

III. Alternatively, the thick quartzose deposits could have been formed from reworked bull quartz veins found along the Taconic thrust faults or from eroded pegmatites associated with the roots of the Taconic volcanic arc. The parent deposit of all this Silurian-age quartz is, as yet, a mystery.

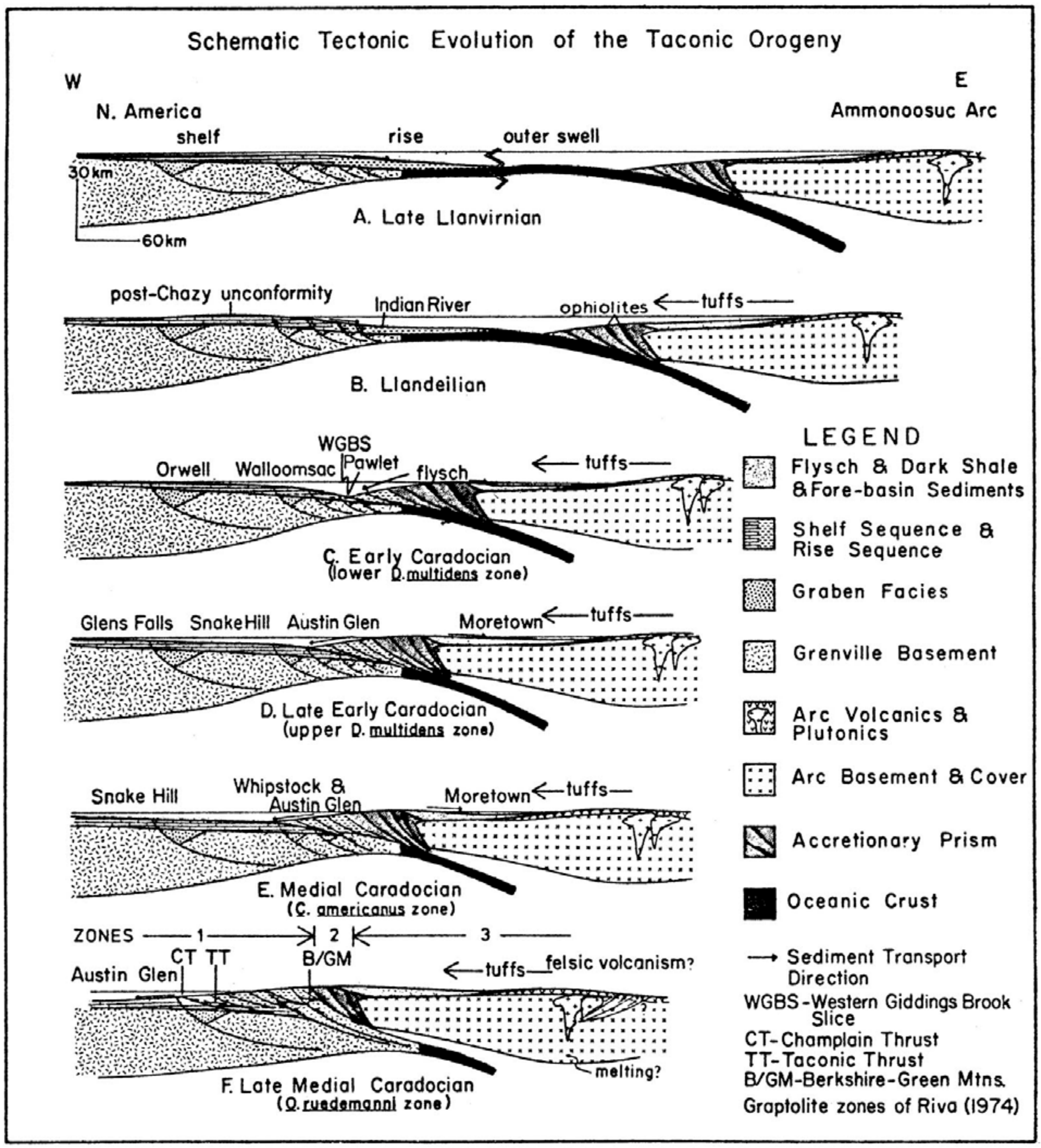

Figure 6 - Sequential tectonic cross-sections for the Taconic orogeny in New England. (From Rowley and Kidd 1981.)

GEOLOGICAL BACKGROUND OF NEW YORK CITY AND VICINITY

NYC is situated at the extreme southern end of the Manhattan Prong (Figure 7), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terrains of New England. Southward from NYC, the rocks of the Manhattan Prong plunge nonconformably beneath predominately buried Mesozoic rocks, younger Cretaceous strata, and the overlying Pleistocene (glacial) sediment found capping much of the region including all of Long Island and much of Staten Island.

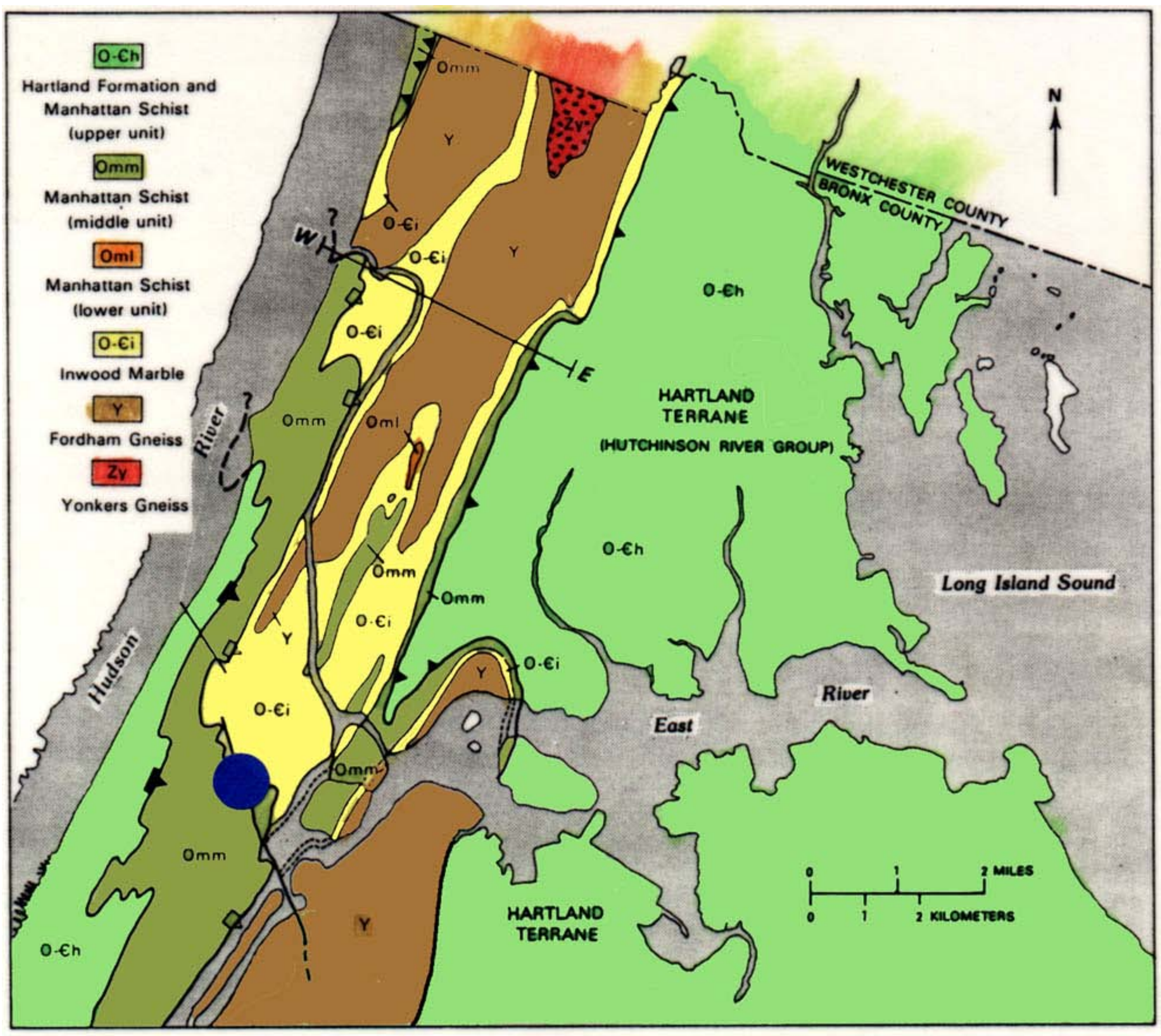

Figure 7 – Geological map of New York City showing the generalized structural geology of the region. Adapted from Merguerian and Baskerville (1987) and Merguerian and Merguerian (2004). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most faults and intrusive rocks have been omitted. Blue dot shows epicenter of a magnitude 2.4 earthquake that took place in 21 January 2001.

Bedrock Stratigraphy of New York City – Will the Real Manhattan Schist Please Stand Up!

The history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991) so the following is simply a brief overview. In 1890, Merrill named the Manhattan Schist for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of L. D. Gale (1839, 1843), and 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 and others (1902) produced the United States Geological Survey New York City Folio (#83) and following Dana, chose to use the name Hudson Schist (rather than Manhattan Schist) for the schistose rocks of NYC. This pioneering work by Merrill and coworkers set the stage for a series of detailed investigations by many geologists in the 1900's that helped define the details of lithology and structure of NYC bedrock units.

Based on study of over 900 natural exposures, a multitude of drill core and construction excavation analyses, CM's investigations of the bedrock geology of NYC since 1972 have portrayed a complex structural history and suggests that the Manhattan Schist formation exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three separable map units known as the **Hartland, Manhattan, and Walloomsac** formations. (See Figure 7.) These subdivisions agree with designations proposed by Hall (1976, 1980) but suggest the presence of a hitherto-unrecognized, structurally higher unit that is a direct correlative of the Hartland Formation of western Connecticut (Merguerian 1981, 1983, 1985, 1987). The three schistose units are imbricated along regional ductile faults known as the St. Nicholas thrust and Cameron's Line (Merguerian 1994, 1996) as depicted in a simplified cross section across the northern tip of Manhattan into the Bronx (Figure 8).

Keyed to Figure 7, the W-E section of Figure 8 shows the general structure of NYC and how the St. Nicholas thrust and Cameron's Line overthrusts position the Manhattan and Hartland formations above the Walloomsac formation and the Fordham-Inwood basement-cover sequence. Late-stage major folds produce digitations of the structural- and stratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward topping of tectonostratigraphic units exposed in central Manhattan and the effects of the yet younger NW-trending asymmetric folds. The structural geology of NYC is detailed in a later section and the stratigraphy is simplified as diagrammed in Figure 9.

Hartland Formation. The structurally high Hartland formation (Ꞓ-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and migmatite (Figure 10) with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite±garnet. ***(Note: Minerals in descriptions herein are listed in relative decreasing order of abundance.)*** The formation consists of interlayered schist, gneiss, granofels, and amphibolite. The schistose facies is lustrous and consists of dense, aligned fine- to coarse-textured muscovite that splits readily along the foliation. The gneiss and granofels varieties are massive, commonly migmatitic, and may or may not show pronounced foliation. Although typically not exposed at the surface, the Hartland underlies most of the central part and southern half of Manhattan and the eastern half of The Bronx. Because it is lithologically identical to the Late Proterozoic to Ordovician Hartland Formation of western Connecticut and

Massachusetts, CM has extended the name Hartland into NYC (Merguerian 1983) and considers the formation part of the **Taconic Sequence**.

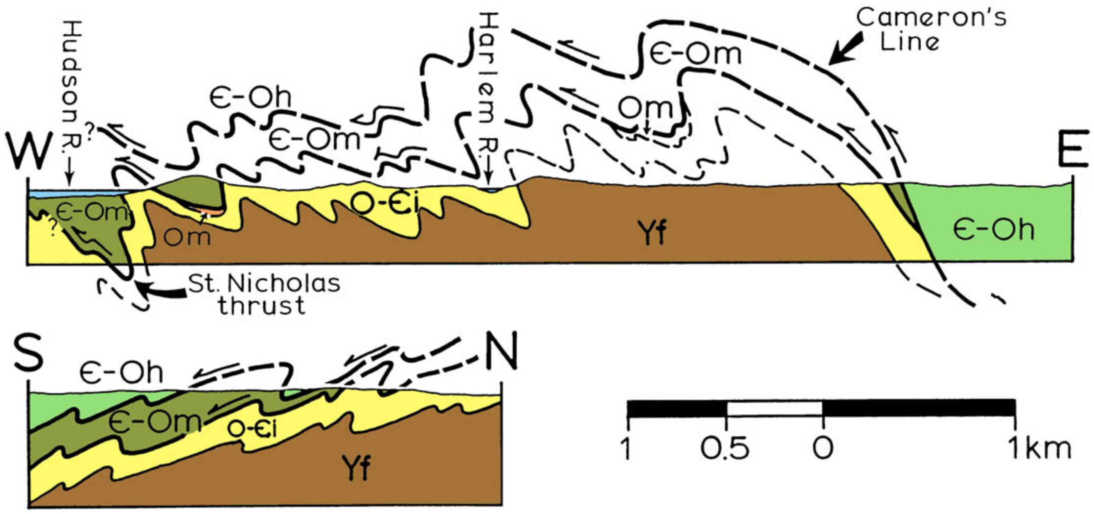

Figure 8 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). See Figure 7 for the line of the W-E section. The N-S section runs through the east edge of Central Park. [**Note** – the unit Om is the same as Ow in this guide.]

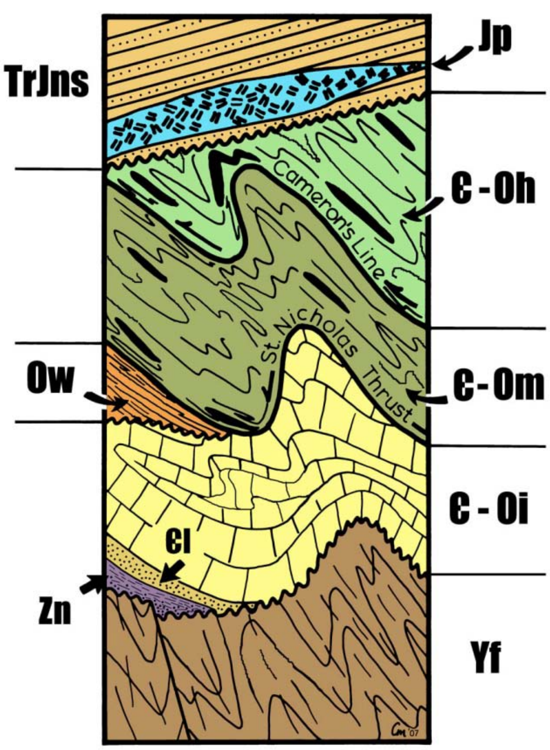

Figure 9 - Bedrock stratigraphy of New York City as described in text. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).

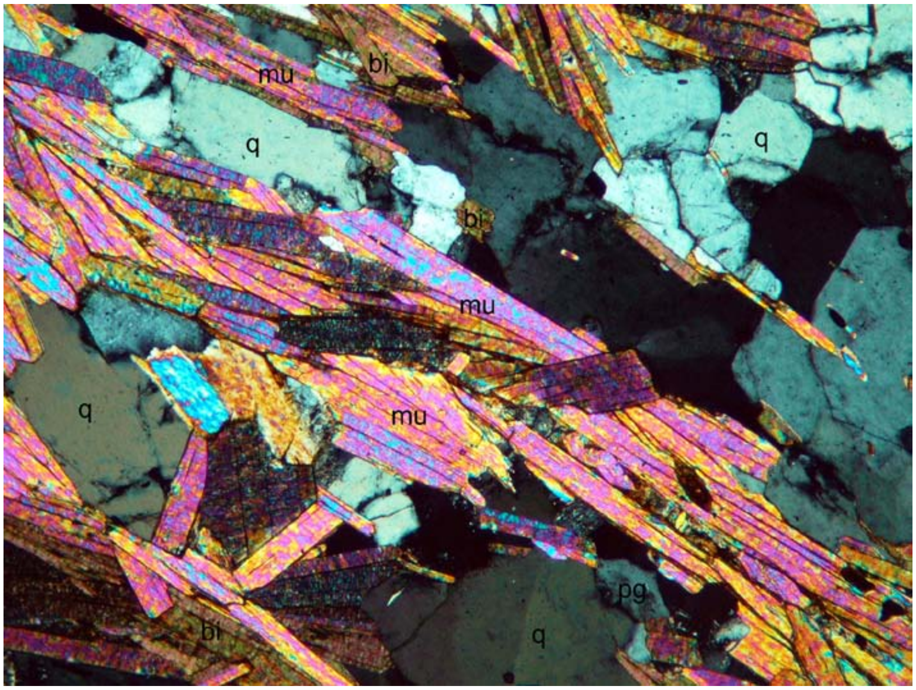

Figure 10 - Photomicrograph in cross-polarized light of Hartland schist (Є-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the high mica content and prevalence of muscovite and quartz, diagnostic mineralogical characteristics of the Hartland. (CM Sample N125; 112th Street and Riverside Drive, Manhattan; 2 mm field of view.)

Manhattan Formation. The Manhattan formation (Є-Om) consists of very massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite-magnetite gneiss, migmatite, and to a lesser degree, schist (Figure 11). The unit is characterized by the lack of internal layering except for the presence of kyanite+sillimanite+quartz+magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite, and scarce quartzose granofels. The unit is a major ridge former in northern Manhattan, a testament to its durability to weathering owing to the lack of layering and presence of wear-resistant minerals quartz, feldspar, garnet, kyanite, and sillimanite. Owing to the presence of disseminated magnetite the formation shows a strong attraction to a magnet.

The Manhattan Formation forms the bulk of the “exposed" Paleozoic metamorphic rocks of northern Manhattan including most northern Central Park exposures. The Manhattan is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Late Proterozoic to Ordovician ages in New England (Hall 1976; Merguerian 1983, 1985). These rocks, which contain calc-silicate interlayers in western Connecticut (Merguerian 1977), are inferred to represent metamorphosed sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America. As such they are grouped, along with the Hartland Formation, with the **Taconic Sequence**.

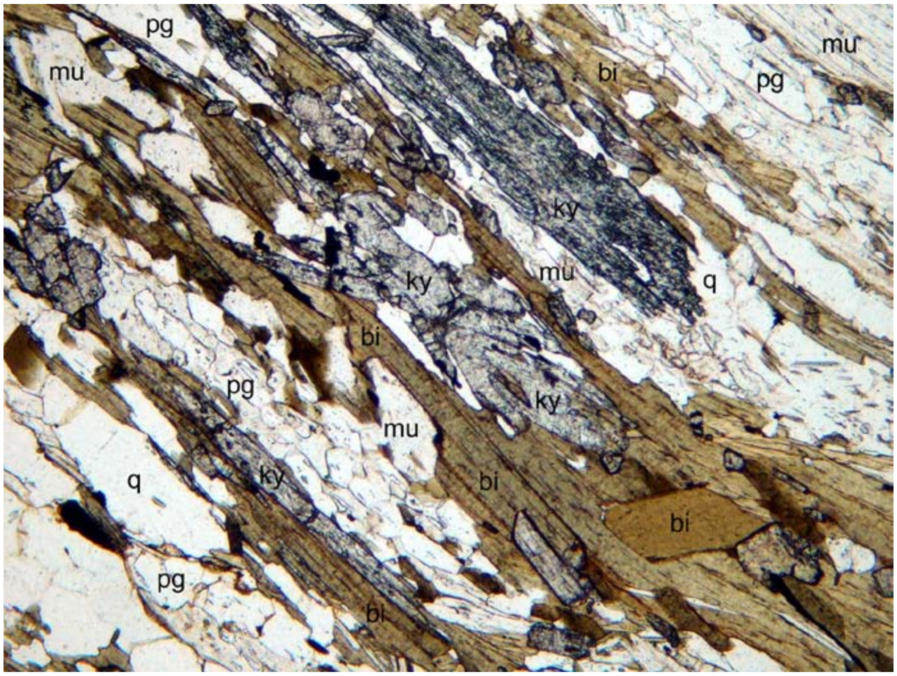

Figure 11 - Photomicrograph in plane-polarized light of the Manhattan Schist (Ꞓ-Om) showing an aligned intergrowth of biotite (bi), kyanite (ky), and muscovite (mu) in a fine-textured matrix of intergrown plagioclase (pg) and quartz (q). The penetrative foliation in this view, which consists of aligned micas and kyanite as well as flattened quartz and feldspar, is diagonal across the image and marks a structural discontinuity that may split readily. (CM Sample N217; South of George Washington Bridge approach, Manhattan; 2 mm field of view.)

Walloomsac Formation. This discontinuous unit (Ow) is composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-pyrite-graphite schist and migmatite containing interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of diopside±tremolite±phlogopite ("Balmville") calcite and dolomitic marble, and hard calc-silicate rock. Pinkish garnet occurs as porphyroblasts up to 1 cm in size and amphibolite is absent. As shown in the photomicrograph of Figure 12, strongly pleochroic reddish biotite, pinkish garnet, graphite, and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation.

Exposed Walloomsac Formation can be found interlayered with the underlying Inwood at five localities in Manhattan - (1) at the north end of Inwood Hill Park in Manhattan, (2) beneath the St. Nicholas thrust on the north and east sides of Mt. Morris Park (Merguerian and Sanders 1991), and (3) in the northwestern corner of Central Park (Merguerian and Merguerian 2004). The Walloomsac has also been detected sheared against Hartland rocks in numerous borings and excavations from (4) northern and (5) southern Manhattan (Merguerian and Moss 2006, 2007) including the new World Trade Center site (Merguerian 2010).

In The Bronx, four areas of Walloomsac rocks have been found; (1) on the Grand Concourse and I-95 overpass (Merguerian and Baskerville 1987), (2) beneath the St. Nicholas thrust in the western part of Boro Hall Park (Fuller, Short, and Merguerian 1999), (3) below the St. Nicholas thrust in the north part of the New York Botanical Garden (Merguerian and Sanders

1998), and (4) in the northeastern part of Crotona Park (unpublished data). Because it is interpreted as being autochthonous (depositionally above the Inwood Marble and underlying Fordham gneiss), it is assigned a middle Ordovician age. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels enables the interpretation that the Walloomsac Schist is the metamorphosed equivalent of middle Ordovician carbonaceous shale and interlayered greywacke strata of the Tippecanoe Sequence and is therefore considered correlative with parts of the Annsville and Normanskill formations of SE New York and the Martinsburg formation of eastern Pennsylvania (Merguerian and Sanders 1991, 1993a, 1993b).

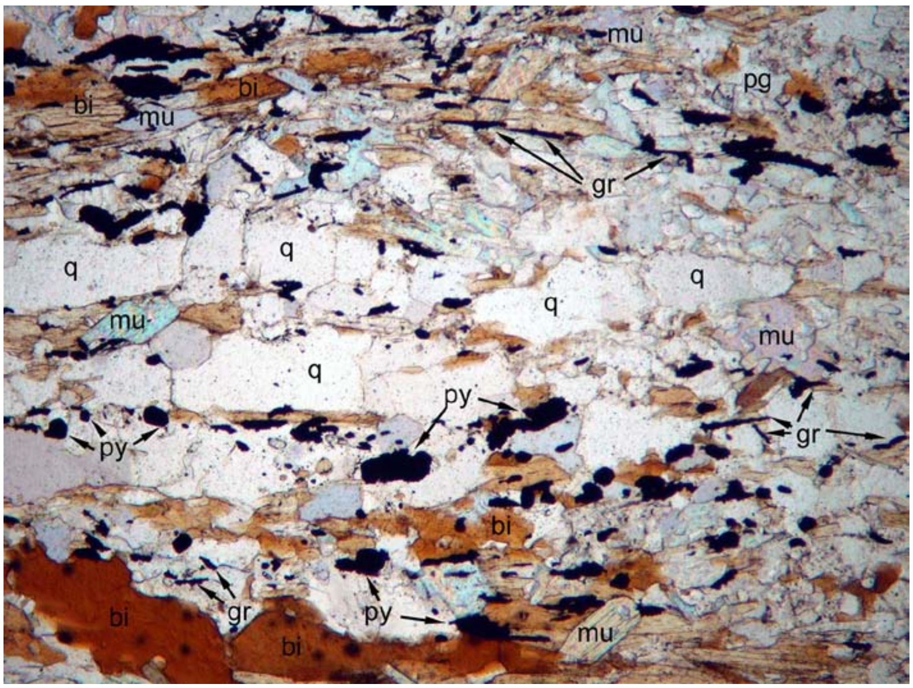

Figure 12 - Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal in this view) defined by aligned biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals locally overgrow the foliation. Diagnostic petrographic characteristics of the Walloomsac include the presence of graphite and pyrite and strongly pleochroic red-brown biotite. (CM Sample N113-3L; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

Origins of the Hartland, Manhattan, and Walloomsac Formations

Now metamorphosed to amphibolite facies grade, the exposed metamorphic cover rocks of NYC (Hartland, Manhattan, and Walloomsac formations) were originally deposited as sediment and intercalated volcanic and volcaniclastic materials, though in vastly different environments (Figure 13). The Hartland Formation was originally deposited in a deep ocean basin fringed by offshore volcanic islands. The marginal ocean basin was the receptor of a huge influx of terrigenous and volcanogenic material. This produced a thick sequence of interlayered clay, silt, sand, and interlayered volcanogenic strata which resulted in a variable rock sequence after Paleozoic dynamothermal metamorphism. Compositional layering was preserved in the

Hartland, forming a dominantly well-layered metamorphic rock mass consisting of interlayered and locally migmatitic schist, gneiss, granofels, and amphibolite.

The Manhattan Formation originated along the edge of the former North American continental margin as thick clay-rich sediment with occasional sand interlayers. (See Figure 13.) As a result, the Manhattan is often more massive in character than the Hartland. The Walloomsac Formation is mineralogically unique since it originated under restricted oceanic conditions and consisted of thick accumulations of carbonaceous and sulphidic clay-rich sediment with occasional sandy and calcareous interlayers. This has resulted in mineralogically distinct schistose rock enriched in biotite, graphite, and pyrite together with layers of calcite marble and calc-silicate rock. The contrast in internal compositional layering and mineralogy allows for separation of the three units in the field and also during routine core analysis though petrographic work is by far the most diagnostic indication.

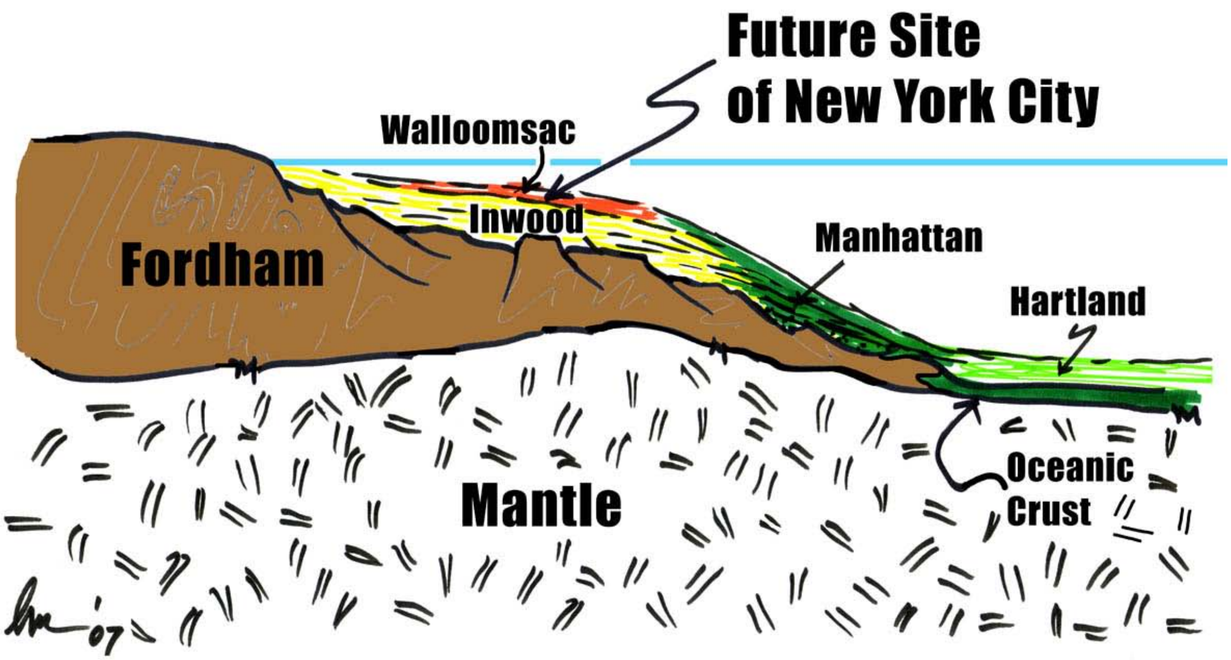

Figure 13 - Diagrammatic cartoon of eastern North America after rifting from Rodinia and during deposition of the Paleozoic strata that are to become the Hartland, Manhattan, and Walloomsac formations. Note the correlation of units and their relationships to the underlying units of the partly coeval Inwood and older Fordham.

NYC Bedrock Formations Beneath the Hartland, Manhattan, and Walloomsac Formations

The metamorphic rocks described above are in structural or unconformable contact with the predominately older units described below.

Inwood Marble. The Inwood (Ꞓ-Oi in Figures 7–9) consists of typically 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 (Figure 14) together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite

(Merguerian, Merguerian, and Cherukupalli, 2011). Layers of fine grained gray quartzite with a cherty appearance are also locally present. The unit is found in the Inwood section of northern Manhattan, the Harlem lowland NE of Central Park, in thin belts in the East River channel, in the subsurface of southeastern Manhattan, and also crops out in The Bronx and Westchester County. The Inwood is correlative with an outcrop belt of non-metamorphosed Cambro-Ordovician rocks (Sauk Sequence) found along the entire Appalachian chain of North America.

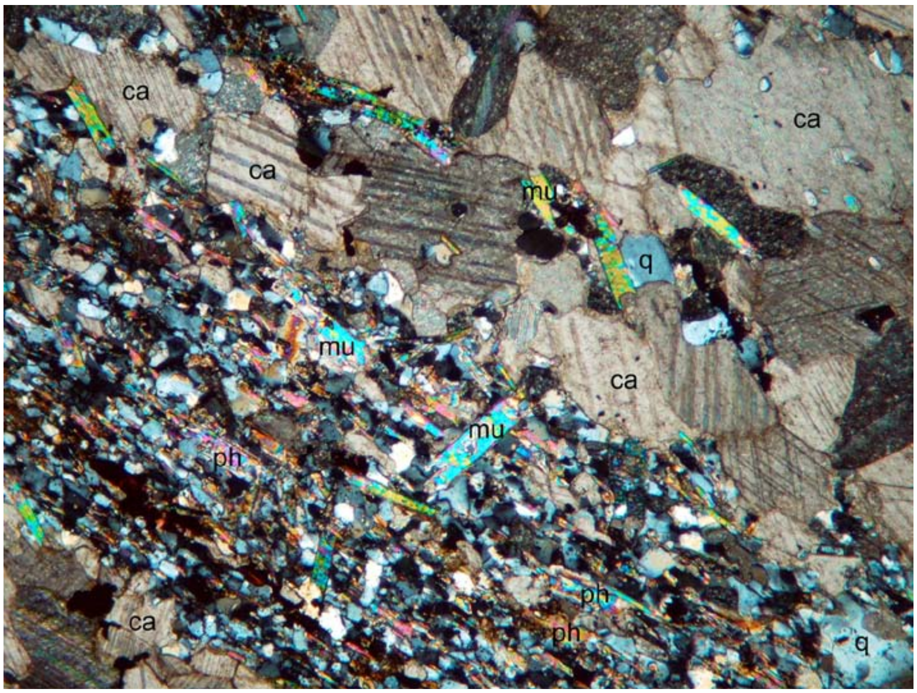

Figure 14 - Photomicrograph in cross-polarized light of the Inwood Marble near the contact with the Walloomsac showing the granoblastic texture produced by recrystallized twinned calcite (ca). A fine-textured mica-rich zone cutting diagonally across the slide defines a foliation which here consists of aligned muscovite (mu) and phlogopite (ph) in a matrix of recrystallized quartz (q), calcite, and biotite (bi). Normally the Inwood is quite pure and consists of coarse textured granoblastic calcite or dolomite. (CM Sample N113-4; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

Fordham Gneiss. The Fordham Gneiss (Yf in Figures 7–9) constitutes the oldest underpinning of rock formations in the NYC area and consists of a complex assemblage of Proterozoic Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks. In NYC, only a few attempts have been made to decipher the internal stratigraphic relationships, hence, the three-dimensional structural relationships remain obscure. Based on detailed studies in the Queens and Brooklyn NYC water tunnels (Merguerian 2000; Merguerian, Brock, and Brock 2001; Brock, Brock, and Merguerian 2001) the Fordham consists of predominately massive mesocratic, leucocratic, and melanocratic orthogneiss with subordinate schistose rocks. They have been metamorphosed to the high pressure granulite facies which has produced a tough, anhydrous interlocking mineral texture consisting of primary pyroxene, plagioclase, and garnet that has partially resisted hornblende and biotite grade retrograde regional metamorphism (Figure 15).

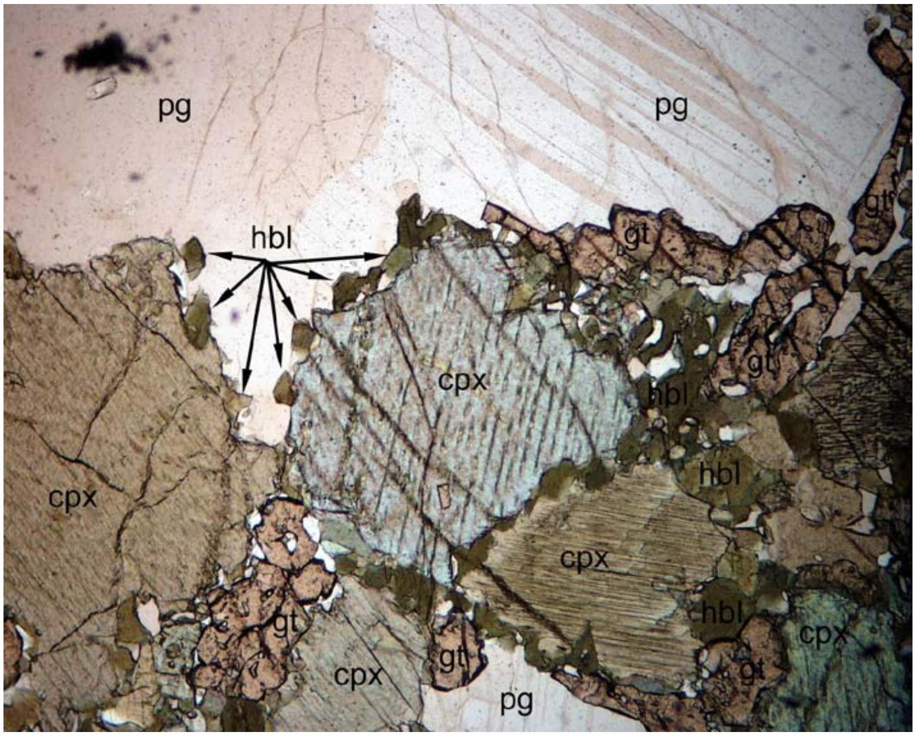

Figure 15 - Photomicrograph in plane-polarized light of mid-Proterozoic mafic orthogneiss showing a coarse-textured granular intergrowth of clinopyroxene (cpx), plagioclase (pg), and garnet (gt) produced during an early stage of metamorphic recrystallization of a former mafic igneous rock. Granular hornblende (hbl) was produced during a secondary metamorphism but the older interlocking metamorphic texture has prevailed. (CM Sample Q114; Queens Tunnel Station 015+90; 2 mm field of view.)

The Fordham is found in the Bronx, in the subsurface of SE Manhattan, the East River channel, and western Queens and Brooklyn, and underlies most the entire region at greater depth. (See Figure 13.) Occurring locally between the Inwood and Fordham are two minor units. One is the very local Lowerre Quartzite (Norton 1959) and the other a late Proterozoic unit known as the Ned Mountain Formation (unit Zn in Figure 9) of Brock (1989, 1993). The Ned Mountain is correlative with Proterozoic Z rocks mapped as the Yonkers Gneiss (Scotford 1956) and the Ravenswood Granodiorite Gneiss (Ziegler 1911) found in Westchester County and in western Queens, respectively.

Other Rock Types Associated with the Bedrock Series

Serpentinite. In addition to the famous Staten Island serpentinite, many scattered bodies of serpentine rock have been encountered in the subsurface of NYC over the years (Figure 16). In addition to a few bodies known in Manhattan near 59th Street and 10th Avenue, the Bruckner Boulevard/Cross Bronx Expressway/Hutchinson River Parkway interchange at the north end of the Bronx-Whitestone Bridge approach in The Bronx, and a few bodies that were penetrated during construction of the Brooklyn Tunnel (Schnock 1999). Serpentinite has also been found in a building construction site at 43rd Street and Sixth Avenue in midtown Manhattan (Merguerian and Moss 2005) and in northern Manhattan (Merguerian and Moss 2007). These sheared masses are interpreted as ophiolitic scraps and are commonly found in ductile fault contact with the surrounding Hartland Formation or near the Manhattan-Hartland contact (Merguerian 1979). The serpentinites are black to greenish fine-textured rocks containing serpentine group minerals including chrysotile, chromite, magnetite, orthoamphibole, magnesite, talc, calcite, chlorite together with relict olivine and pyroxene.

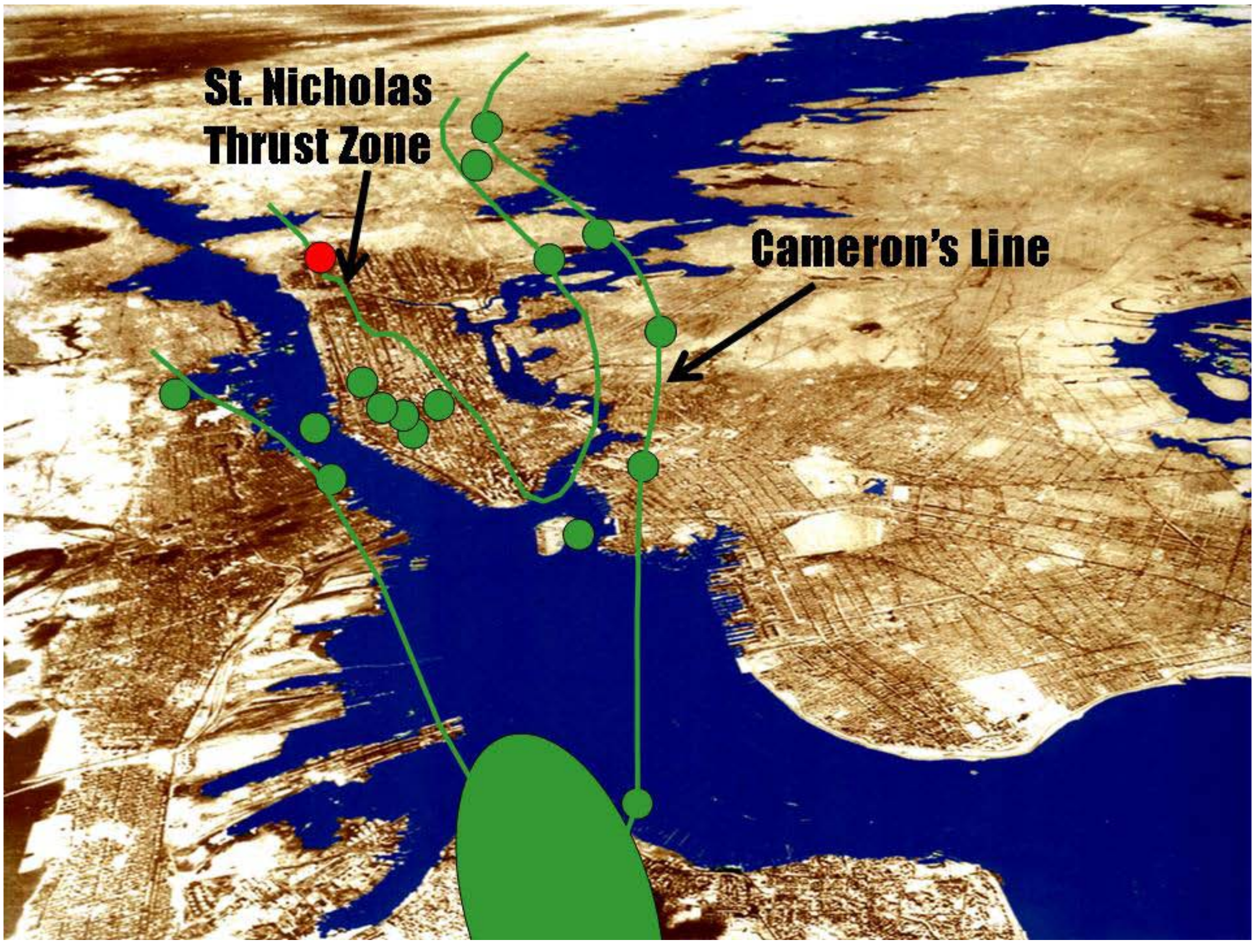

Figure 16 - Cartoon showing distribution of 18 known areas of serpentinite in the New York City area. The green lines surround areas of serpentinite defining a zone of sheared rock broadly coincident with the St. Nicholas thrust and Cameron's Line, two important elements of the Taconian suture zone in New York City. The red dot shows the location of a newly discovered serpentinite in northern Manhattan described by Merguerian and Moss (2007).

Granitoid. All units of the NYC bedrock described above have been intruded by granitoids that range from foliated and internally sheared pre- and syn-tectonic intrusives to post-tectonic bodies. They range from fine-textured to pegmatitic and occur as dikes, sills, stocks, and small plutons consisting of essential microcline, orthoclase, quartz, plagioclase, biotite, hornblende, muscovite, and subordinate garnet. Minor tourmaline and beryl are also reported.

Rhyodacite. Found exclusively beneath the area of Woodside, Queens, a swarm of five thin sub-parallel rhyodacite dikes, all displaying pristine igneous textures, were penetrated during construction of the Queens Tunnel (Merguerian 2000, 2001). They occurred as tabular, discordant injections roughly oriented N53°W and average roughly 3 m in thickness. The larger dikes vary from 5.3 m down to 1 m and taper off to thinner dikelets. The rhyodacites are reddish, glassy to aphanitic igneous rocks with no metamorphic fabric and low average density (2.58 g/cm^3).

The unique devitrified texture of the groundmass and the presence of vesicles unequivocally identify the Queens Tunnel rhyodacite as a hypabyssal rock. The dikes are Permian in age (~295 Ma) and crosscut folded Proterozoic Y granulite facies rocks of the Queens Tunnel orthogneiss complex with which they are genetically and temporally unrelated. The injection of a suite of Permian rhyodacite dikes that are chemically, texturally, and temporally unrelated to their bedrock hosts, mark an anomalous geological formation that adds a new chapter to the evolution of the NYC area.

Alkalic and Mafic Dike Rocks. Mapping in conjunction with construction of NYC Water Tunnels # 1 and 2 also defined alkalic and mafic dike rocks (Berkey 1911, 1933, 1948) and we have seen mafic dikes in the Queens Tunnel and elsewhere in NYC and throughout New England. Some of them are foliated and of Ordovician age and others contain pristine igneous textures and are most likely associated with the early Jurassic Palisades intrusive epoch.

STRUCTURAL GEOLOGY OF NEW YORK CITY

Deformational Episodes. All bedrock units in NYC have shared a complex Paleozoic structural history which involved three superposed phases of deep-seated deformation (D_1-D_3) followed by three or more episodes of open- to crenulate folds (D_4-D_6). The synmetamorphic juxtaposition of the various units occurred very early in their structural history (D_2) based upon field relationships. The Fordham harbors a more complex history as a result of its great age. It has experienced deformation and metamorphism during the Grenville orogeny (~1.1 Ga) in addition to the three Paleozoic orogenies (Taconian, Acadian, and Allegenian) experienced by the overlying Inwood, Walloomsac, Manhattan, and Hartland rocks. Below, I will restrict my discussion to the Paleozoic deformation with the understanding that the Fordham is more complexly deformed and highly metamorphosed.

The obvious map scale 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 Figures 7 and 8.) The folds are typically overturned to the NW with a steep SE-dipping schistosity (Figure 17). Shearing 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. The third-generation structures deform two earlier structural fabrics (S_1 and S_2). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of overturned F_3 folds). We suspect that all of these structures (D_1, D_2, and D_3) are products of the protracted middle Ordovician Taconic orogenesis (Merguerian 1996).

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 addition, porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to F_3 hingelines in the bounding Inwood Marble (Merguerian and Maerguerian 2012).

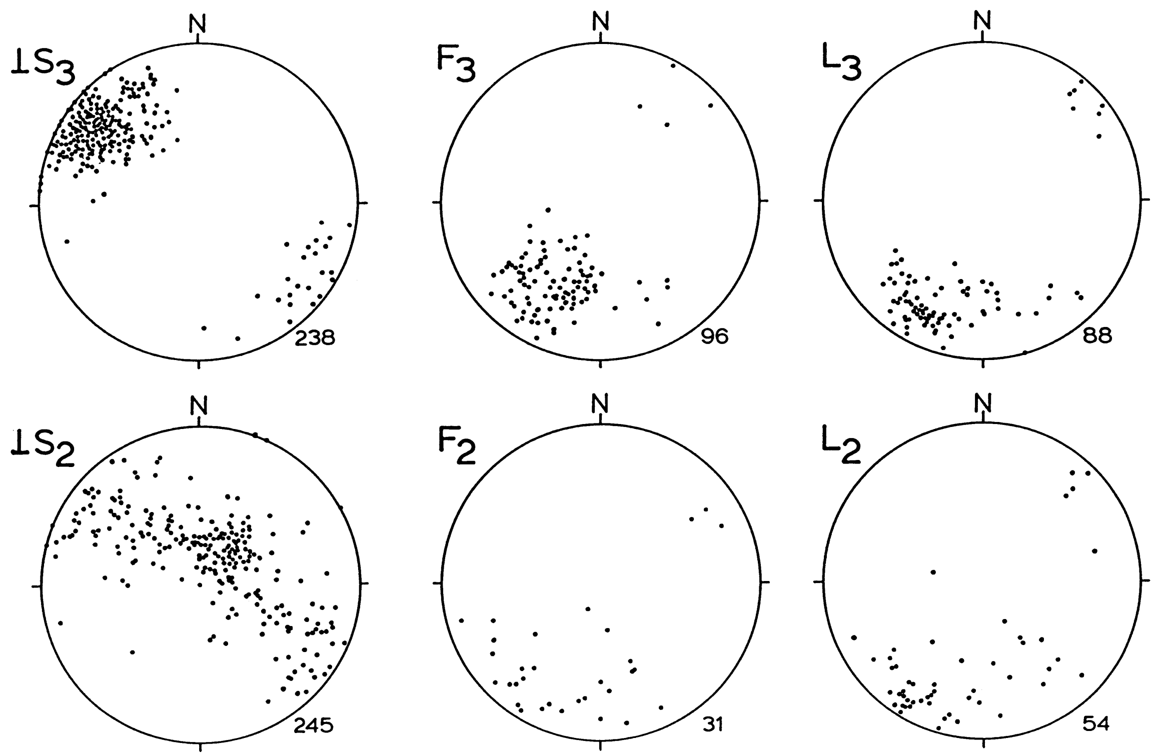

Figure 17 - Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, Figure 26, p. 113.)

Although the regional S_2 metamorphic grain of the NYC bedrock trends N50˚W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25˚. (See Figure 17.) 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 identical grade with D_2 which resulted in kyanite overgrowths and annealing of former mylonitic textures (Merguerian 1988).

Originating within the convergent walls of a major subduction zone formerly situated off shore from proto-North America, the D_1 to D_3 folds and crosscutting fabrics presumably 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. The younger fold phases record the effects of the Acadian- and terminal-stage Appalachian orogeny.

A geological map of Central Park (Merguerian and Merguerian 2004) shows the F_4 folds as a series of warps and open folds with axial traces that strike roughly N30°W and exhibit dominantly steep dips to the SW. The effects on map contacts of these late features is negligible but the scatter of poles to S_3 and localized northward plunges of F_3 fold axes and L_3 lineations are the result of post-D_3 deformation. (See Figure 17.) Brittle S_4 cleavages in the bedrock may have helped localize the late stage brittle NW-trending faults that cut the region. Idioblastic muscovite pseudomorphs after D_3 kyanite are common throughout Central Park. Their abundance suggests a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of wet late Devonian granitoids throughout the Manhattan Prong as discussed by Brock and Brock (1999) and Merguerian and Merguerian (2004).

Brittle Faults and Joints

Five generations of brittle faults and joints cut polydeformed bedrock units of the NYC area (Merguerian 2002). The brittle faults include NW-trending gently SW-dipping faults **(Group A)**, younger ENE-trending faults with moderate to steep dips **(Group B)**, subhorizontal faults and fractures **(Group C)**, and a steep dip-slip NNE-trending fault set **(Group D)** with thick clay- and zeolite-rich gouge zones. These are cut by NW- to NNW-trending strike-slip faults of the "Manhattanville" fault set **(Group E)**. Reactivation of older faults is quite common. The two youngest brittle fault sets (Groups D and E) cross cut all metamorphic structures in NYC and cut the late Paleozoic (295 Ma) glassy rhyodacite dikes.

The NYC Water Tunnel #3 cuts through the 125th Street "Manhattanville" fault beneath Amsterdam Avenue in Manhattan. Here, in an abrupt zone of highly fractured Manhattan Schist 40 m wide, the Manhattanville fault dips 55˚ to 75˚ SW and cuts orthogonally across the tunnel line and the steeply dipping foliation in the schist. In the crown of the tunnel, 2 to 3 m blocks of the Manhattan, which remained internally coherent within the broad zone of cataclastic rock, showed a minimum of 90˚ rotation about a vertical axis. Clearly, this observation indicates that along the Manhattanville fault, much of the motion has been strike-slip. Indeed, slickensides indicate that right-lateral, normal, oblique slip was the most recent offset sense. Cross-fault offset of the prominent Manhattan ridge indicates over 200 m of composite right-lateral slip.

Joint Orientations. Protracted brittle faulting in the NYC area has developed three mutually intersecting fracture orientations (NW, NNW, and NNE) that together produce a pattern of crustal weakness. Five joint sets, which are parallel to the brittle faults, are found in the NYC area. These include:

1) NW-trending, NE-dipping joints and their conjugates. The NW-trending joints are A-C joints related to southward-plunging F_3 folds.

2) NNE-trending joints with steep dips related to Group D faults. Also includes foliation parting joints and conjugate joint surfaces. Typically with a NE trend these are found more commonly in areas of regional F_3 fold limbs where parallelism of axial surfaces of folds, compositional layering, and foliation occur.

3) Gentle SW-dipping foliation joints developed parallel to SW-dipping foliation and original compositional layering at F_3 fold hinges.

4) Subhorizontal unloading joints and joints related to subhorizontal shear zones, and,

5) Steep ENE joints related to the oldest brittle fault set.

Enough about the geological background for the field trip. Below are the sordid details of our main objective for today's (07 September 2014) morning trip – Isham and Inwood Parks in NYC.

Isham and Inwood Hill Parks, Inwood Section of Manhattan

UTM Coordinates: 590.97E / 4524.72N, Central Park quadrangle and 590.66E / 4525.40N, Yonkers quadrangle, respectively.

Today's field trip will concentrate where bedrock is exposed on the northernmost tip of Manhattan Island in Isham and Inwood Hill parks (Figure 18). The complex bedrock geology of New York City can best be explained in a layer cake fashion. (See Figure 9.)

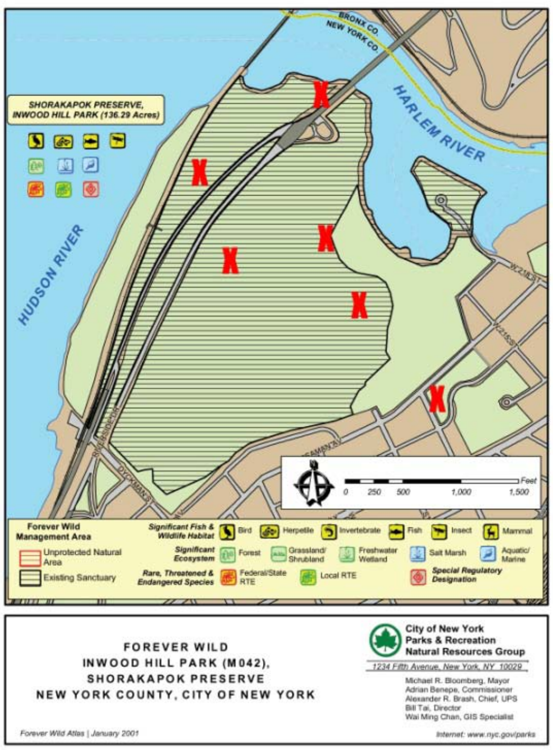

Figure 18 - Index map of Isham and Inwood Hill Parks showing the location of our field stops.

Northern Manhattan boasts the highest natural point of elevation at 265.5' achieved atop ridges of Manhattan Schist in Bennett Park. These rocky ridges rise with abrupt relief above the flat lowland plain to the east underlain by Inwood Marble with the adjacent prominent ridges underlain by the venerable Manhattan Schist. Our analysis of the area departs a bit from published work in that we recognize schistose rocks in northern Manhattan aside from the Manhattan Schist. Indeed, in Inwood Hill Park representatives of all three ductile fault bounded schistose units can be found (Walloomsac, Manhattan and Hartland formations).

A cut-away cross-sectional view of northern Manhattan has been drawn on a Google basemap below in Figure 19. Note the interpretation of the structure based on field work over the years suggesting that the rocky ridges of northern Manhattan are overturned synforms of Manhattan Schist rooted by a major shear zone known as the St. Nicholas thrust (Merguerian 1983) that cuts both the Inwood Marble and locally, the Walloomsac Schist. Below the flat plains of northeastern Manhattan, the Inwood is folded upward to the earth's surface along the eroded cores of two F_3 antiforms and an intervening F_3 synform overturned toward the NW.

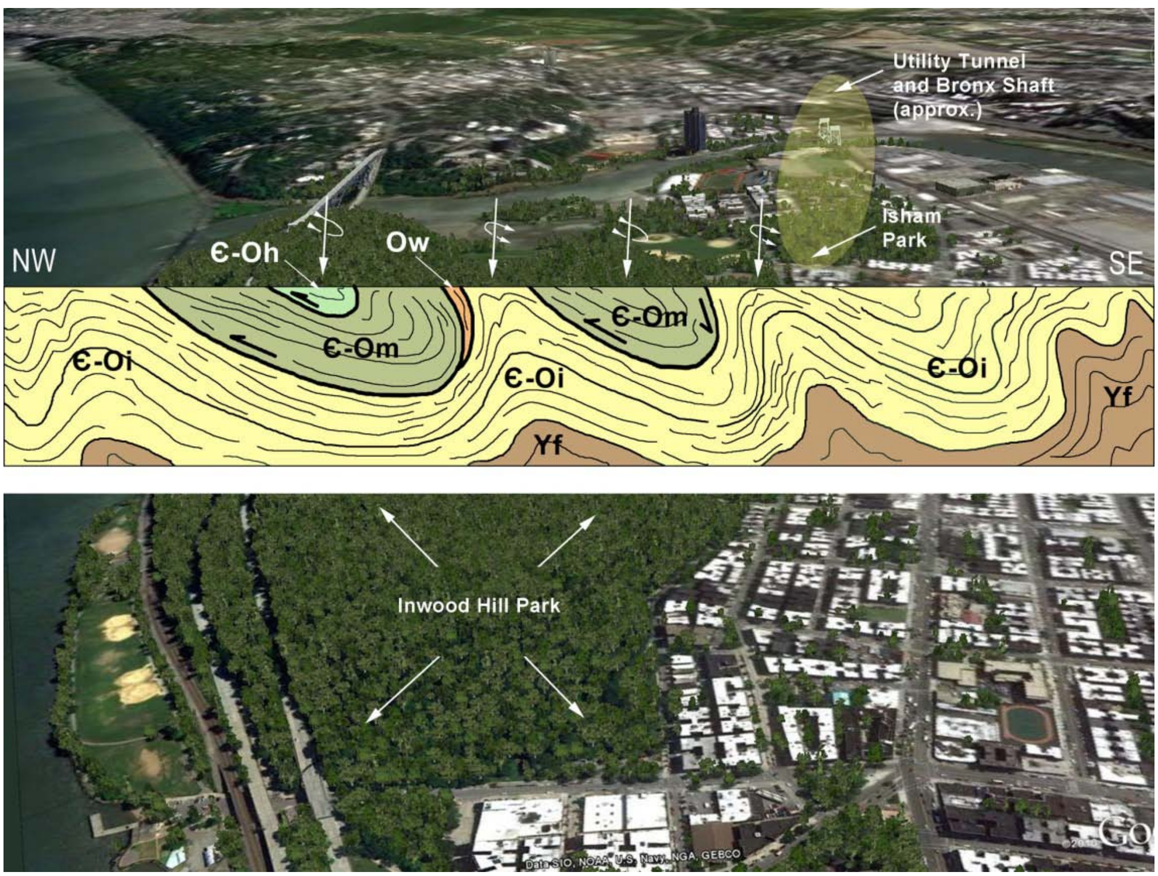

Figure 19 - Oblique northeastward Google Earth terrain view of northern Manhattan and The Bronx with Dyckman Street near the edge of the lower section. Interpretive geological section in cut-away slice roughly across Isham Street in Manhattan. Proposed along-strike correlation between Isham Park and the Bronx Shaft of the a utility tunnel (approximately located for security reasons) shown in yellow shading marks the along strike extension of the SE-dipping limb of an overturned SW-plunging F_3 antiform. Note the positions of major overturned F_3 antiforms and synforms (shown in white), the folding of sheared lithologic contacts, and the position of a thin slice of Waloomsac Schist (Ow) in Inwood Hill Park.

Isham Park

Isham Park contains near continuous exposure of white to blue-white Inwood Marble cut by high-angle conjugate joints which have facilitated the weathering process by allowing aqueous solutions to permeate the rocks (Figure 20). Several lithologies occur such as dolomitic marble, calcite marble, foliated calc-schist, and dolomitic marble containing siliceous layers and calc-silicate aggregates that stand in relief on the weathered surface (Figure 21).

Figure 20 - Northward view of highly jointed east-dipping Inwood Marble exposed in Isham Park in Manhattan. Although well-foliated, the obvious compositional layering preserves ancient bedding in the rock mass. (CM digital image taken 19 August 2007.)

Figure 21 - View of a cluster of aligned 6-12 cm tremolite porphyroblasts found to overgrow the S_1 x S_2 composite foliation in dark gray marble with interlayered calc-schist. We are convinced that these are pseudomorphs after diopside. Exposed portion of knife is 6 cm long. (CM digital image taken 16 November 2008.)

Depending on the amount of impurities the Inwood Marble weathers gray or tan and produces a sugary-textured surface on outcrops that ultimately develops into residual calcareous sand. Overall, the outcrops illustrate profound differential weathering with dolomite-silicate units standing in higher relief and calcite marble forming local depressions. With a bit of imagination, an overview of the outcrop at Isham Park allows a vision of mini-karst-like topography. Perched on this eroded surface are a number of Palisades diabase erratics and red-colored till, products of glacial advance from the NW.

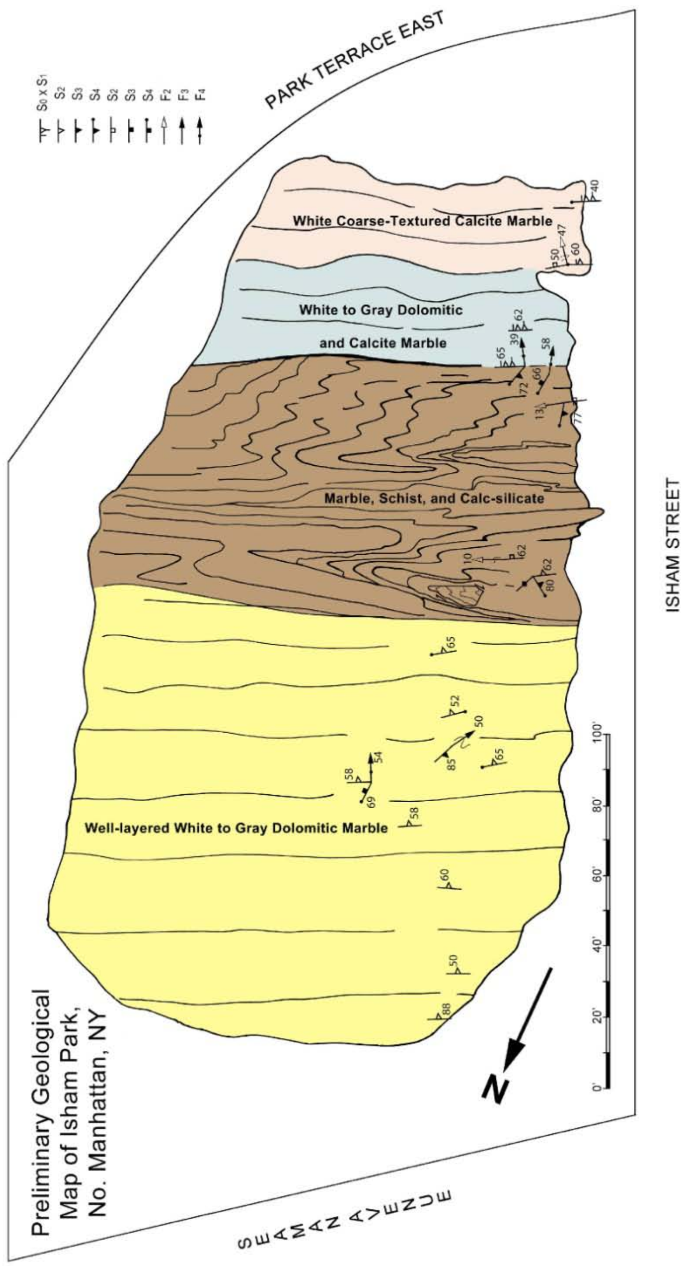

Figure 22 - Preliminary geological map of Isham Park showing the four major lithologic varieties and the form lines of the composite S_1 x S_2 foliation and parallel compositional layering. (From Merguerian, Merguerian, and Cherukupalli, 2011.)

A recently produced preliminary geological map of Isham Park is shown above as Figure 22. Four major lithotypes are shown – white, coarse-textured calcite marble, white to gray dolomitic and calcite marble, marble, schist and calc-silicate rock and well-layered white to gray dolomitic marble. Although variable, the Inwood trends roughly N55°E, 73° SE and forms the eastern overturned limb of a large F_3 synform which is cored to the west by the Manhattan Schist in Inwood Hill Park as described earlier. (See Figure 19.)

The marble, schist, and calc-silicate unit is intensely sheared and internally deformed by F_2 tight- to isoclinal and F_3 asymmetric folds producing complex interference patterns, boudinage and internal shearing of schistose boudins over a meter in dimension (Figure 23). Clearly, the marble + schist + calc-silicate sub-unit shows overthickening and repetition of layers however most of the remaining carbonate sequence in Isham Park is homoclinal. Perhaps the overthickening of the sub-unit is the result of the buttressing effect of the massive, well-layered marble that surrounds it. Asymmetric south-plunging F_3 folds are locally developed in the Inwood of Isham Park (Figure 24). Abundant examples of boudinage of the quartzite and calc-silicate layers into lenses occur presumably the result of ductility contrast between the more competent siliceous rocks and the surrounding marble (Figure 25).

The broad outcrop-scale folding and warping of the S_1 x S_2 fabric is controlled not only by regional F_3 folds but also are affected by open 2m-wavelength SE-plunging F_4 folds (~ 55° plunge) with axial planar slip cleavage (S_4), solution cleavage and joints trending ~ N-S with moderate to steep dips. (See Figure 22.)

Figure 23 - View on internal deformation in the Inwood Marble of Isham Park in Manhattan showing shearing and disarticulation of resistant quartzite and calc-silicate interlayers and meter-scale blocks of marble and the overall complex patterns produced by gently plunging upright F_2 isoclinal folds. (CM digital image 08 Sept 2007.)

Figure 24 - View of a south-plunging asymmetric F_3 z-fold of layering and foliation in the Inwood Marble of Isham Park in northern Manhattan. Pen points in plunge direction. (CM digital image taken 08 Sept 2007.)

Figure 25 - View of disarticulated boudin of quartzite (former chert?) in differentially weathered Inwood Marble exposed in Isham Park in northern Manhattan. Such features result from the mechanical differences between the competent quartzite and the less competent marble which undoubtedly flowed around the resilient quartzite layers and lenses. Note 9-cm long black pocket knife to left of boudin for scale. (CM digital image taken 19 August 2007.)

Con Edison Harlem River Cable Tunnel

For security reasons we will not identify the exact position of the Con Edison Harlem River Tunnel and its two shafts. Suffice to say that the tunnel connects Manhattan and the Bronx near the northeastern tip of Manhattan Island. (See Figure 19.) In 2009 the Merguerians were retained to perform mapping of the Con Edison tunnel and Bronx shaft and the results of these investigations are summarized in Merguerian, Merguerian, and Cherukupalli, 2011. To summarize the results of our mapping and petrographic studies

Metacarbonate Textures

Inwood Marble textures vary from foliated to granoblastic with individual crystals ranging from <0.1mm to ~ 1.0 cm in the coarse-textured calcite marble sub-units. The primary foliation (S_1 x S_2) is a composite fabric found parallel to compositional layering in most of Isham Park and also in the Con Edison tunnel and shafts. It is principally defined by major color changes controlled by compositional variations at the outcrop scale and by aligned phlogopite and graphite flakes and by flattened and lineated brown tourmaline with a hand lens. Late porphyroblasts of calcite, diopside, tremolite, and plagioclase overgrow the S_1 x S_2 foliation and are typically a few cms in size but the tremolite can range up to 12 cm in long dimension as also found at the east end of Isham Park. (See Figure 21). [***Remember - No Hammering or Rock or Mineral Collecting Allowed in NYC parks!***]

Metamorphism

Studies on the metamorphism of NYC rocks indicate that they have equilibrated in the amphibolite facies of regional metamorphism. Our preliminary studies of the Inwood indicate the presence of tremolite + diopside and absence of fosterite which are indicative of amphibolite facies metamorphism in accord with the following reactions from Goodwin-Bell (2008):

Tremolite-in: 5 dolomite + 8 quartz + H_2O = tremolite + 3 calcite + 7 CO_2

Diopside-in: tremolite + 3 calcite + 2 quartz = 5 diopside + 3 CO_2 + H_2

Diopside + Dolomite-in: tremolite + 3 calcite = dolomite + 4 diopside + H_2O + CO_2

Fosterite-in: diopside + 3 dolomite = 2 fosterite + 4 calcite + 5 CO_2

Thus, Inwood metacarbonate rocks at Isham Park and the Con Edison site contain minerals that are consistent with metamorphic facies estimates from the kyanite-staurolite-garnet-bearing pelitic rocks surrounding the marble of NYC. Late tremolite pseudomorphic after diopside (See Figure 21.) suggests that post-tectonic retrograde metamorphism has affected the rock mass in the replacement of diopside. As this is a work in progress, we continue our efforts in mapping, petrography, and x-ray microprobe studies to better refine this preliminary study.

Inwood Hill Park

The area of Manhattan north of Dyckman Street is known as the Inwood section. Except for Inwood Hill Park most of the region is underlain by the Inwood Marble marking the type-locality for that particular unit of NYC bedrock. This unit was originally called the Inwood Limestone by Merrill (1890). The geology of Inwood Hill Park is published elsewhere (Merguerian and Sanders 1991; Merguerian, Merguerian, and Cherukupalli 2011) but a brief summary is in order. Inwood Hill Park is located in the extreme northwest of Manhattan Island (Figure 26). The park is bordered by Dyckman Street on the south, the Hudson River on the west, Spuyten Duyvil (Harlem Ship Canal) on the north, and Payson and Seaman Avenues on the east. Isham Park occupies the flat area northeast of Inwood Hill Park extending eastward to Broadway between Isham and West 214th Streets.

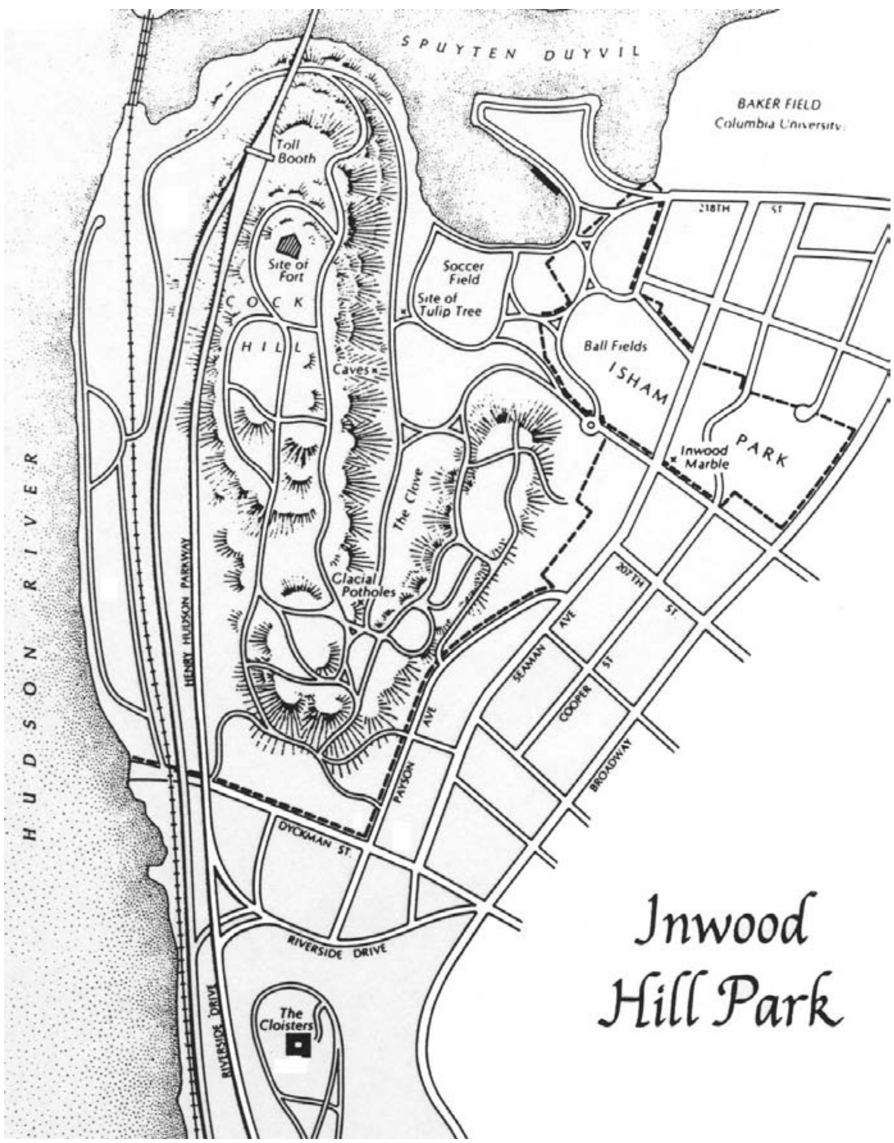

Figure 26 - Index map showing the location of our field trip area in Isham and Inwood Hill parks in northern Manhattan.

We enter Inwood Park by following the path past the playground. The first prominent ridge to your left is composed of kyanite-garnet-bearing Manhattan Schist (Ꞓ-Om) which dips steeply toward the SE, essentially parallel to the foliation of the Inwood Marble exposed in Isham Park. We will examine the politic rocks of this first ridge in a few places.

The Inwood and Manhattan form part of a south-plunging syncline with the Manhattan Schist preserved in the central core of the structure (Figure 27). Here, the downfolds (synforms) hold up ridges and the upfolds (antiforms) underlie the flat valleys in northern Manhattan. Such inverted topography results from the marked contrast in weathering susceptibility afforded by the marble and schist. In the overall wet temperate climates such as we experience in this region, carbonate rocks (such as the Inwood Marble) weather and dissolve much more readily than do silica-rich rocks of the Manhattan Schist. As a result, structural synclines tend to be preserved to form topographically high ridges and structural anticlines are breached by weathering and erosion and commonly underlie the low valleys. (See Figure 27.) Such topographic inversions are well known in the folded central and northern Appalachians.

Follow the path to where it curves around to the west side of the ridge and enters a valley underlain by a south-plunging F_3 antiform which exposes tan weathering, gray-white Inwood Marble striking N40°E, and dipping 58°NW.

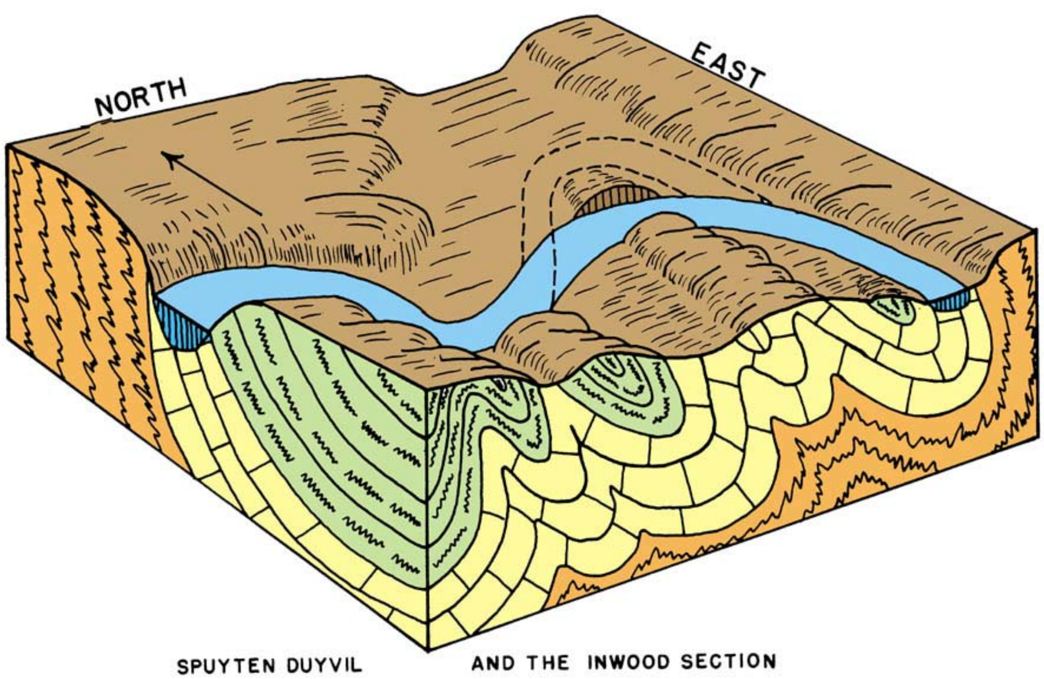

Figure 27 - Block diagram illustrating the structural geology of Inwood and Isham parks. Note that the topographically higher portions of Inwood Park are underlain by the Manhattan Schist (green) and that the topographically lower portions are underlain by the Inwood Marble (yellow). This is the result of the difference in weathering susceptibility of the Inwood and Manhattan. In overall humid, wet climates such as we experience in this region, carbonate rocks (such as the Inwood) weather much more readily than do silica-rich rocks of the Manhattan Schist. Note how the topographically higher ridges are structural synclines (downfolds) yet the valleys are underlain by structural upfolds (anticlines). Such relationships are common in the folded Appalachians and are termed “inverted topography”.

Next, take the “high-road” path going southward to examine the dual potholes drilled into the east-facing slope of the westernmost synclinal ridge. The structure of the westernmost ridge is another south-plunging syncline overturned toward the northwest. (See Figure 27.) The foliation in the schist is related to folds with axial surfaces oriented N41°E, 75°SE with south-plunging hingelines. Visible in many exposures south of the Henry Hudson bridge approach ramp, at the north end of the ridge the foliation changes trend from NE to NW and wraps around the synclinal trough.

At the top of the trail, two circular potholes were produced by torrents of meltwater during the Pleistocene deglaciation (Figure 28). Clearly the potholes are cut into an already glacially polished rock outcrop. Here, we assume that resistant glacial drift boulders settled into a small depression (perhaps in ridge hugging drift) and then began to drill downward in response to vortices produced during turbulent flow associated with glacial meltback. A self-fulfilling prophesy, once the drilling begins the resistant boulders are constantly replenished by boulders moved by water. In this case the upper pothole skipped over to drill a second, adjacent pothole. Since the potholes are developed on a sloping glaciated surface (pre-Woodfordian?), it may be possible to envision that the potholes formed during a younger glaciation (Woodfordian?).

Figure 28 - View of dual potholes “drilled” by resitant boulders driven by glacial meltwater torrents. (CM digital image 13 Nov 2004.)

Farther up at the top of the trail past the potholes but before the trail bends into a hairpin turn to the right, note the highly polished outcrop of Manhattan Schist (Figure 29). The glacial striae and grooves are oriented N35°W to S35°E indicating the same glaciation that brought Palisades boulders from New Jersey. As suggested by Merguerian and Sanders (1996), this glaciation (from the NW to SE) was responsible for most of the deep glacial erosion in the NYC area and produced the prominent Harbor Hill moraine that extends across Staten Island, Brooklyn, Queens, and Long Island (Figure 30). Based on superposition and stratigraphic relationships discovered elsewhere (Sanders and Merguerian, 1991, 1994a,b, 1995, 1998), the glacier that flowed from NW to SE across the NYC area is of pre-Woodfordian age, that is, one notch older than the youngest glacial event which was characterized by flow from NNE to SSW.

Figure 29 - View from the NNW of a glacially polished outcrop of Manhattan Schist in Inwood Hill Park showing a smooth up-glacier side (foreground) and steep, rough down-glacier side (behind White Fang). The glacial striae and grooves are oriented N35°W to S35°E, a product of the pre-Woodfordian glaciation. (CM digital image, Nov. 2007.)

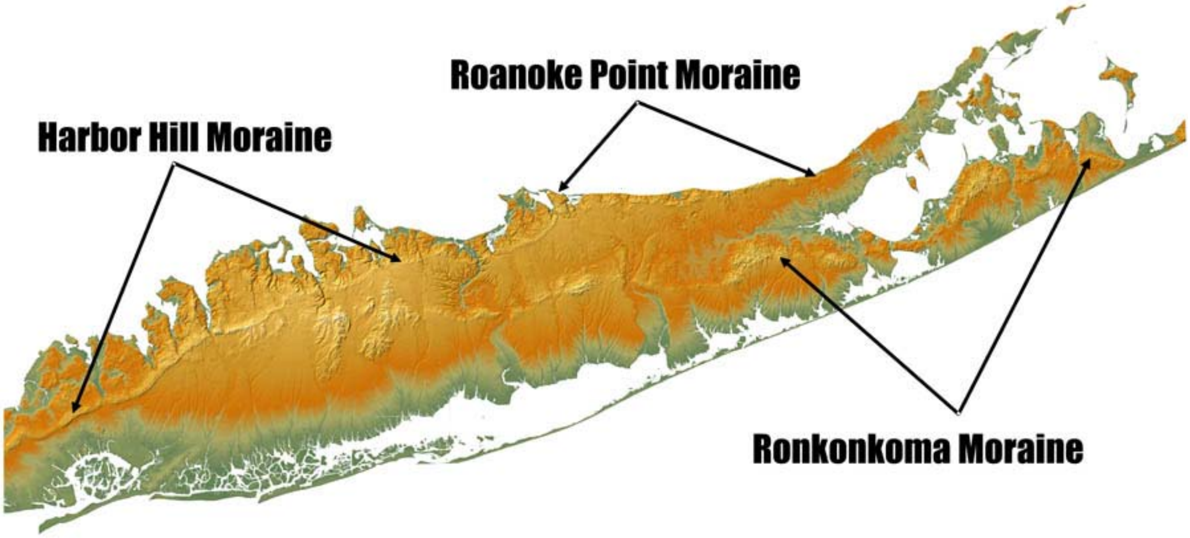

Figure 30 - Digital elevation model diagram of Long Island showing the prominent moraine ridges. (Adapted from DEM model created by J Bret Bennington and Gil Hanson.)

Scenic Overlook of Hudson River and Palisades Intrusive Sheet

Continue up the trail on top of the westernmost ridge and jog left after awhile to get to the fine overlook across the Hudson to the Palisades ridge of New Jersey (Figure 31). Here, the columnar joints of the Palisades ridge are quite visible forming a steep wall of mafic rock that was intruded at shallow depth during the late Triassic-Early Jurassic split up of Pangea. Thus, we view across the Hudson, the products of a totally different type of tectonic activity than we have been viewing today. The metamorphic rocks of New York City were produced during deep-seated compressive deformation while the sedimentary and igneous rocks of New Jersey were produced by extensional tectonics associated with initial formation of the Altantic Ocean basin. Is it little surprise that the chemistry of the Palisades intrusive sheet and the associated Watchung basalts of the central Newark Basin are similar to oceanic crust basalts? Indeed, a cross sectional view from Manhattan to central New Jersey (Figures 32 and 33) shows that the entire Newark Basin is a rotated block of the earth's crust with downward motion and westward tilting accommodated along the Ramapo fault. In this way the ancient Newark Basin is analogous to the modern rift basins of East Africa. The red-colored sandstones and shales of the Newark Basin and lakebed strata of the underlying Lockatong formation are lithically identical to modern sediments forming in the East African rift basins. In order to explain this similarity, geologists argue that the climate during the late Triassic and early Jurassic periods of eastern North America were analogous to those in East Africa today. What goes around - comes around!

Figure 31 - View from the overlook atop the westernmost ridge of Inwood Hill Park across the Hudson River towards New Jersey. Note the glacially polished exposure of schist and the NW-SE trending grooves and striae pointing to the Palisades sheet of New Jersey. (CM digital image taken November 2007.)

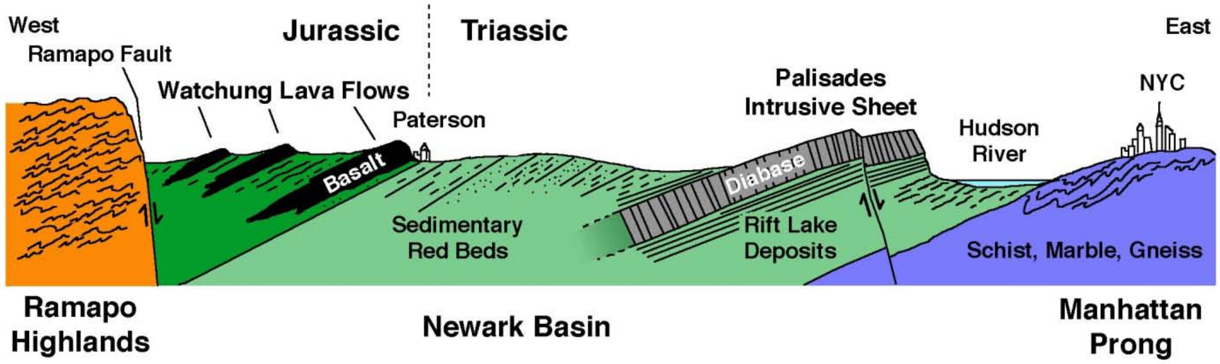

Figure 32 - Cross section showing the geology of the Newark Basin and its relationship to the basin marginal Ramapo fault. Note also the disconformable contact with the complexly deformed rocks of New York City. The nonconformity spans roughly 300 million years of missing time and projects with regional tilt of about 12° above Manhattan. (From Bennington and Merguerian, 2007.)

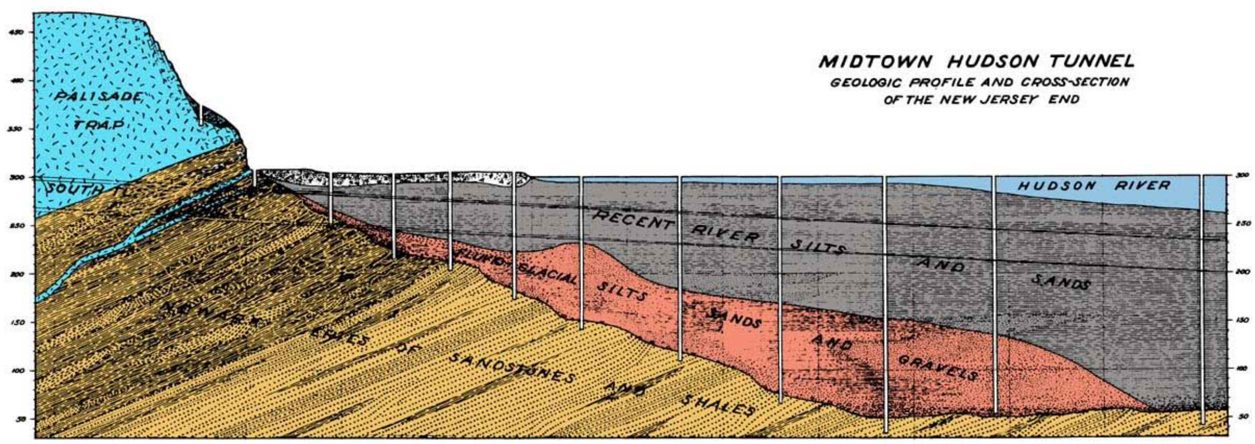

Figure 33 - Geological cross section based on borings showing the geology of the western half of the Hudson River valley in the vicinity of the Midtown Hudson Tunnel (Lincoln Tunnel). Note the U-shape of the rock floor – the product of Pleistocene glaciation and the thickness of west-dipping Mesozoic strata. Overlying Holocene silt and sand overly the Mesozoic strata and cover thenonconformity that intersects the earth's surface at the eastern side of the Hudson channel. (From Berkey 1948.)

From the scenic overlook walk northward toward the Henry Hudson bridge and note that the foliation in the Manhattan Schist is oriented northwesterly at the end of the trail before it heads downward toward the bridge. The S_3 foliation in the schist is related to F_3 folds with axial surfaces oriented N4l°E, 75°SE and south-plunging hingelines. The F_3 structures are superimposed on an older gently inclined S_2 metamorphic layering which trends across Manhattan at roughly N50°W, 25°SW (Merguerian, 1983, 1996).As explained earlier, this is the result of the wrapping of the early foliation in the schists about the southward-plunging keel of the overturned syncline that holds up the westernmost ridge. Overall, the structure of the western ridge is yet another south-plunging F_3 synform overturned toward the northwest.

The contact between the middle and lower schist units (the St. Nicholas thrust of Figure 18) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. Structurally beneath the Manhattan Schist unit, a 0.5 m layer of sheared (mylonitic) disarticulated amphibolite is deformed by folds. Unlike the amphibolite in the schist unit above, which contains subidioblastic hornblende, this exposure of Manhattan amphibolite has been retrograded by intense shearing. Green hornblende porphyroclasts are set in a wavy, anastomosing foliation consisting of colorless amphibole, biotite, and quartz ribbons. The thrust zone is structurally complex consisting of intercalated lithologies of the Wallomsac and Manhattan schists together with mylonitic amphibolite.

Directly beneath the bridge, where a dirt trail leads down to the river, a coarse-grained gray-white calcite marble with differentially eroded calc-silicate nodules is exposed at low tide. It is unknown whether the marble exposed at the low-tide mark is an interlayer in the Walloomsac schist (Ow in Figure 9) or a part of the Inwood Marble. Unquestionably, the Inwood Marble lurks nearby as it wraps around the westernmost ridge of Manhattan Schist and underlies the Spuyten Duyvil, Marble Hill in the Bronx, and the Hudson River. As a geometric result of the southward plunge of the major folds, the oldest unit of the NYC bedrock (Fordham Gneiss) projects up to the surface in the Bronx in a huge vertical exposure immediately across the Harlem Ship Canal. Here, in the Bronx, the Fordham is painted blue with the Columbia University "C" (or should that be pre-Є?).

Table 1 – GEOLOGIC TIME CHART

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

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

PALEOZOIC 245

(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line and St. Nicholas Thrusr Zone). Arc-continent collision. Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata.
(Ordovician)		Ultramafic rocks (oceanic lithosphere) sliced off and transported structurally above deposits of continental shelf. Shallow-water clastics and carbonates accumulate in west of basin. (= **Sauk Sequence**; protoliths of the Lowerre Quartzite, Inwood
(Cambrian)		Marble, Walloomsac Schist). Transitional slope/rise sequence (Manhattan Schist) and deep-water terrigenous strata (Hartland Formation) form to east. (= **Taconic Sequence**).

PROTEROZOIC

	570	Period of uplift, rifting,and erosion followed by subsidence of margin and development of **Iapetan Passive-Margin Stage I**.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).

ARCHEOZOIC

	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 2 – 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.

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

Xenoliths and screens of both Stockton Arkose and Lockatong Argillite are present near the base of the Palisades sheet. 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, 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**; extreme thermal activity and folding, including metamorphism on a regional scale, ductile deformation, and intrusion of calc-alkaline plutons dated at ~360 Ma].

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

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

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

[**Taconic orogeny:** ~460 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. Mafic and ultramafic plutoins intrude across Taconian suture from NJ, NY, to CT ~450 Ma (Ratcliffe at al., 2012). In Newfoundland, a full ophiolite sequence, 10 km thick, has been thrust over shelf-type sedimentary strata]. In Rye, NY, NYC and throughout New England dismembered ophiolite is common (Merguerian 1979; Merguerian and Moss 2005, 2007).

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

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

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

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

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

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

LAYER IIA [W] - SAUK SEQUENCE

Western shallow-water platform
(L. Cambrian - M. Ordovician)

Copake Limestone (Stockbridge,
Rochdale Limestone (Inwood Marble)
Halcyon Lake Fm.
Briarcliff Dolostone
Pine Plains Fm.
Stissing Dolostone
Poughquag Quartzite
Lowerre Quartzite
Ned Mtn Fm.

LAYER IIA [E] - TACONIC SEQUENCE

Eastern deep-water zone
(L. Cambrian-M. Ordovician)
Taconian slates, graywacke, chert

(Ꞓ-Oh) Hartland Fm.
(Ꞓ-Om) Manhattan Fm.

[**Pre-Iapetus Rifting Event**; extensional tectonics, rift-facies sedimentation, volcanism, and alkalic plutonic igneous activity precedes development of Iapetus ocean basin. Extensional interval yields protoliths of the Ned Mountain Formation (Brock, 1989, 1993), Pound Ridge and Yonkers granitoid gneisses. 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.

Selected References

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

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.Amenta, R. V., and Mose, D. G., 1985, Tectonic implications of Rb-Sr ages of granitic plutons near Cameron's Line in western Connecticut: Northeastern Geology, v. 7, no. 1, p. 11-19.

Amenta, R. V., and Mose, D. G., 1985, Tectonic implications of Rb-Sr ages of granitic plutons near Cameron's Line in western Connecticut: Northeastern Geology, v. 7, no. 1, p. 11-19.

Armstrong, R. L., and Dick, H. J. B., 1974, A model for the development of thin overthrust sheets of crystalline rock: Geology, v. 2, no. 1, p. 35-40.

Baskerville, C. A., 1982a, Adoption of the name Hutchinson River Group and its subdivisions in Bronx and Westchester Counties, southeastern New York: United States Geological Survey Bulletin 1529-H, Stratigraphic Notes, 1980-1982, Contributions to Stratigraphy, p. Hl-HlO.

Baskerville, C. A., 1982b, The foundation geology of New York City: in Legget, R. F., ed., Geology under cities, Reviews in Engineering Geology, Geological Society of America, Boulder, Colorado, v. 5, p. 95-117.

Baskerville, C. A., 1987, Bedrock (sic) and engineering geologic maps of Bronx County and parts of New York and Queens Counties, New York: United States Geological Survey Open-File Report 87-360, scale 1:24,000, 3 sheets.

Baskerville, C. A., 1989, New York City: juxtaposition of Cambrian and Ordovician Miogeoclinal and eugeoclinal rocks: p. 39-48 in C. A. Baskerville, ed., Geology and engineering geology of the New York Metropolitan area, International Geological Congress, 28th, Washington, D. C., Guidebook to Field Trip T361, 59 p.

Baskerville, C. A.; and Mose, D., 1989, The separation of the Hartland formation and the Ravenswood granodiorite from the Fordham gneiss at Cameron's Line in the New York City area: Northeastern Geology, v. 11, p. 22-28.

Berkey, C. P., 1907, Structural (sic) and stratigraphic features of the basal gneisses of the Highlands: New York State Museum Bulletin 107, p. 361-378.

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

Berkey, C. P., 1910, Areal (sic) and structural geology of southern Manhattan Island: New York Academy of Sciences Annals, v. 19, no. 11, part 2, p. 247-282.

Berkey, C. P., 1911, Geology of the New York City (Catskill) aqueduct: New York State Museum Bulletin 146, 283 p.

Berkey, C. P., 1930, The water supply of a great city: Natural History, v. 20, p. 406-421.

Berkey, C. P., 1933, Engineering geology of the City of New York, p. 77-123 in Berkey, C. P., ed., Guidebook 9, New York Excursions, New York City and vicinity: International Geological Congress, 16th, United States, 1933, Guidebook 9, New York excursions: Washington, D. C., United States Government Printing Office, 151 p.

Berkey, C. P., 1933, New York City and vicinity: International Geological Congress, 16th, United States, Guidebook 9, New York excursions: Washington, D. C., U. S. Government rinting Office, 151 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.

Berkey, C. P., and Colony, C. P., 1933, Structural geology between New York and Schunemunk Mountain: in Berkey, C. P., ed., Guidebook 9, New York Excursions, New York City and vicinity: 16th International Geological Congress, United States, 1933, Washington, D. C., United States Government Printing Office, p. 40-41.

Berkey, C. P., and Healy, J. R., 1911, The geology of New York City and its relations (sic) to engineering problems: Municipal Engineers Journal Paper No. 62

Berkey, C. P., and Rice, Marion, 1919, Geology of the West Point quadrangle, New York: New York State Museum, Bulletin 225-226, 179 p.

Berkey, C. P.; and Fluhr, T., 1948, Engineering geology of New York City water supply, p. 121-135 in Creagh, Agnes, ed., Geological Society of America, Annual Meeting, 61st, New York City, Guidebook of Excursions, 135 p.

Berry, W. B. N., 1960, Graptolite faunas of the Marathon region, west Texas: University of Texas Publication 6005, 179 p.

Berry, W. B. N., 1962, Stratigraphy, zonation, and age of Schaghticoke, Deepkill, Normanskill shales, eastern New York: Geological Society of America Bulletin, v. 73, p. 695-718.

Berry, W. B. N., 1963, Ordovician correlations in the Taconic and adjacent region, p. 21-31 in Bird, J. M., ed., Stratigraphy, structure, sedimentation, and paleontology of the southern Taconic region, eastern New York: Geological Society of America, Annual Meeting, 76th, New York City, Guidebook for Field Trip 3, 67 p.

Bird, J. M., and Dewey, J. F., 1975, Selected localities in the Taconics and their implications for plate tectonic (sic) origin of the Taconic region, p. 87-121 in Ratcliffe, N. M., ed., New England Intercollegiate Geology Conference, Annual Meeting, 67th, Guidebook for field trips in western Massachusetts, northern Connecticut and adjacent areas of New York, 334 p.

Blank, H. R., 1934 ms., The geology of Rikers Island and vicinity: New York City Board of Water Supply report, 45 p., with geologic record drawing of City Water tunnel #2 excavation.

Blank, H. R., 1972, Hornblende schists in the Manhattan formation, in the Bronx, New York: Geological Society of America Bulletin, v. 83, p. 1397-1412.

Blank, H. R., 1973, Observations on the Brooklyn injection gneiss and related formations: New York Academy of Sciences, Transactions, series II, v. 35, no. 8, p. 645-660.

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

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

Brock, P. W. G., and Mose, D. G., 1979, Taconic (sic) and younger deformation (sic) and metamorphism in the Croton Falls area, southeastern New York--summary: Geological Society of America Bulletin, v. 90, p. 705-707.

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.

Carey, S. W., 1955, The orocline concept in geotectonics: Royal Society of Tasmania Papers and Proceedings, v. 89, p. 255-288.

Clark, G. S., and Kulp, J. L. 1968, Isotopic age (sic) study of metamorphism and intrusion in western Connecticut and southeastern New York: American Journal of Science, v. 266, p. 865-894.

Clarke, J. M.; and Schuchert, C., 1899, The nomenclature of the New York series of geological formations: Science, new series, v. 10, p. 874-878.

Cook, F. A., and Oliver, J. E., 1981, The Late Precambrian-Early Paleozoic continental edge in the Appalachian orogen: American Journal of Science, v. 281, p. 993-1008.

Cook, F. A.; Albaugh, D. S.; Brown, L. D.; Kaufman, Sidney; Oliver, J. E.; and Hatcher, R. D., Jr., 1979, Thin-skinned tectonics in the crystalline southern Appalachians; COCORP seismic-reflection profiling of the Blue Ridge and Piedmont: Geology, v. 7, no. 12, p. 563-567.

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.

Dewey, J. F., 1969, Evolution of the Appalachian/Caledonian orogen: Nature, v. 22 , -. 124-129.

Dewey, J. F., and Bird, J. M., 1970a, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, no. 14, p. 2625-2647.

Dewey, J. F., and Bird, J. M., 1970b, Plate tectonics and geosynclines: Tectonophysics, v. 10, p. 625-638.

Dewey, J. F., and Bird, J. M., 1971, Origin (sic) and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: Journal of Geophysical Research, v. 76, p. 3179-3206.

Drake, A. A., Jr., and Epstein, J. B., 1967, The Martinsburg Formation (Middle and Upper Ordovician) in the Delaware Valley, Pennsylvania - New Jersey: U. S. Geological Survey Bulletin 1244-H, 16 p.

Drake, A. A., Jr.; and Lyttle, P. T., 1980, Alleghanian thrust faults in the Kittatinny Valley, New Jersey, p. 92-114 in Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York Geological Association, Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, NJ, Rutgers University Newark College of Arts and Sciences Geology Department, 398 p.

Epstein, J. B., and Epstein, A. G., 1969, Geology of the Valley and Ridge Province between Delaware Water Gap and Lehigh Gap, Pennsylvania, p. 132-205 in Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Geological Society of America, Annual Meeting, 82nd, Atlantic City, New Jersey, 1969: New Brunswick, New Jersey, Rutgers University Press, 382 p.

Epstein, J. B., and Epstein, A. G., 1972, The Shawangunk Formation [Upper Ordovician(?) to Middle Silurian] in eastern Pennsylvania: United States Geological Survey, Professional Paper 744, 45 p.

Epstein, J. B., and Lyttle, P. T., 1987, Structure (sic) and stratigraphy above (sic), below (sic) and within the Taconic unconformity, southeastern New York, P. C1-C78 in Waines, R. H., ed., New York State Geological Asociation, Annual Meeting, 59th, New Paltz, New York, Guidebook to field trips, not consecutively paginated.

Fettke, C. R., 1914, The Manhattan Schist of southeastern New York and its associated igneous rocks: New York Academy of Sciences Annals, v. 23, p. 193-260.

Finks, R. M., 1968, Taconian islands and the shores of Appalachia, p. 116-153 in Finks, R. M., ed., New York State Geological Association Annual Meeting, 40th, Flushing, New York, October 1968, Guidebook to Field Trips: Flushing, NY, Queens College Department of Geology, 253 p.

Fisher, D. W., and Warthin, A. S., Jr., 1976, Stratigraphic (sic) and structural geology in western Dutchess County, New York, Trip B-6, p. B-6-1 to B-6-36: in Johnsen, J. H., ed., Guidebook to field excursions: New York State Geological Association, Annual Meeting, 46th, 15-17 October 1976, Poughkeepsie, New York: Vassar College, Department of Geology and Geography, not consecutively paginated.

Fisher, D. W., Isachsen, Y. W., and Rickard, L. V., 1971, Geologic map of New York, 1970: New York State Museum and Science Service, Geological Survey, Map and Chart Series, No. 15.

Fluhr, T. W., 1957, Geology of the Queens Midtown tunnel, New York: Geological Society of America Engineering Geology Case Histories 1, p. 1-10.

Fluhr, T. W., 1969, Recent engineering data on the New York City Group of formations, p. 1-11 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.

Fluhr, T. W., and Terenzio, C. G., 1984, Engineering geology of the New York City water supply system: Albany, New York, New York State Museum and Science Service, Geological Survey Open-File Report 05.08.001, 183 p.

Fluhr, T. W.; King, H.; et al., 1944, The Queens Midtown tunnel under the East river between mid-Manhattan and Queens, New York City: American Society of Civil Engineers Transactions, v. 109, p. 679-762.

Friedman, G. M., Sanders, J. E., and Kopaska-Merkel, D. C., 1992, Principles of sedimentary deposits. Stratigraphy and sedimentology: New York, NY, Macmillan Publishing Company, 717 p.

Fuller, Tyrand; Short, Lesley; and Merguerian, Charles, 1999, Tracing the St. Nicholas thrust and Cameron's Line through The Bronx, NYC, p. 16-23 *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.

Gale, L. D., 1839, Geology of New York Island: In 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.

Gale, L. D., 1839, Report on the geology of New York County, p. 177-199 in New York (State) Geological Survey, Annual Report, 3rd: Albany, New York, 339 p.

Gale, L. D., 1843, Diary of a geological survey of the Island of New York, p. 581-604 in Mather, W. W., The 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.

Gratacap, L. P., 1909, Geology of the City of New York (2nd ed.): Henry Holt Publishing Company, New York, 232 p.

Grauert, B., and Hall, L. M., 1973, Age (sic) and origin of zircons from metamorphic rocks in the Manhattan Prong, White Plains area, southeastern New York: Washington, D.C., Carnegie Institute Yearbook, v. 72, p. 293-297.

Hall, L. M., 1968, 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

Hall, L. M., 1968, 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., 1968, 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, Virginia, Virginia Polytechnic Institute and State University, Department of Geological Sciences, Memoir 2, 329 p.

Hall, L. M.; Helenek, H. C.; Jackson, R. A.; Caldwell, K. G.; Mose, Douglas; and Murray, D. P., 1975, Some basement rocks from Bear Mountain to the Housatonic Highlands, p. 1-29 in Ratacliffe, N. M., ed., New England Intercollegiat Geological Congress 1975

Harwood, D.S., 1975, Fold-thrust tectonism in the southern Berkshire massif, Connecticut and Massachusetts: in Ratcliffe, N.M. ed., Guidebook for fieldtrips in western Massachusetts, northern Connecticut, and adjacent areas of New York, 67th Annual Meeting, New England Intercollegiate Geological Conference, Department of Earth and Planetary Science, City College of New York, New York, p. 122-143.

Hatch, N. L., Jr., and Stanley, R. S., 1973, Some suggested stratigraphic relations (sic) in part of southwestern New England: United States Geological Survey Bulletin 1380, 83 p.

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

Henderson, J. R., and Smith, F. C., 1962, Aeromagnetic map of parts of the Monroe and Maybrook quadrangles, Orange County, New York: United States Geological Survey, Geophysical Investigations Map GP-339.

Hobbs, W. H., 1905, The configuration of the rock floor of greater New York: United States Geological Survey Bulletin 270, 96 p.

Hobbs, W. H., 1905a, Origin of the channels surrounding Manhattan Island, New York: Geological Society of America Bulletin, v. 16, p. 151-182.

Holzwasser, Florrie, 1926, Geology of the Newburgh quadrangle: New York State Museum, Bulletin 270, 95 p. (includes colored geologic map on scale of 1:62,500).

Isachsen, Y. W., 1964, Extent (sic) and configuration of the Precambrian in northeastern United States: New York Academy of Sciences, Transactions, Series II, v. 26, no. 7, p. 812-829.

Isler, D. E., Vellone, D. A., Merguerian, Charles; and Merguerian, J. M., 2009, Redefining the southern terminus of the intrusive contact between the Yonkers and Fordham gneiss in Van Cortlandt Park, New York City, NY: *in* Hanson, G. N., *chm*., Sixteenth Annual Conference on Geology of Long Island and Metropolitan New York, 28 March 2009, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 15 p.

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.

Kemp, J. F., 1907, Buried channels beneath the Hudson and its tributaries: American Journal of Science, 4th series, v. 26, p. 302-323.

Kemp, J. F., 1909, Our knowledge of the filled channel of the Hudson in the Highlands and the submerged gorge on the continental shelf (abs.): Science, new series, v. 29, p. 279.

Kemp, J. F., 1910, Further light on the gorge of the Hudson (abs.): Geological Society of America Bulletin, v. 231, p. 760-761.

Knopf, E. B., 1962, Stratigraphy (sic) and structure of the Stissing Mountain area, Dutchess County, New York: Stanford, California, Stanford University, Publications in Geological Sciences, v. 7, no. 1, 55 p.

Knopf, E.B., 1927, Some results of recent work in the southern Taconic area: American Journal of Science, 5th series, v. 14, p. 429-458.

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.

Langer, A. M.; and Bowes, D., 1969, Polyphase deformation in the Manhattan Formation, Manhattan Island, New York City, p. 361-377 *in* Larsen, L. H.; Prinz, M.; and Manson, V., eds., Igneous (sic) and metamorphic geology: Boulder, CO, Geological Society of America Memoir 115, xxx p.

Leveson, D. J., and Seyfert, C. K., 1969, The role of metasomatism in the formation of layering in amphibolites of Twin Island, Pelham Bay Park, the Bronx, New York, p. 379-399 in Larsen, L. H.; Prinz, M.; and Manson, V., eds., Igneous (sic) and metamorphic geology: Boulder, CO, Geological Society of America Memoir 115, xxx p.

Lobeck, A. K., 1918, The superb position of New York City as a center for physiographic study: New York Academy of Sciences Annals, v. 28, p. 1-50.

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

Long, L. E., 1961, Isotopic ages from northern New Jersey and southeastern New York: Annals of the New York Academy of Sciences, v. 91, p. 400-407.

Long, L. E., 1969a, Isotopic ages from the New York City Group, p. 77 (only) in 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, Queens College Department of Geology Geological Bulletin 3, Queens College Press, 83 p.

Long, L. E., 1969b, Whole-rock Rb-Sr age of the Yonkers gneiss, Manhattan prong: Geological Society of America Bulletin, v. 80, no. 10, p. 2087-2090.

Long, L. E., and Kulp, J. L., 1958, Age of the metamorphism of the rocks of the Manhattan Prong: Geological Society of America Bulletin, v. 69, p. 603-606.

Long, L. E., and Kulp, J. L., 1962, Isotopic age (sic) study of the metamorphic history of the Manhattan and Reading Prongs: Geological Society of America Bulletin, v. 73, no. 8, p. 969-995.

Long, L. E., Cobb, J. C., and Kulp, J. L., 1959, Isotopic ages on some igneous and metamorphic rocks in the vicinity of New York City: Annals of the New York Academy of Sciences, v. 80, p. 1140-1147.

Long, L.E., 1969, Isotopic ages from the New York City Group: in Alexandrov, E.A., ed., Symposium on the New York City Group of Formations, 40th Annual Meeting of the New York State Geological Association, Queens College Press, Flushing, New York, p. 77.

Lovegreen, J. R., 1974 ms., Paleodrainage history of the Hudson Estuary: New York, N. Y., Columbia University, Department of Geological Sciences, Master's Thesis, 151 p., 8 pl.

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

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

Lowe, K. E., 1958, Pre-Cambrian (sic) and Paleozoic geology of the Hudson Highlands, p. 41-52 in K. E. Lowe, ed., New York State Geological Association Annual Meeting, 30th, Peekskill, New York, Field Guide Book, 53 p.

Lowe, K. E., 1959, Structure of the Palisades intrusion (sic) at Haverstraw and West Nyack, New York, p. 1127-1139 in Lowe, K. E., Chm. and Consulting Ed., Modern aspects of the geology of New York City and environs: New York Academy of Sciences Annals, v. 80, art 4, p. 1047-1170.

Lowe, K. E.; and Schaffel, S., 1958, The New York City Series: in K. E. Lowe, ed., New York State Geological Association Annual Meeting, 30th, Peekskill, New York, Field Guide Book, 53 p.

Lucas, M.; Hull, J.; and Manspeizer, Warren, 1988, A foreland-type fold and related structures in the Newark rift basin, Chapter 12, p. 307-332 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margins: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Lyttle, P. T., and Epstein, J. B., 1987, Geologic map of the Newark 1° by 2° quadrangle, New Jersey, Pennsylvania, and New York: United States Geological Survey Miscellaneous Investigations Series Maps, Map I-1715 (2 sheets; scale 1:250,000).

Maclure, William, 1817, Observations on the geology of the United States of America: Philadelphia, 127 p., with map, scale 1:7,603,200 (facsimile reprint in 1966 by Werner Fritsch, Munchen).

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; 1977 ms., Contact metamorphism and intrusive relations of the Hodges Complex along Cameron's Line, West Torrington, Connecticut: New York, NY, The City College of New York, Department of Earth and Planetary Sciences, Master's Thesis, 89 p., with maps (also on open-file Connecticut Geological Survey, Hartford, Connecticut).

Merguerian, Charles; 1979, Dismembered ophiolite along Cameron's Line, West Torrington, Connecticut (abstract): Geological Society of America Abstracts with Programs, v. 11, p. 45 only.

Merguerian, Charles; 1980, Metamorphosed manganiferous sediments (coticules) in the Ordovician of southern New England (abstract): Geological Society of America Abstracts with Programs, v. 12, p. 73 (only).

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

Merguerian, Charles, 1981b, Coticules in New England - Ancient examples of metalliferous sediments (abstract): American Geophysical Union Transactions, v. 62, p. 310 (only).

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

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

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

Merguerian, Charles, 1985, Diachroneity of deep-seated versus supracrustal deformation in both the Appalachian Taconic and Cordilleran Antler orogenic belts (abs.): Geological Society of America Abstracts with Programs, v. 17, p. 661.

Merguerian, Charles, 1985a, Geology in the vicinity of the Hodges Complex and the Tyler Lake granite, West Torrington, Connecticut, p. 411-442 in R.J. Tracy, ed., New England Intercollegiate Geological Conference, 77th, New Haven, Connecticut: Connecticut Geological and Natural History Survey Guidebook No. 6, 590 p.

Merguerian, Charles, 1985b, Diachroneity of deep-seated versus supracrustal deformation in both the Appalachian Taconic and Cordilleran Antler orogenic belts (abstract): Geological Society of America Abstracts with Programs, v. 17, p. 661 (only).

Merguerian, Charles, 1986a, The bedrock geology of New York City (NYC) (abstract), p. 8 (only) in Symposium on the geology of southern New York, Abstracts with Programs, Hofstra University, New York: Hempstead, NY, Hofstra University Department of Geology, xx p.

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

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.

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

Merguerian, Charles, 1995, The Taconic problem--alive and well in New York City (NYC) (abstract): Geological Society of America Abstracts with Programs, v. 27, no. 1, p. 68 (only).

Merguerian, Charles, 2001a, Young rhyodacite dikes found in the Queens Tunnel, beneath Woodside, Queens: p. 9-19 *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.

Merguerian, Charles, 2002a, Rhyodacite dikes of the Queens Tunnel Complex, NYC Water Tunnel #3 (abs.): Geological Society of America Abstracts with Programs, v. 34, no. 1, p. A75.

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, 2003, The Narrows flood – Post-Woodfordian meltwater breach of the Narrows channel, NYC: *in* Hanson, G. N., *chm*., Tenth Annual Conference on Geology of Long Island and Metropolitan New York, 12 April 2003, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 13 p.

Merguerian, Charles, 2004a, Brittle fault chronology of New York City (NYC): Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 73.

Merguerian, Charles, 2005a, Geological controls on effective hard-rock TBM tunneling in crystalline terrains: *in* 84th Annual Meeting, 9-13 January 2005, Compendium of Papers CD-ROM, Transportation Research Board of the National Academies, 11 p.

Merguerian, Charles, 2005b, Lithologic and structural constraints on TBM tunneling in New York City (NYC), p. 704-724 *in* Hutton, John D. and Rogstad, W.D., *eds.*, Rapid Excavation and Tunneling Conference, 2005 Proceedings Society of Mining, Metallurgy, and Exploration, 1371 p.

Merguerian, Charles, 2006a, Dismembered ophiolite in New York City: Geological Society of America Abstracts with Programs, v. 38, no. 2, p. 86.

Merguerian, Charles, 2008b, Evaluating geological controls on hard rock excavation, New York City, NY: *in* Proceedings, Manhattan On the Rocks, American Society of Civil Engineers, Metropolitan Section, 08 May 2008, 31 p.

Merguerian, Charles, 2008c, Geological controls on means and methods of hard rock excavation, New York City, NY: p. 79-109 *in* Gorring, M. L., ed., Environmental and Engineering Geology of Northeastern New Jersey, Geological Society of New Jersey, XXV Annual Conference Proceedings, 17 October 2008, 111 p.

Merguerian, Charles, 2009b, Geology of Central Park: Field guide for American Institute of Professional Geologists, 20 May 2009, 112 p.

Merguerian, Charles, 2010a, Tectonics implications of bedrock studies at the World Trade Center Site (WTC), NYC: Geological Society of America Abstracts with Programs, v. 42, no. 1, p. 171.

Merguerian, Charles, and Bennington, J Bret, 2010, Physical Geology Laboratory Manual: Hofstra University Geology Department, Eleventh Edition, 99 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; 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, 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 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 Ozdemir, Levent, 2003, Rock Mass Properties and Hard Rock TBM Penetration Rate Investigations, Queens Tunnel Complex, NYC Water Tunnel #3, Stage 2: p. 1019-1036 *in* Robinson, R.A. and Marquardt, J.M., *eds.*, Rapid Excavation and Tunneling Conference, 2003 Proceedings Society of Mining, Metallurgy, and Exploration, 1334 p.

Merguerian, Charles; and Sanders, J. E., 1988, Trip 03: Geology of Manhattan and the Bronx, 20 November 1988: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 29 p.

Merguerian, Charles; and Sanders, J. E., 1989, Trip 08: Geology of the Taconic range of eastern New York, 21-22 October 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 98 p.

Merguerian, Charles; and Sanders, J. E., 1989b, Trip 09: Geology of the Shawangunks and Bellvale Mountain: 11 November 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 56 p.

Merguerian, Charles; and Sanders, J. E., 1990, Trip 11: Geology of the Little Appalachians and the Catskills, 26-27 May 1990: New York Academy of Sciences Section of Geological Sciences 1989-90 Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1990, Trip 12: Geology of Franklin Furnace, New Jersey, 17 June 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 83 p.

Merguerian, Charles; and Sanders, J. E., 1990, Trip 15: Glacial geology of Long Island, 17-18 November 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 96 p.

Merguerian, Charles; and Sanders, J. E., 1990a, Trip 10: Croton Point and Peekskill Hollow, 12 May 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 74 p.

Merguerian, Charles; and Sanders, J. E., 1990b, Trip 11: Geology of the Little Appalachians and the Catskills, 26-27 May 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1990c, Trip 12: Geology of Franklin Furnace, New Jersey, 17 June 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 83 p.

Merguerian, Charles; and Sanders, J. E., 1991, Variations in style of Paleozoic fold-fault deformation in the southern New England Appalachian foreland of New York and New Jersey - A case for basement control of structures (abstract): Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 103 (only).

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., 1991c, Trip 17: Geology of Stokes State Forest, New Jersey, 19 May 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 88 p.

Merguerian, Charles; and Sanders, J. E., 1992, Trip 22, Taconic Range of eastern New York and Massachusetts (revision of Trip 08, 21-22 October 1989), 09-10 May 1992: New York Academy of Sciences Section of Geological Sciences 1991-92 Trips on the Rocks Guidebook, 107 p.

Merguerian, Charles; and Sanders, J. E., 1992, Xenoliths as indicators of paleoflow and paleoenvironmental conditions in the Palisades sheet, New York and New Jersey (abs.): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 62-63.

Merguerian, Charles; and Sanders, J. E., 1992b, Trip 23, Geology of the Delaware Water Gap and vicinity, 20 June 1992: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 109 p.

Merguerian, Charles; and Sanders, J. E., 1992c, Trip 25, Geology of Croton Point and Peekskill Hollow, 21 November 1992, (revision of Trip 10, May 1990): New York Academy of Sciences Section of Geological Sciences 1992 Trips on the Rocks Guidebook, 107 p.

Merguerian, Charles; and Sanders, J. E., 1993, Trip 29, Geology of the northeastern Newark basin, 14 November 1993: New York Academy of Sciences Section of Geological Sciences 1993 Trips on the Rocks Guidebook, 93 p.

Merguerian, Charles; and Sanders, J. E., 1993a, Trip 29, Geology of the northeastern Newark basin, 14 November 1993: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 93 p.

Merguerian, Charles; and Sanders, J. E., 1993b, Trip 27, Geology of the Newark basin in the Delaware Valley, 19 June 1993: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1994, Trip 30: Geology of the Hudson Highlands and Bear Mountain: Guidebook for On-The-Rocks 1994 Fieldtrip Series, 21 May 1994, Section of Geological Sciences, New York Academy of Sciences, 112 p.

Merguerian, Charles; and Sanders, J. E., 1994a, Danbury anticline of Sanders (1960) revisited: Postdepositional structural explanation for northeast end of Newark Basin, Rockland County, NY (abstract): Geological Society of America Abstracts with Programs, v. 26, no. 3, p. 62 (only).

Merguerian, Charles; and Sanders, J. E., 1994b, Post-Newark folds and -faults: implications for the geologic history of the Newark Basin (extended abstract), p. 57-64 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994: Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Merguerian, Charles; and Sanders, J. E., 1994c, Trip 32: Geology of the Little Appalachians and the Catskills, 24-25 September 1994; revision of Trip 11, 26-27 May 1990): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 103 p.

Merguerian, Charles; and Sanders, J. E., 1995, Trip 34: Palisades and the Newark basin, 26 October 1991 (revision of Trip 20, 26 October 1991): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 120 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.

Merguerian, Charles; Brock, Pamela Chase; and Brock, Patrick W. G., 2001, The Queens Tunnel Complex – a granulite facies orthogneiss terrane exposed in NYC Water Tunnel #3 (abs.): Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A46.

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; Mose, D.; and Nagel, S., 1984, Late syn-orogenic Taconian plutonism along Cameron's Line, West Torrington, Connecticut (abstract): Geological Society of America Abstracts with Programs, v. 16, p. 50 (only).

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., 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., 1981, Avalonian igneous rocks with high initial 87Sr/86Sr ratios: Northeastern Geology, v. 3, p. 129-133.

Mose, D. G., 1982, 1,300-million-year-old rocks in the Appalachians: Geological Society of America Bulletin, v. 93, p. 391-399.

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.

Mose, D. G.; and Nagel, S., 1982, Chronology of metamorphism in western Connecticut: Rb-Sr ages, p. 247-262 in Joesten, R., and Quarrier, S. S., eds., New England Intercollegiate Geological Conference Annual Meeting, 74th, Guidebook for field trips in Connecticut and south central (sic) Massachusetts, 482 p.

Mose, D.G., 1981, Avalonian igneous rocks with high initial 87Sr/86Sr ratios: Northeastern Geology, v. 3, p. 129-133.

Mose, D.G., and Hayes, J., 1975, Avalonian igneous activity in the Manhattan Prong, southeastern New York: Geological Society of America Bulletin, v. 86, p. 929-932.

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

Murphy, J. J., 1940, Rock data map of Manhattan: New York City, Manhattan Borough President's Office (scale 1:7,200).

Nehru, C. E., and Merguerian, Charles, 2006, Orchard Beach ultramafic erratics – Where are they from?: *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, 4 p.

Norton, M. F., 1959, Stratigraphic position of the Lowerre Quartzite: p. 1148-1158 in Lowe, K. E., chm. and consulting ed., Modern aspects of the Geology of New York City and environs: New York Academy of Sciences, Annals, v. 80, art. 4, p. 1047-1169.

Norton, M. F.; and Giese, R., 1957, Lowerre Quartzite problem: Geological Society of America Bulletin, v. 68, p. 1577-1580.

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

Pepper, J. F., 1934, The Taconic and Appalachian orogenies in the Hudson River region: Science, new series, v. 80, p. 186.

Pierce, James, 1820, Account of the geology (sic), mineralogy (sic), scenery of the secondary region of New-York and New-Jersey, and adjacent regions: American Journal of Science, v. 2, p. 181-199.

Prucha, J. J., 1956, Stratigraphic relationships of the metamorphic rocks in southeastern New York: American Journal of Science, v. 254, p. 672-684.

Prucha, J. J., 1959, Field relationships bearing on the age of the New York City Group of the Manhattan Prong, p. 1159-1169 in Lowe, K. E., chm. and consulting ed., Modern aspects of the Geology of New York City and environs: New York Academy of Sciences, Annals, v. 80, art. 4, p. 1047-1169.

Prucha, J. J., Scotford, D. M., and Sneider, R. M., 1968, Bedrock geology of parts of Putnam and Westchester counties, New York, and Fairfield County, Connecticut: New York State Museum and Science Service Map and Chart Series, No. 11, 26 p.

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

Ratcliffe, N. M., 1970, Ancient strike-slip fault tectonics in the Hudson Highlands and Manhattan Prong: New York Academy of Sciences Transactions, series II, v. 32, p. 1009-1021.

Ratcliffe, N. M., 1980, Brittle faults (Ramapo fault) and phyllonitic ductile shear zones in the basement rocks of the Ramapo seismic zones New York and New Jersey, and their relationship to current seismicity, in Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association, 52nd Annual Meeting, Rutgers University, Newark College of Arts and Sciences, Geology Department, Newark, New Jersey, p. 278-311.

Ratcliffe, N. M., and Knowles, R. R., 1969, Stratigraphic relations (sic) along the western edge of the Cortlandt intrusives and their bearing on the Inwood-Manhattan problem, p. 49-54 in E. A. Alexandrov, ed., Symposium on the New York City Group of Formations: New York State Geological Association Annual Meeting, 40th, Flushing, New York: Flushing, NY, Queens College Department of Geology Geological Bulletin 3, Queens College Press, 83 p.

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

Ratcliffe, N. M., Bender, J. F., and Tracy, R. J., 1983, Tectonic setting, chemical petrology and petrogenesis of the Cortlandt Complex and related igneous rocks of southeastern New York State: Guidebook for Field Trip 1, Geological Society of America Meeting, March 23-26, 1983, Concord Hotel, Kiamesha Lake, New York, 101 p.

Ratcliffe, N.M., Tucker, R.D., Aleinikoff, J.N., Amelin, Yuri; Merguerian, Charles; and Panish, P.T., 2012, U-Pb zircon and titanite ages of late- to post-tectonic intrusions of the Cortlandt-Beemerville magmatic belt, CT, NY, and NJ: relation to Iapetan closure in the Taconic orogeny: Geological Society of America Abstract # 200033, Abstracts with Programs, v. 44, no. 2, p. 73.

Reeds, C. A., 1925, The geology of New York City and vicinity: American Museum of Natural History Guide Leaflet 56, 21 p.

Reeds, C. A., 1926, New York City as a field for earthquake study: Science, v. 63, p. 415-418.

Reeds, C. A., 1930, Geology of New York City and vicinity (3rd ed.): New York, New York, The American Museum of Natural History, Guide Leaflet No. 56, 36 p.

Robinson, P.; and Hall, L. M., 1980, Tectonic synthesis of southern New England, p. 73-82 in Wones, D. R., ed., International Geological Correlation Project, Proceedings, Project 27: The Caledonides in the U. S. A.: Blacksburg, Virginia, Virginia Polytechnic Institute and State University Department of Geological Sciences Memoir 2, 329 p.

Rodgers, John, 1970, The tectonics of the Appalachians: New York, NY, Wiley-Interscience, 271 p.

Rodgers, John, 1989, The Taconic controversies, p. 32-39 in International Geological Congress, 28th, Washington, D. C., Guidebook to Field Trip T169, xx p.

Rodgers, John; Gates, R. M.; and Rosenfeld, J. L., 1959, Explanatory text for the preliminary geological map of Connecticut, 1956: Connecticut Geological and Natural History Survey Bulletin 84, 64 p.

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.

Ruedemann, Rudolf, 1901, Trenton conglomerate of Rysedorph Hill, Rensselaer County, New York, and its fauna: New York State Museum Bulletin 49, 114 p.

Ruedemann, Rudolf, 190l, Hudson River beds near Albany and their taxonomic equivalents: New York State Museum, Bulletin 42, 109 p.

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.

Salisbury, R. D., and Peet, C. E., 1894, Section V. Drift phenomena of the Palisade ridge, p. 157-224 in Geological Survey of New Jersey, Annual Report of the State Geologist for the year 1893: Trenton, New Jersey, The John L. Murphy Publishing Company Printers, 457 p.

Sanders, J. E., 1969, Bedding thrusts and other structural features in cross section through "Little Mountains" along Catskill Creek (Austin Glen and Leeds Gorge), west of Catskill, New York, Trip 19 p. 19-1 to 19-38 in Bird, J. M., ed., New England Intercollegiate Geological Conference, Annual Meeting, 61st, Albany, New York, 10-12 October 1969, Guidebook for field trips in New York, Massachusetts, and Vermont: Albany, State University of New York at Albany, not consecutively paginated.

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

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

Sanders, J. E., 1983, Reinterpretation of the subsurface structure of the Middletown gas well (Crom-Wells, Inc. 1 Fee) in light of concept of large-scale bedding thrusts: Northeastern Geology, v. 5, no. 3/4, p. 172-180.

Sanders, J. E., 1995, Lower Paleozoic carbonate-clast diamictites: Relationship to thrust sheets that advanced across the floor of the Northern Appalachian Ordovician foreland basin: Northeastern Geology and Environmental Sciences, v. 17, no. 1, p. 23-45.

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, 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, 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, 1992, Directional history of Pleistocene glaciers inferred from features eroded on bedrock, New York metropolitan area, SE NY (abs.): Geological Society of America Abstracts with Programs, v. 24, no. 1, p. 72.

Sanders, J. E.; and Merguerian, Charles, 1994a, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island (extended abstract), p. 103-113 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Sanders, J. E.; and Merguerian, Charles, 1994b, Glacial geology of the New York City region, p. 93-200 in Benimoff, A. I., ed., The geology of Staten Island, New York: Geological Association of New Jersey Annual Meeting, 11th, Somerset, NJ, 14-15 October 1994, Field guide and proceedings, 296 p.

Sanders, J. E. and Merguerian, Charles, 1995, Evidence for pre-Woodfordian ages of Long Island's terminal moraines (extended abstract), p. 91-106 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 22 April 1995, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 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.

Sanders, J. E., Friedman, G. M., and Sternbach, C. A., 1981, Extinct (sic) and active continental margin (sic) deposits and their tectonic-switchover products: Appalachian orogen ("Eastern overthrust belt")-Catskill Plateau-Newark basin-Atlantic Coastal Plain, p. 104-232 in Hobbs, G. W., ed., Field guide to the geology of the Paleozoic, Mesozoic, and Tertiary rocks of New Jersey and the central Hudson Valley: American Association of Petroleum Geologists, 1981 Eastern Section Meeting, Atlantic Margin Energy Symposium, Atlantic City, New Jersey, 4-6 October 1981: New York, N. Y., Petroleum Exploration Society of New York, 232 p.

Sanders, J. E., Platt, L. B., and Powers, R. W., 1961, Bald Mountain Limestone, New York: new facts and interpretations relative to Taconic geology: Geological Society of America Bulletin, v. 72, no. 3, p. 485-488.

Scotford, D. M., 1956, Metamorphism and axial-plane folding in the Poundridge area, New York: Geological Society of America Bulletin, v. 67, p. 1155-1198.

Seyfert, C. K., and Leveson, D. J., 1968, Structure and petrology of Pelham Bay Park, p. 175-195 in Finks, R. M., ed., New York State Geological Association Annual Meeting, 40th, Queens College, Flushing, New York, Guidebook to Field Excursions: Flushing, NY, Queens College Department of Geology, 253 p.

Seyfert, C. K., and Leveson, D. J., 1969, Speculations on the Hutchinson River Group and the New York City Group, p. 33-36 in Alexandrov, E. A., Geological Bulletin 3, ed., Symposium on the New York City group of formations: New York State Geological Association, Annual Meeting, 40th, Flushing, New York, Queens College: Flushing, New York, Queens College Press, Department of Geology, 83 p.

Sharp, H. S., 1929, A pre-Newark peneplane and its bearing on the origin of the lower Hudson River: American Journal of Science, 5th series, v. 18, p. 509-518.

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

Stanley, R. S., and Ratcliffe, N. M., 1985, Tectonic synthesis of the Taconian orogeny in western New England: Geological Society of America Bulletin, v. 96, p. 1227-1250.

Taterka, B. D., 1987, Bedrock geology of Central Park, New York City: Amherst, MA, University of Massachusetts Department of Geology and Geography Master's Thesis (Department of Geology and Geography Contribution 61), 84 p. with maps.

Vellone, D. A., and Merguerian; Charles; 2007, Measuring engineering properties of NYC rocks using a Schmidt rebound hammer – Preliminary results: *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, 7 p.

Vellone, D. A., Merguerian; Charles, and Moss, Cheryl J., 2007, Determination of mechanical properties of New York City rocks using a Schmidt rebound hammer: in Association of Environmental and Engineering Geologists, Program and Abstracts, 50th Annual Meeting, September 24-29, 2007, Los Angeles, CA, p. 297.

Wicander, Reed; Monroe, J. S., Bennington, J. B., and Merguerian, Charles, 2007, Essentials of Geology with Geology of New York and New Jersey: Thomson Brooks/Cole, 510 p.

Yagiz, S., Merguerian, C., and Kim, T., Geological controls on the breakthrough of tunnel boring machines in hard rock terrains: *in* Zhao, Labiouse, Dudt, and Mathier *editors*: EUROCK'10, Rock Mechanics in Civil and Environmental Engineering, Proceedings of the ISRM European Rock Mechanics Symposium, p. 401-404.

Yagiz, S., Rostami, J., Kim, T., Özdemir, L., and Merguerian, C., Factors influencing performance of hard rock tunnel boring machines: *in* Vrkljan, *editor*: EUROCK'09, Rock Engineering in Difficult Ground Conditions, Soft Rocks and Karst, Proceedings of the ISRM Regional Symposium, Dubrovnik, Cavtat, Croatia, p. 695-700.

Zen, E-an, 1963, Structural relations (sic) in the southern Taconic region: an interpretation, p. 1-4 in Bird, J. M., ed., Stratigraphy, structure, sedimentation, and paleontology of the southern Taconic region, eastern New York: Geological Society of America, 76th Annual Meeting, New York City, Guidebook for Field Trip 3, 67 p.

Zen, E-an, 1967, Time (sic) and space relationships of the Taconic allochthon and autochthon: Geological Society of America Special Paper 97, 107 p.

Zen, E-an, 1972, The Taconide zone and the Taconic orogeny in the western part of the northern Appalachian orogen: Geological Society of America Special Paper 135, 72p.

Ziegler, V., 1911, The Ravenswood grandiorite: New York Academy of Sciences Annals, v. 21, p. 1-10.