Stratigraphy, Structure and Tectonic Implications of the New York Botanical Garden, Bronx, NY

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Introduction

This extended abstract reports on our compiled field mapping, structural analysis and petrography of bedrock at the New York Botanical Garden (NYBG) in Bronx, NY. Starting with our dear late colleague Dr. John E. Sanders, our analysis began with research in support of our On-The-Rocks field trip program of the NY Academy of Science of post-Woodfordian Bronx River diversion (Merguerian and Sanders 1993a, 1996a), mapping and petrography of a NYBG building site (Pfizer Building) then under construction in the NW corner of the Garden (Merguerian and Sanders 1998) and adjacent Bronx parks (Fuller, Short and Merguerian 1999). Research continued in 2011 with outcrop mapping of the entire grounds and a recent guidebook and field trip (Merguerian and Merguerian, 2024a). Here we compile the results of these NYBG studies and offers two preliminary geological maps and a location map (Plates 1, 2, 3 at end of extended abstract) and our findings on the structural geology and tectonic setting of the NYBG.

NYBG Location

The NYBG is located in the central Bronx, NY just north of E. Fordham Road and east of Fordham University (Figure 1).

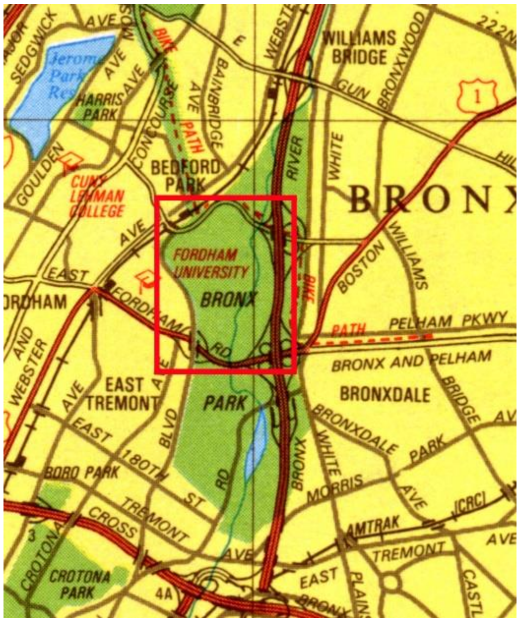

Figure 1 – Location map of the NY Botanical Garden which is bounded on the east by the Bronx River Parkway, on the south by East Fordham Road, on the west by Southern Boulevard and on the north by the Mosholu Parkway. Outline of Plate 1, 2 and 3 maps of the NYBG shown as a red rectangle. (Hagstrom).

GEOLOGIC BACKGROUND

The NYBG is situated within the southerly terminus of the Manhattan Prong (Figure 2), a region of low rolling ridges and valleys underlain by a northeast-trending, deeply eroded crystalline sequence of Proterozoic- to Lower Paleozoic metamorphic rocks. South of NYC, the crystalline rocks of the Manhattan Prong plunge southwestward and disappear beneath a gently inclined covering of Cretaceous coastal-plain sedimentary strata and an overlying blanket of Pleistocene (glacial) drift.

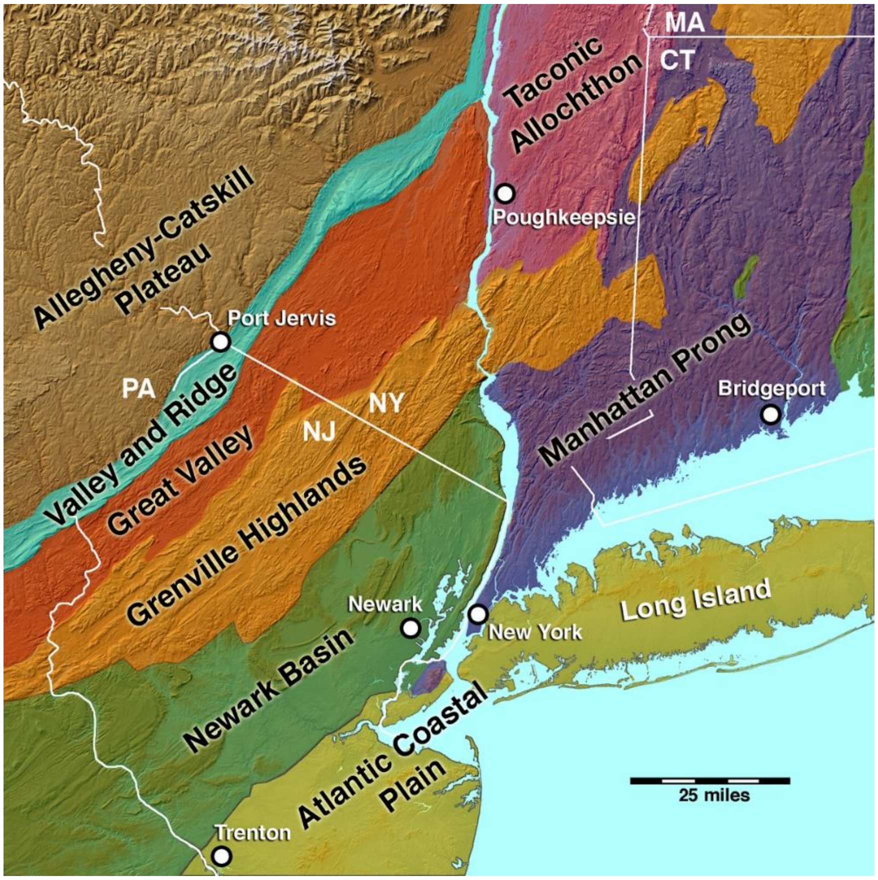

Figure 2 – Physiographic diagram showing the major geological provinces in southern New York, northern New Jersey, and adjoining states. The NYBG is within the Manhattan Prong. (From Bennington and Merguerian, 2007.)

BEDROCK UNITS

Under this section we briefly describe the history of local bedrock investigations to provide an overview of the geology of the region and the specifics of the stratigraphy-, geologic structure-, and metamorphic geology of the NYBG.

Although the rocks underlying the Bronx were first studied by naturalists in the 1700's, and by geologists and mineral collectors from the NY Mineralogical Club in the 1800's and 1900's, detailed geologic mapping began in the mid- to late 1800s to earliest 1900s by W. W.

Mather (1843) and F. J. H. Merrill et al (1902). The rich history of NYC geologic investigations is covered elsewhere (Merguerian and Sanders 1991b). Suffice to say that in 1890 (p. 390), Merrill named the Manhattan Schist to include all of the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, New York. Merrill (1890) states that *"the name Manhattan Group was proposed by R. P. Stevens, Esq., to include the rocks of New York Island"*.

F. J. H. Merrill (1890, 1902), in concert with other geologists published the first comprehensive geologic map of New York City in the United States Geological Survey New York City Folio 83. In this compilation Merrill outlined the basic stratigraphic- and structural framework that modern geologists would test and refine (Figure 3). Merrill's major contribution was subdivision of Mather's Primitive Series into mappable units. He first defined the correct relative chronology of the basal Proterozoic Fordham Gneiss (fgn), the overlying Cambrian to Silurian (sic) Stockbridge dolomite (ꞒSs) and the Silurian (sic) Hudson Schist (Sh) – now known as Ordovician and older Manhattan Schist and associated Lower Paleozoic schistose rocks).

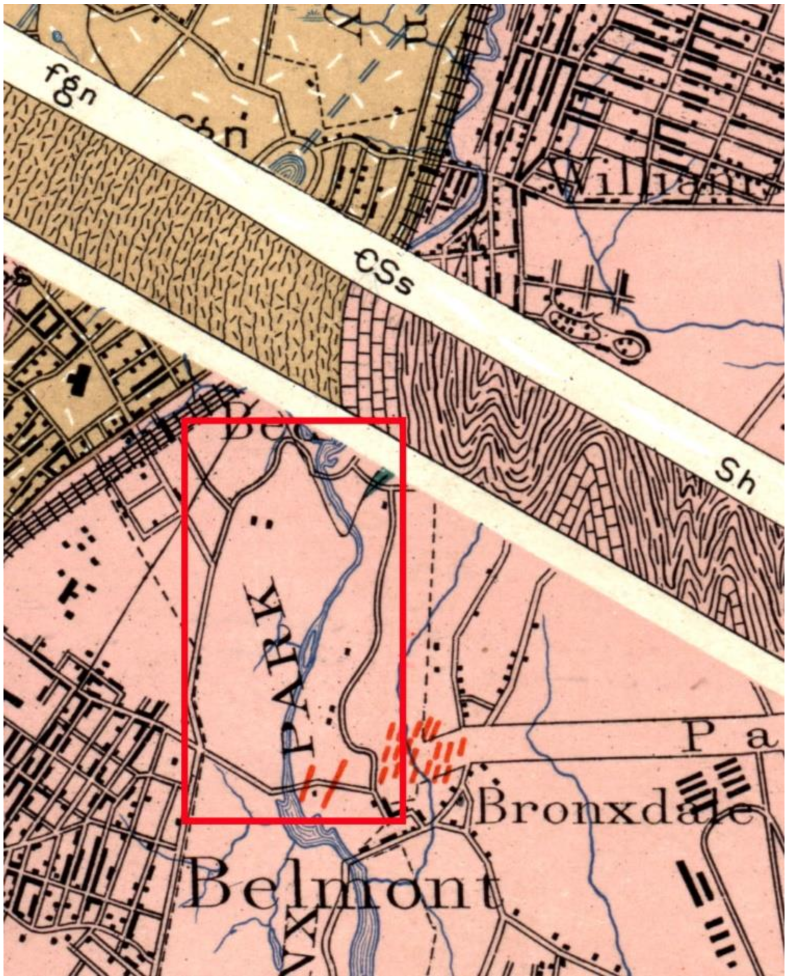

Figure 3 – Map and diagonal section of Merrill et al (1902) USGS folio map of the region of the Bronx that includes the NYBG (red rectangle) and shows a simplified view of the folded structure of NYC bedrock. The area of the NYBG shown in Plates 1, 2 and 3 is shown as a red rectangle.

Following our revisions in the stratigraphy and structure of NYC (Merguerian 1981a, 1983a; Merguerian, Baskerville and Okulewicz, 1982; Baskerville and Merguerian, 1982, 1983; Mose and Merguerian, 1985, and Merguerian and Sanders 1991b), Baskerville's (1992) USGS map of the Bronx showed a more complex geological interpretation of NYC that embraced <u>some</u> of the stratigraphic and structural ideas proposed by many in the 1980s. A portion of his map of the region surrounding the NYBG is reproduced below as Figure 4.

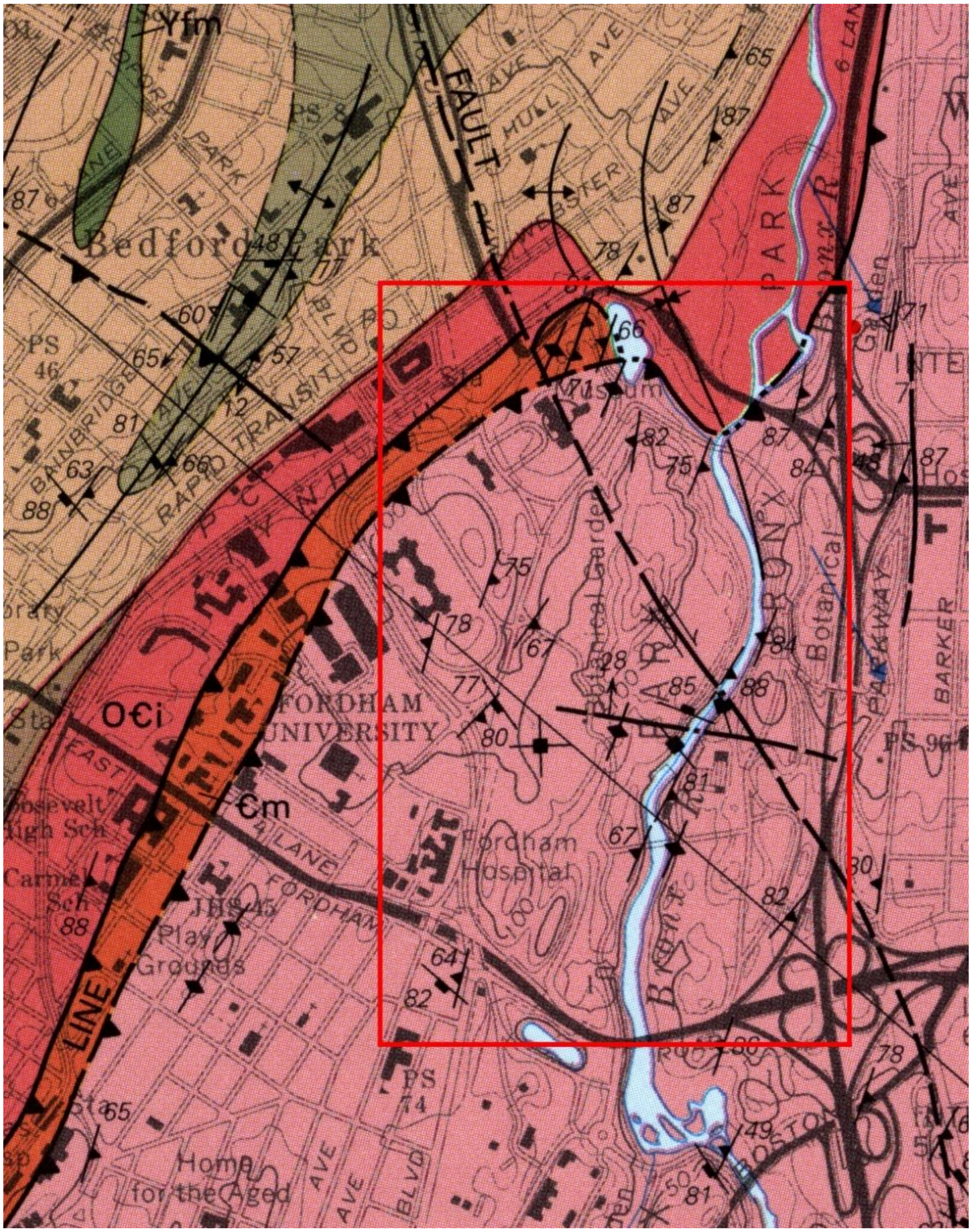

Figure 4 – Geological map of the NYBG showing the position of Fordham Gneiss (Yfd and Yfm - brown and green units, the Inwood Marble (OЄi – reddish unit), Manhattan Schist (Єm – red-brown unit), and the Hartland Formation (OЄh - pink unit) and the trace of the right-lateral Mosholu fault and Cameron's Line. The area of our new NYBG geological map (See Plates 1, 2, 3 below) shown in red rectangle. (Adapted from Baskerville 1992).

Our field- and laboratory investigations of the bedrock geology in the NYC area over the past 40 years have drawn heavily from earlier- and contemporary studies and suggest that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, structurally complex, roughly coeval, tectonostratigraphic units. The major findings from this period have been presented elsewhere (Merguerian 1983b, 1984, 1994a, 1996c, 2002b, 2015b; Merguerian and Baskerville 1987; Merguerian and Merguerian 2004, 2012, 2014a, b, 2016a, b; and Merguerian and Moss 2005, 2006a, 2007, 2015).

Our investigations agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-not-recognized, structurally higher schistose unit that is a lithostratigraphic correlative of the Hartland Formation of western Connecticut and we thus carry the name into NYC. CM's renegade interpretations on the stratigraphy and subdivision of the Manhattan Schist were presented during a lecture at the New York Academy of Sciences on the evening of 17 December 1984 entitled *"Will the Real Manhattan Schist Please Stand Up!"*

Bedrock Stratigraphy of New York City and the Bronx

The following section outlines our new views on the stratigraphy and ductile- and brittle structure of New York City which includes the Garden grounds. Two basic subdivisions of NYC crystalline bedrock (Figure 5) include:

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

Both rock sequences were internally folded and sheared during extended Paleozoic orogenesis and cut by younger brittle fractures (fault- and joint discontinuities). They are distinguishable in the field using the following field- and petrographic criteria:

Hartland Formation (Ꞓ-Oh). Gray weathering, fine- to coarse-textured, typically well-layered muscovite-quartz-biotite-plagioclase± kyanite±garnet schist, gneiss, and migmatite with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite± biotite± garnet. Known for relatively easy excavation because of pervasive weakness parallel to layering, the unit has been encountered in the Central and Riverside parks, East Side Access, Second Avenue Subway, Manhattan Water Tunnel, #7 Line IRT Extension and Con Edison Steam Tunnel projects and crops out mostly east of the Bronx River near the NYBG. It is considered a southernly, more metamorphosed correlative of the slates and interlayered lithic sandstones (graywackes) of the Taconic allochthon (Merguerian and Sanders 1996b). Hartland rocks are exposed in a vertically plunging structure involving Cameron’s Line and the Saint Nicholas thrust in the east part of the NYBG but mostly occurs east and south of the park. (See Table 1; Plates 1-3.)

Manhattan Formation (Ꞓ-Om). Massive rusty- to maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz±garnet±kyanite±sillimanite±magnetite ±tourmaline gneiss, migmatite, and schist. Characterized by the lack of internal layering except for kyanite± sillimanite+quartz+magnetite interlayers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite and lesser quartzose granofels, it forms the bulk of exposed Paleozoic metamorphic rocks of northern Manhattan, Central Park and the Bronx including most

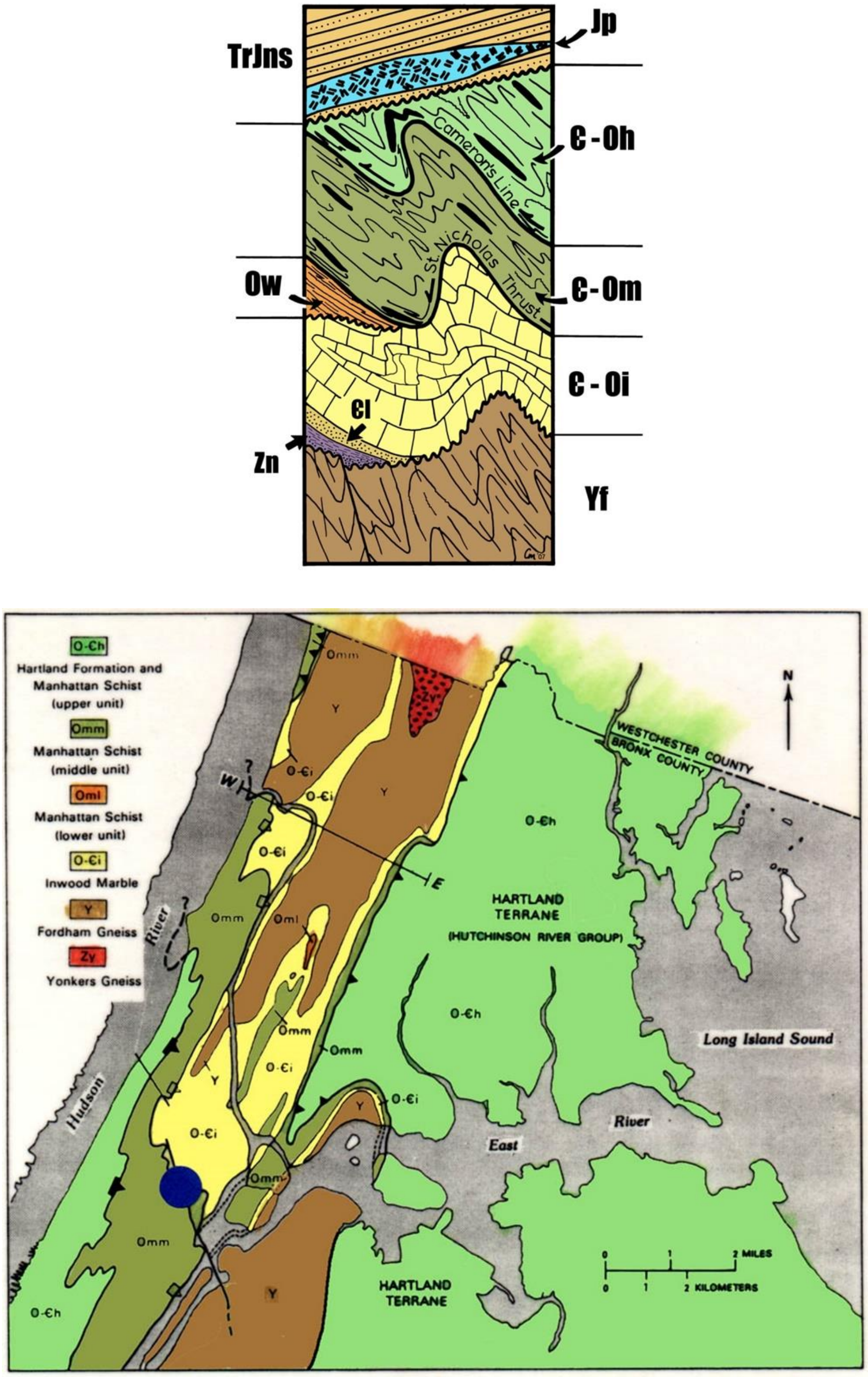

Figure 5 – Bedrock stratigraphy of New York City. The polydeformed bedrock units are in NYC are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive sheet (Jp) west of the Hudson River. Triangles show the dip of Cameron's Line (solid) and the Saint Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. The map depicts the F_3 folding of Cameron's Line and the Saint Nicholas thrust and shows major cross-cutting brittle faults. Blue dot shows earthquake epicenter of magnitude 2.4 (21 January 2001) whose focus projects above the NW-SE trace of the Manhattanville fault. Note that the unit Omm is equivalent to Є-Om in this paper. (Adapted from Merguerian and Baskerville 1987.)

of the central NYBG exposures. From the NYBG they extend southwestward in the Bronx cropping out in the east half of Boro Hall Park and also along the central portion of Crotona Park. These allochthonous rocks are interpreted as a transitional, “proximal to craton” part of the Taconic Sequence deposited on the former slope-rise. (See Table 1; Plates 1-3.)

Walloomsac Formation (Ow). Unit composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase±kyanite± sillimanite±garnet±pyrite ±graphite schist, granofels and migmatite containing interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of diopside±tremolite±phlogopite calcite- and dolomitic marble, calc-schist and greenish calc-silicate rock. Amphibolite is absent although green amphibole-bearing rocks are locally found. Diagnostic mineralogical features of the former pelitic portions of the formation include strongly pleochroic reddish biotite, pinkish garnet as scattered concentrations of small crystals and as porphyroblasts (up to 1 cm), graphite and pyrite. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels invites the interpretation that this unit is metamorphosed middle Ordovician carbonaceous shale + greywacke strata of the autochthonous Annsville, Normanskill and Austin Glen formations of SE New York and the correlative Martinsburg Formation farther southwest. Ow is exposed in the SE and NW edges of the NYBG and extends southward through the Bronx Zoo onto the west edge of Boro Hall Park and on both edges of Crotona Park.

Inwood Marble (Є-Oi). Occurring always west of the NYBG, the Inwood is white to bluish-gray fine- to coarse-textured dolomitic and lesser calcitic marble locally with siliceous interlayers containing diopside, tremolite, phlogopite, muscovite (white mica), and quartz together with accessory graphite, pyrite, tourmaline (dravite), chlorite and zoisite (Merguerian, Merguerian and Cherukupalli 2011). Layers of fine-textured gray quartzite with a cherty appearance and mica-quartz calc-schist are locally present. Inwood Marble is exposed mostly in the Inwood section of Manhattan, the shoreline along the NW edge of Inwood Park and Mt. Morris Park of Manhattan. Exposures on I-95 (Cross Bronx Expressway) and beneath the Webster Avenue valley are known in the Bronx. The Inwood is correlative with the Cambro-Ordovician carbonate platform or “Sauk” Sequence of the Appalachians.

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

Paleozoic Orogenesis

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

Now metamorphosed to amphibolite facies grade, the exposed Paleozoic metamorphic cover rocks of NYC were originally deposited on the proto–North American shelf edge as sediment and intercalated volcanic and volcaniclastic materials, though in vastly different depositional environments (Figure 6). Protoliths of the Hartland were originally deposited in a deep ocean basin fringed by offshore volcanic islands. Protoliths of the Manhattan originated along the shelf edge of the Laurentian continental margin as slope-rise strata including thick clay-rich sediment with occasional sand interlayers and mafic dikes or flows.

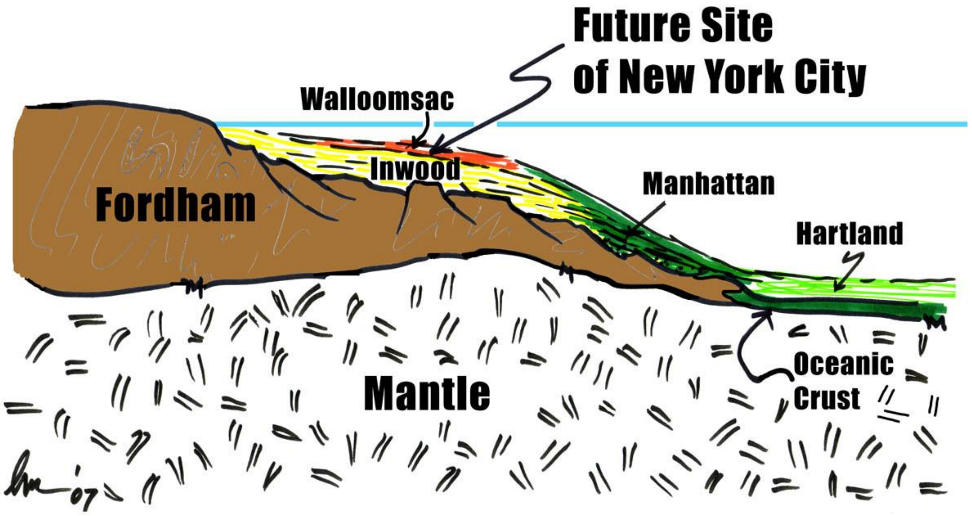

Figure 6 – Reconstruction snapshot cartoon of proposed depositional realms at Laurentian margin of protoliths of the Inwood, Walloomsac, Manhattan and Hartland strata before the Taconian arc-continent collision deformed them in mid-Ordovician time (~450 Ma). (CM drawing.)

Formed in the back-arc environment and being closed off from open-ocean conditions with the encroachment of the Taconic arc and subduction complex, protoliths of the Walloomsac became compositionally unique since they originated under restricted oceanic conditions (a reducing environment) which fostered thick accumulations of carbonaceous and sulphidic clay-rich sediment with occasional sandy and calcareous interlayers in a rapidly subsiding intracontinental foreland basin. Loading of the continental shelf edge by the Taconic arc may have been the agent that triggered the subsidence of the Walloomsac foreland basin and allowed for thick accumulations of black shale and turbidites on shelf-sequence carbonates of the Sauk sequence as seen in the Hudson Valley (Annsville, Normanskill, Austin Glen and correlatives).

In our view, underthrusting within the accretionary prism associated with the Taconian arc-continent collision produced the internal shearing, imbrication, deep-seated deformation, and amphibolite facies regional metamorphism of the Paleozoic cover rocks with some basement involvement and the coeval development of Cameron's Line and the Saint Nicholas thrust zones. The Taconian arc-continent collision is depicted in a series of time slices in Figure 7.

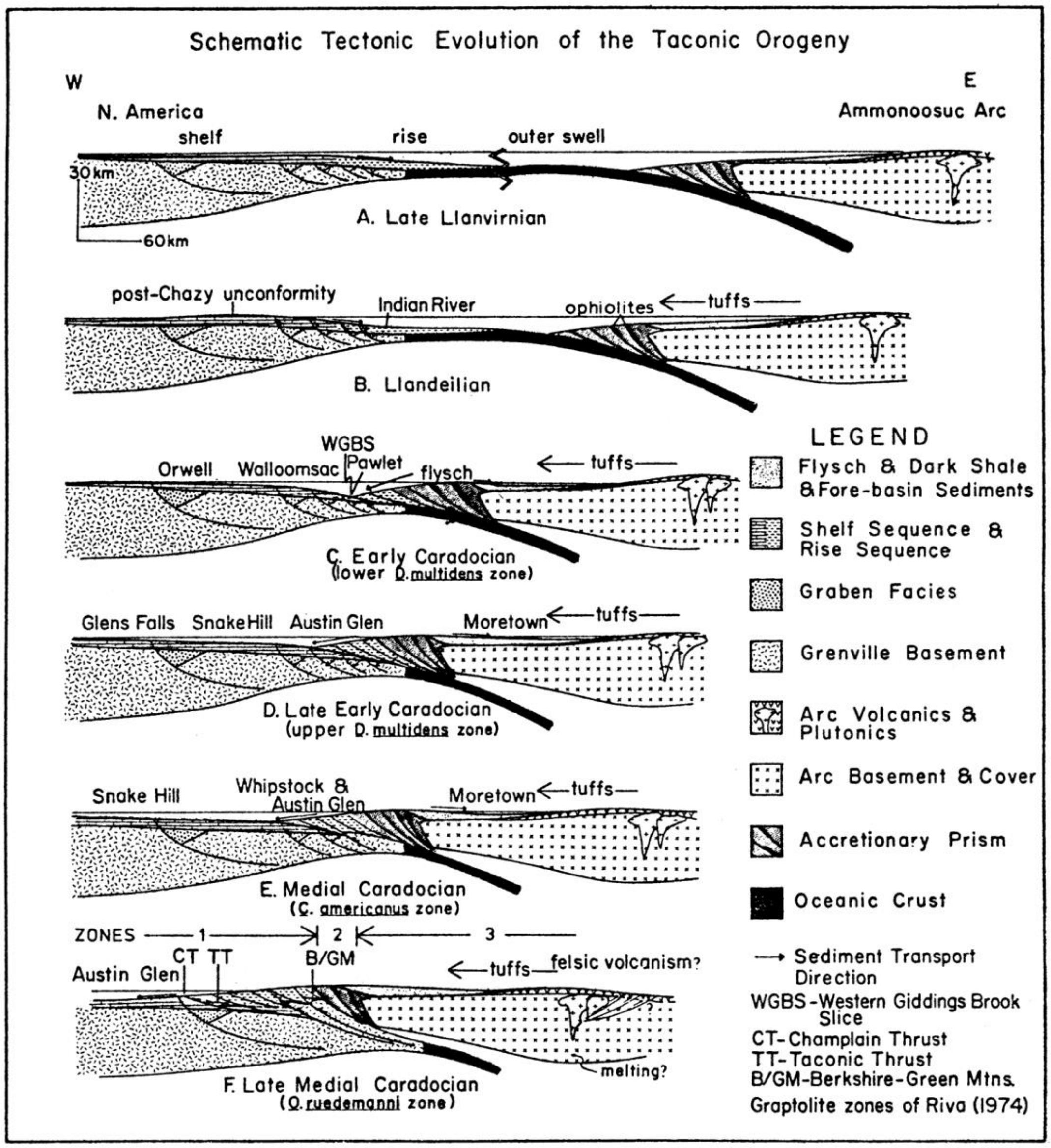

Figure 7 - Sequential tectonic cross sections for the Taconic orogeny in New England that show from the top downward the development of the Taconic suture zone. From Rowley and Kidd (1981).

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval shelf- (Ow), transitional slope/rise- (Ꞓ-Om), and deep-water (Ꞓ-Oh) lithotopes that were juxtaposed during telescoping of the ancestral North American shelf edge in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny. (See Figure 7.)

Arc-Trench Tectonics

The development of plate tectonic theories to better explain the mountain building process has been strengthened by remapping of former geologic terrains and also by studying modern convergent margins. One such study that stands out was an investigation of deep sea drilling and study of extracted core from the Nankai Trough area of the Shikoku subduction zone in southwestern Japan (Moore and Karig 1976).

Two figures from their paper are combined below as Figure 8 that demonstrate the shallow level isoclinal folding and imbrication of strata detected in the upper levels of thrust sheets within the upper plate subduction complex. Our model of the Taconic orogeny (Figure 9) takes into account the attenuation of strata during deep-seated convergent tectonics and how complex the original starting strata may have been before the obscurities produced by metamorphism. As such, traditional formational mapping in uplifted mobile belts produced in arc-continent or arc-arc convergent margin settings may be best understood by abandoning layer-cake stratigraphic models and entertaining the idea that shear zones and thrust faults may be more pervasive than outcrop mapping may indicate – even away from major shear zones. The card-carrying field geologist in deeply eroded core zones of mountain belts may inquire “are there shear zones around every outcrop”? We have seen many examples of confusion in the field trying to determine which formation is which but we should be open to imbrication (mixed zones) and intimate shearing of strata at the small scales as they descend to the deeper levels of a subduction zone, especially in light of the fold-thrust complexities of starting materials within the developing subduction complex. (See Figure 8.)

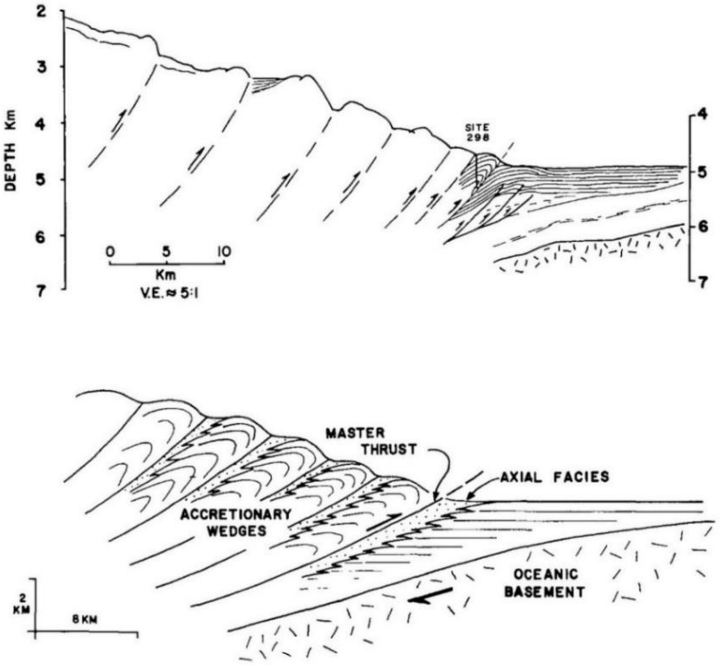

Figure 8 – Two views of internal structure of the trench wall of accretionary wedge associated with modern subduction in the Shikoku subduction zone of the Japanese trench based on drilling (Sites 297, 298). Their study of bedding-cleavage relationships demonstrated that isoclinal folding and imbrication of subducted strata took place in concert with thrust faulting in the upper plate at high crustal levels. (From Moore and Karig, 1976, figs 11, 12.)

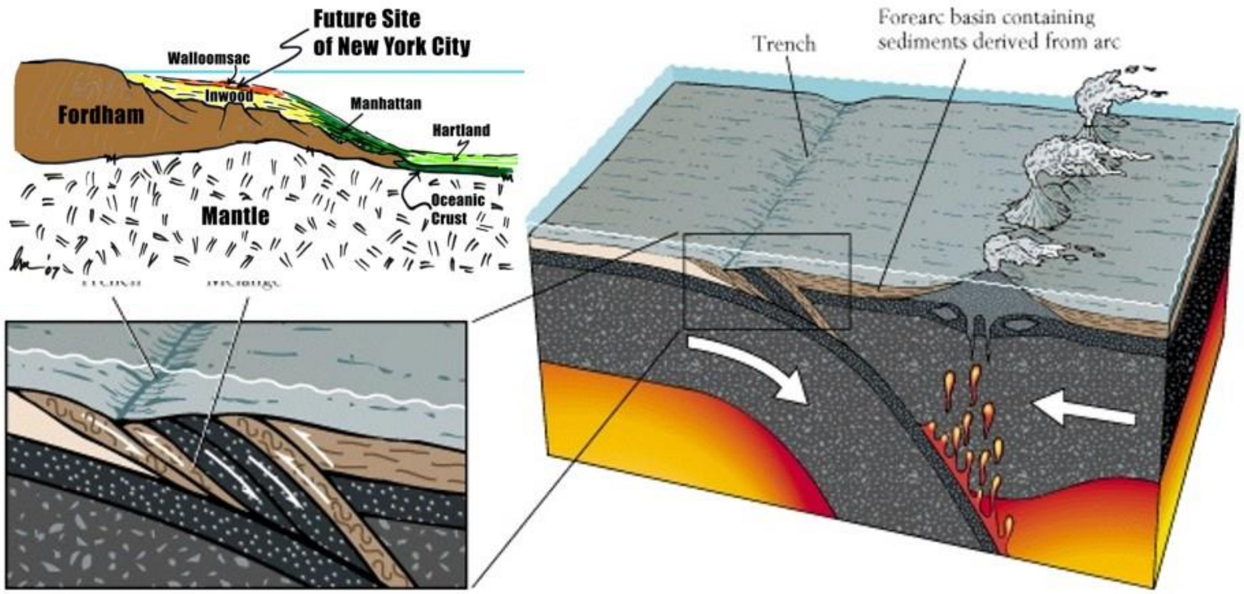

Figure 9 – Composite diagram showing the subduction zone imbrication and deeper area of deformation, metamorphism and imbrication along ductile faults of former sedimentary strata that would produce the Inwood, Walloomsac, Manhattan and Hartland Formations. These rocks and structures developed at the deep levels of a mid-Ordovician arc-continent collision zone of the ~450 Ma Taconic orogeny. In our view, the development of the Saint Nicholas Thrust and Cameron's Line involved the juxtaposition of disparate former sedimentological realms of the Laurentian shelf, slope and rise, and abyssal regions formerly adjacent to the continental margin.

Structural Geology of New York City

All Paleozoic strata in the Bronx have shared a complex structural history which involved three superposed phases of deep-seated Taconian deformation (D_1, D_2, D_3) followed by three or more episodes of open- to crenulate folds (D_4, D_5, D_6) in mid- to late Paleozoic or younger time. Synmetamorphic juxtaposition of the bedrock units along ductile thrusts (Saint Nicholas Thrust and Cameron's Line) occurred very early in their structural history, culminating during D_2 and deformed during D_3 based upon field relationships. The three Paleozoic orogenies (Taconian, Acadian, and Alleghenian) developed prograde (D_1, D_2, D_3) and later retrograde (D_4, D_5, D_6) effects in the Inwood, Walloomsac, Manhattan, and Hartland rocks. Only Taconian structures of D_1, D_2, D_3 are shown plotted on Plates 1 and 2.

The obvious map scale F_3 folds in NYC are those with steep NNE- to NE-trending axial surfaces (S_3) and variable but typically shallow plunges toward the S and SW. (See Figure 5.) The F_3 folds are typically overturned to the NW with a steep SE-dipping foliation. Shearing in fold limbs and along S_3 axial surfaces typically creates a transposition foliation that combines S_1, S_2, and S_3 that is commonly invaded by granitoids to produce migmatite during both the D_2 and subsequent D_3 events. These third-generation structures deform two earlier penetrative structural fabrics (S_1 and S_2). Regionally, the older penetrative fabrics are detected as enveloping surfaces that trend roughly N50°W and dip gently toward the SW except along the limbs of F_3 folds. We suspect that all of these structures (D_1, D_2, and D_3) are all products of protracted Taconian orogenesis.

D_1 to D_3 folds and crosscutting fabrics that formed during the Taconic orogeny are overprinted by two- and possibly three- fold phases that, based on their style and general lack of attendant foliation, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics. Presumably, the younger fold phases D_4 to D_6 record the effects of the Acadian- and terminal-stage Appalachian orogenies.

During D_2, the rocks acquired a penetrative S_2 foliation consisting of oriented mica and intergrown sillimanite and kyanite with flattened quartz together with staurolite and garnet porphyroblasts. Distinctive layers and lenses of kyanite + quartz + magnetite developed in the Manhattan Formation and very locally in the Hartland during D_2. Near ductile fault contacts the S_2 fabric is highly laminated with frayed and rotated mica and feldspar porphyroclasts, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins all developed parallel to the axial surfaces of F_2 folds. The D_3 folding event, a period of L-tectonism, smeared the previously flattened kyanite + quartz layers and lenses into elongate shapes parallel to F_3 axes in schistose rocks. Large porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to F_3 hingelines in the Inwood Marble of northern Manhattan. Metamorphism associated with D_3 annealed and recrystallized the older D_2 mylonites in NYC (Merguerian 1988; Merguerian and Sanders 1998).

Preliminary Geological Map of the New York Botanical Garden

Found at the end of this paper in tabloid format Plates 1, 2 and 3 (two geological maps and a stop location and sample map) display our current view on the bedrock geology of the NYBG although we need a couple of more visits to finalize the maps. The maps show folded thrust slices of Manhattan (Ꞓ-Om), Hartland (Ꞓ-Oh), and Walloomsac (Ow) rocks in a complex pattern of steep to vertically inclined ductile faults which imbricate metamorphic rocks of identical steep to vertical orientation. The Manhattan is thrust against the Walloomsac (Ow) along the Saint. Nicholas thrust in the NW and W part of the park. Baskerville (1992) showed a thin belt of Manhattan against Inwood along an unnamed thrust did not recognize the belt of Walloomsac (where he mapped Manhattan) in the NW and W part of the park. (See Figure 4.) He also showed a broad belt of Hartland rocks thrust against Manhattan along Cameron's Line in the same area we place the Saint Nicholas thrust.

Hartland rocks (OꞒh in pink) are simply not where Baskerville shows them in the bulk of the park. Rather, based on our mapping the overall structure of the NYBG is synformal with Manhattan Schist at the center SW-plunging asymmetrical F_3 synform with gentle plunge but steep to vertical limbs overturned to the NW. The SE-limb of the synform is truncated by Cameron's Line (CL) near the course of the Bronx River where Hartland rocks were first detected by us in the Garden. They terminate to the SW in a vertical F_2 fold with NNE-trending subvertical axial surface. This structure is cut by the Saint Nicholas thrust toward the SE. The two shear zones are marked by imbricated lithologies and broad zones of mylonite ± migmatite and foliated granitoid (g). The granitoid in the SE portion of the park shows the effects of late syn-tectonic shearing at the juncture of the regional shears (SNT and CL) and shows brittle offset by NW-trending faults. Indeed, all of the bedrock units and ductile faults are cut by the NW-trending, right-lateral Mosholu fault and various splays showing minor left- and right lateral offset.

Brittle Faults in NYC

NYC Paleozoic cover rocks are cut by two main sets of brittle faults trending ~N30°E [paralleling the long axis of Manhattan] and those ranging from N20°W to N50°W with steep dips toward the SW [diagonally across Manhattan]. Proterozoic basement rocks show a more complex brittle fault history (Merguerian 2002b, 2004a). The NE-trending faults, which locally reactivate annealed ductile fault zones (Cameron's Line and the Saint Nicholas thrust), are steep-to vertical and show dominantly dip-slip slickenlines. The NW-trending faults are steep to moderate in dip (toward SW) and show complex movement dominated by strike-slip offset followed by dip-slip or oblique-slip reactivation. The NW-trending faults have produced map-scale offset and geomorphic evidence in the NYBG suggesting post-glacial ground effects.

North of NYC, contemporary seismicity along the NW-trending Dobbs Ferry fault in late October 1985 included two small (~4.0) tremors and many aftershocks. As shown in Figure 10, more robust earthquakes in and around the vicinity of NYC were recorded in 1884, 1783, and 1737. Unequivocal post-glacial ground rupture is difficult to demonstrate in NYC where most bedrock faults are (especially by seismologists) deemed to have formed at depth and then later elevated to the surface. Yet, the Bronx River, which formerly flowed SSW in an open valley underlain by the Inwood Marble belt shows diversion away from its "pirated" marble valley along the NW-trending right-lateral Mosholu fault, suggesting neotectonic displacement.

Merguerian and Sanders (1997) did not prove that the surface displacement of the bedrock near the East 204th Street bulge accompanied an earthquake generated by sudden slippage along the reactivated Mosholu fault nor did they prove that surface rupture took place. However, in many seismically active zones, surface displacement, such as the bedrock contour bulging mentioned above adjacent to the Mosholu fault, typically is associated with energetic earthquakes (e.g. – the Palmdale Bulge along the San Andreas fault in California).

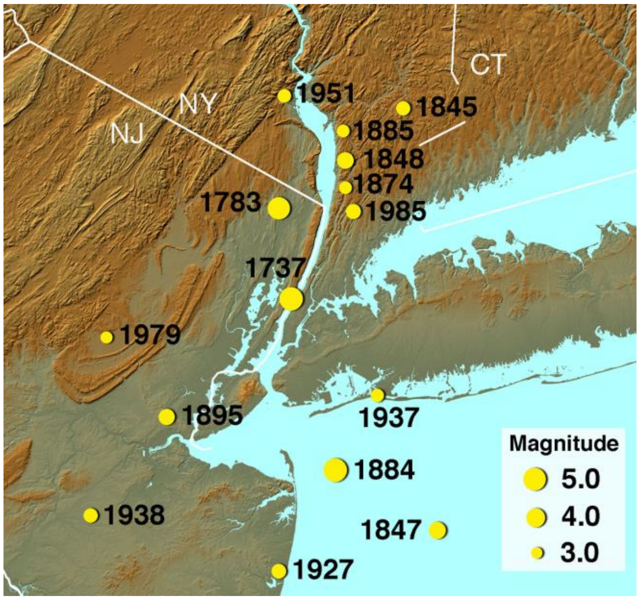

Figure 10 – Map showing historic seismic activity in the vicinity of New York City showing a diffuse zone of seismicity and the position of M3 and greater events before 1986. (From Bennington and Merguerian 2007.)

No observed surface rupture of crustal rocks has been previously reported in connection with any of NYC's strongest earthquakes of 1737 (~M5.2), 1783 (~M4.9), and 1884 (~M5.2). Yet, the August 1884 earthquake produced 4 m long by 3 m deep soil openings, cracked buildings and chimneys in Brooklyn and was felt over a hundred miles from the epicenter, which was located in the New York Bight. No historic earthquake has caused surface rupture of a fault anywhere along the east coast seismic zone. Equivalent shaking in NYC today would likely cause failure of older masonry walls, shatter glass windows in skyscrapers and rupture water and gas mains as soils liquefy and ground shaking ensues.

Because the contemporary stress regime in the lithosphere is oriented N60°E (Sykes et al. 2008), left-lateral offset might be expected in W- to NW-trending faults but NNW-trending faults might exhibit contemporary right-lateral offset. Given the modern stress regime, the presence of NNW- and NW-trending faults in the NYC area portend seismic risk. Knowing the history of time-separated moderate intensity seismic activity in New York City, the potential that a damaging earthquake may affect this densely populated area should not be ruled out. Because earthquakes **have** happened here, **can** happen here, and **will** happen here, effective pre-emptive planning to mitigate seismic hazards is an urban necessity.

Arm waving aside, the NW-trending fractures may be the result of Atlantic ocean ridge push with transcurrent and transform fracture propagation into the edge of the continental crust (Figure 11). This ridge-push model, proposed over twenty years ago at a GSA meeting while the audience snoozed and visited the rest rooms, is still suggested by us as a possible mechanism for neotectonic reactivation of these younger NW-trending brittle discontinuities.

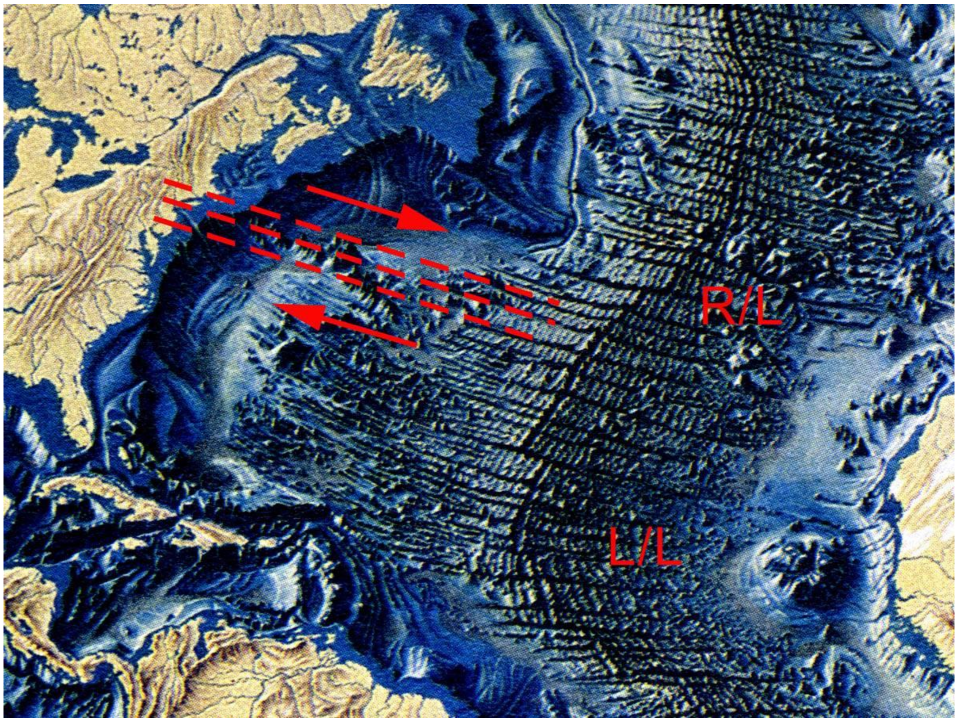

Figure 11 - Contemporary NYC seismicity seems to be localized along NW-trending brittle faults. As diagrammed above, the right-lateral and left-lateral offset sense of active NYC faults may be caused by offset along transcurrent faults that segment to mid-ocean ridge of the Atlantic Ocean basin. (Basemap from Heezen and Tharp, 1968.)

Acknowledgements

This paper is dedicated to the memory of Dr. Gil Hanson, scholar, friend and colleague for many years. His efforts live on in this the first LIG Metropolitan New York conference since his recent passing. We are indebted to Dr. Steven Jaret for agreeing to host the event for the past two years and take over the reins.

Our efforts in the NYBG were aided by our long association with the late Dr. John E. Sanders, an encyclopedic resource and keen observer of both bedrock and regolith in this region. We were assisted in the field by Lesley Short, Tyrand Fuller, P. LaJuke and H. Manne and have always benefitted from discussions with Drs. Patrick and Pamela Brock. Travel support funding for the 2011 mapping project was from the New York Botanical Garden Education Department.

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To Cite this extended abstract:

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

Petrography New York Botanical Garden

N0910	NYBG Stop 17	COm	Myl pg bio qtz musc kf gt gneiss	massive; flaser
N0911	NYBG Stop 21	g	Pg qtz bio musc foliated granitoid	small sample
N0912	NYBG Stop 33	COma	Hbl pg qtz op amphibolite	blackish, dense; tr bio, trem
N0913	NYBG Stop 42	COm	Mig pg qtz bio musc kf gt gneiss	dissem kf; late idio musc
N0914	NYBG Stop 45	COm	Mig pg qtz bio musc kf gt gneiss	mixed w/ Ow?; some rb-bio; kf in mig sweats
N0915	NYBG Stop 49	COm	Myl pg bio qtz gt kf gneiss	
N0916	NYBG Stop 50	COm	Pg qtz bio musc gt gneiss	
N0917	NYBG Stop 58	COm	Mig pg qtz bio gt gneiss	
N0918	NYBG Stop 57	Ow	Pg bio qtz gt ky py grph tour granofels	rb-bio; pale pink gt; fissile; v. fine textured
N0919	NYBG Stop 61	COma	Hbl (75) pg op qtz amphibolite	Blackish, dense
N0920	NYBG Stop 64	COm	Myl pg bio qtz musc ky gt apa gneiss	tr kf, chl; late idioblastic musc and bio; frayed musc
N0921	NYBG Stop 66	COm	Pg bio qtz musc gt gneiss	
N0922	NYBG Stop 70	OCh?	Bio musc pg qtz gt schist	1 cm musc pseudos after ky
N0923	NYBG Stop 78	Ow	Pg qtz bio py grph tour granofels	rb-bio; abundant py; zoned tour; fine textured
N0924A	NYBG Stop 79	Com	Pg bio qtz musc gt gneiss	fine textured; late idioblastic musc and bio
N0924B	NYBG Stop 79	COm	Pg qtz bio musc gt gneiss	gt porphs; ky? or sill?
N0924C	NYBG Stop 79	g/s	Sillimanite nodule near granitoid	in OZm
N0925	NYBG Stop 82	OCh	Pg qtz bio ky gt sill musc gneiss	lustrous; ky clusters w/ bio
N0926	NYBG Stop 83	OCh	Qtz pg bio musc gt granofels	foliated
N0927	NYBG Stop 86	COm	Myl bio qtz musc pg ky gt tour gneiss	
N0928	NYBG Stop 89	COm	Mig pg qtz bio musc gt schist	some kf in sweats
N0929	NYBG Stop 97	Ow	Pg bio qtz kf musc grph gt granofels	rusty weath; pale pink gt; rb-bio; mosaic texture
N0930A	NYBG Stop 28	Ow	Bio pg qtz musc grph gt schist	rusty weath; pale pink gt; rb-bio
N0930B	NYBG Stop 28	Ow	Pg qtz musc bio gt grph granofels	rusty weath; pale pink gt; rb-bio
N0931	NYBG Stop 74	COm	Qtz pg bio musc gt gneiss	red gt; khaki br bio; massive
N0932	NYBG Stop 100	COm	Myl pg qtz bio musc gt gneiss	red gt; musc porphs
N0933A	NYBG Stop 102	OCh	Pg qtz bio musc granofels	foliated granitoid layer?
N0933B	NYBG Stop 102	OCh	Mig musc pg qtz bio gt schist	red gt
N0934	NYBG Stop 103	Ow	Myl pg bio qtz musc gt py grph granofels	rusty weath; pale pink gt; rb-bio; fine textured; op rich
N0935	NYBG Stop 105	Ow	Mig musc bio qtz pg gt schist (OCh?)	rb-bio layers w/ gts; little opaques; no grph
N0936	NYBG Stop 109	Ow	Myl pg qtz bio musc gt py grph granofels	rusty weath; pale pink gt; rb-bio

TABLE 1

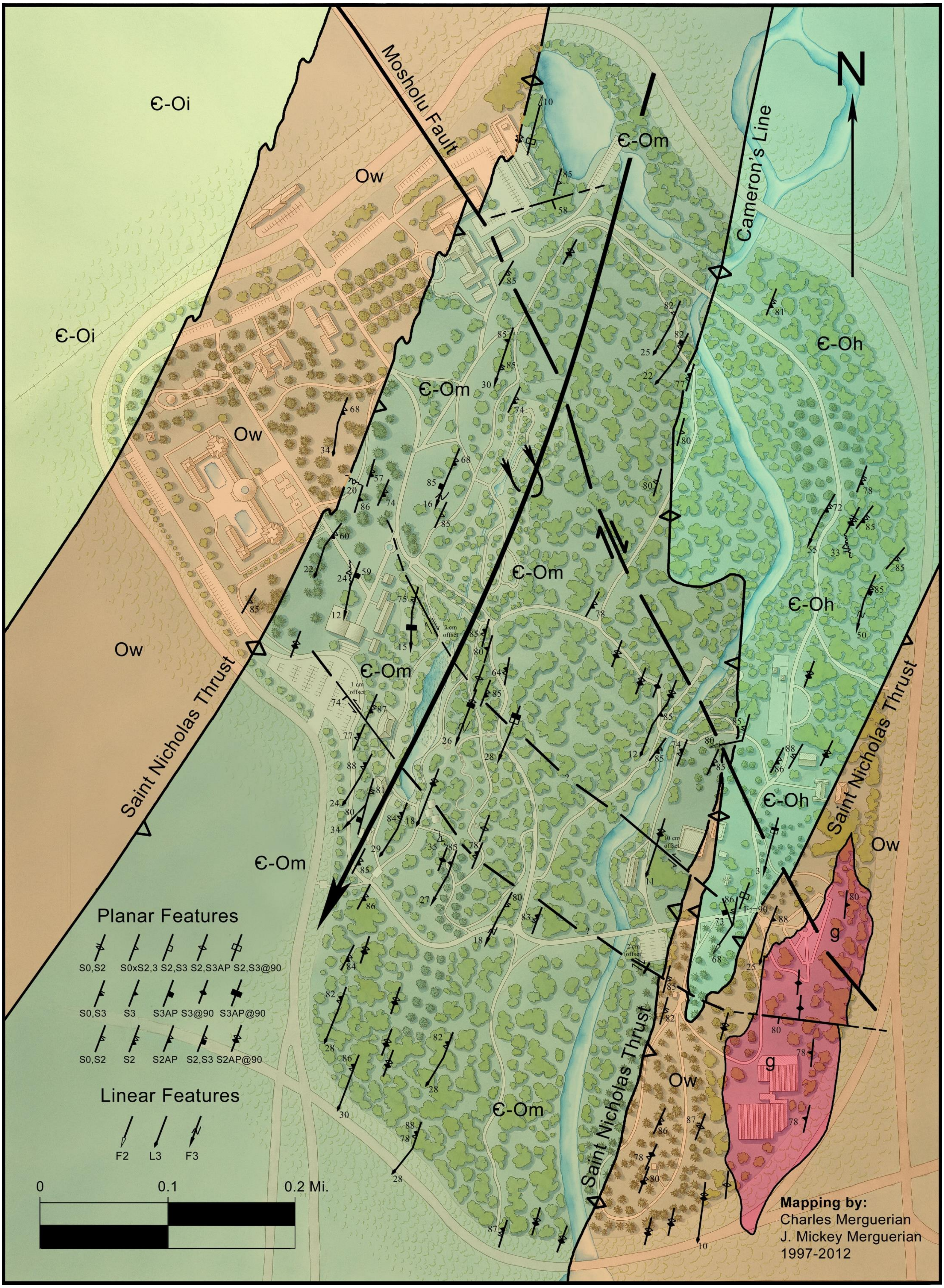

Plate 1 – Preliminary geological map of the New York Botanical Garden showing the ductile faults (Cameron's Line and Saint Nicholas thrust) and brittle faults including the Mosholu fault, associated splays and other mapped brittle faults. Units – Ꞓ -Oi = Inwood Marble, Ow = Walloomsac Formation, Ꞓ -Om = Manhattan Formation, Ꞓ -Oh = Hartland Formation, g = foliated late syn-tectonic granitoid. Foliation and bedding (planar features) and fold axes and lineations (linear features) symbols explained in legend with dip and plunge values plotted. Map scale synformal NW-vergent F_3 axial surface trace shown. See Plate 2 for structural contacts and field data plotted on non-colored park trail map and Plate 3 for sample and stop locations on park trail map. Basemap courtesy NYBG.

Plate 2 – Uncolored preliminary geological map of the New York Botanical Garden showing the ductile faults (Cameron's Line and Saint Nicholas thrust) and brittle faults including the Mosholu fault, associated splays and other mapped brittle faults. Units - Є-Oi = Inwood Marble, Ow = Walloomsac Formation, Є -Om = Manhattan Formation, Є -Oh = Hartland Formation, g = foliated late syn-tectonic granitoid. Foliation and bedding (planar features) and fold axes and lineations (linear features) symbols explained in legend with dip and plunge values plotted. Map scale synformal NW-vergent F_3 axial surface trace shown. See Plate 3 for sample and stop locations plotted on park trail map. Basemap courtesy NYBG.

Plate 3 – NYBG trail map showing sample locations and stop localities used in production of the geological maps. (See Plates 1 and 2.) Basemap courtesy NYBG.