ANNEALED MYLONITES OF THE SAINT NICHOLAS THRUST (SNT) FROM A NEW EXCAVATION AT THE NEW YORK BOTANICAL GARDENS, THE BRONX, NEW YORK

Charles Merguerian and John E. Sanders
Geology Department, Hofstra University, Hempstead, NY 11549-1140
geocmm@hofstra.edu; geojes@hofstra.edu

Introduction

The schistose Lower Paleozoic rocks of New York City consist of three lithologically distinct amphibolite-grade rock sequences (Sauk, Tippecanoe, and Taconic) formerly deposited as temporally correlative lithotopes within a convergent-margin regime which supplanted a former passive-margin regime. Today, they are separated by ductile faults -- the Saint Nicholas thrust **(SNT)** and Cameron's Line **(CL)**. These units were originally lumped together as a single formation, the Manhattan Schist, which was thought to be entirely younger than the Cambro-Ordovician Inwood Marble formation or in sequence terms, to belong to the Tippecanoe Sequence. Lithostratigraphic evidence suggests that the three sequences were deposited in contrasting environments ranging from a former continental shelf seaward across a former continental rise and onto a former sea floor. Although these deposits were formerly separated from one another by distances of perhaps hundreds of kilometers, during the Ordovician Taconian orogeny, they were internally folded, metamorphosed, and telescoped together. During this deep-seated event, the Saint Nicholas thrust and Cameron's Line shear zones developed in a former continentward-facing subduction complex wherein shelf-, rise-, and deep-water facies were juxtaposed.

The **SNT** and **CL** now crop out as steeply oriented, highly laminated, migmatized, complexly folded- and annealed zones of commingled mylonitic rocks. The mylonites developed during progressive synmetamorphic ductile deformation ($F_1 + F_2$) which culminated in the creation of two internally sheared allochthonous sheets now roughly oriented N50°W, 25°SW. Both ductile-fault zones are characterized by megascopic penetrative F_2 isoclinal- and shear folds, and the effects of lit-par-lit granitization. Microscopic textures include sheared mica- and feldspar porphyroclasts, polygonized quartz ribbons, and annealed mylonitic features. Here, we report on field and petrographic investigations of mylonitic rocks temporarily exposed at a building site (in early November 1997) on the grounds of the New York Botanical Gardens.

Cambro-Ordovician Sauk, Tippecanoe, and Taconic Sequences

Expressed in simplified form, the rocks exposed in New York City are the metamorphosed products of two contrasting paleogeographic-paleotectonic regimes separated by a surface of disconformity of regional extent. The lower part of this sequence includes sediments deposited on an ancient passive continental margin, which persisted from early in the Cambrian Period until the middle of the Ordovician Period which featured a carbonate-platform interior (the **Sauk Sequence**) that was bordered by a continental-rise prism of fine-textured terrigenous sediment (the **Taconic Sequence**) and an oceanward volcanic realm. After subaerial exposure of the former carbonate shelf and rapid subsidence to form a foreland basin, the Sauk and Taconic sequences were overlapped by a thick body of fine-textured terrigenous sediment (the **Tippecanoe Sequence**), which filled the foreland basin. This basin formed early in the Ordovician Period and extended through at least the end of the Ordovician. As mentioned above and discussed in detail elsewhere (Merguerian 1983a, 1985, 1996; Merguerian and Baskerville 1987; Merguerian and Sanders 1991, 1993a, 1993b, 1996), the deposits of these disparate sedimentologic realms were juxtaposed during the late middle Ordovician Taconic orogeny.

The important change from a passive continental margin to a convergent margin involved overthrusts toward the continent, slope reversal, and geographic rearrangements. The first of the overthrusts toward the continent broke inboard of the former shelf edge and brought felsic continental basement rocks above the muds on the floor of the foreland basin where the Tipppecanoe Sequence was accumulating. Later, the Taconic allochthons were emplaced, whereby the the fine-textured terrigenous sediments of the Taconic Sequence were displaced physically above carbonates and clastics of the Sauk and Tippecanoe sequences. Two important ductile fault surfaces are connected with the Taconic Sequence: (1) the "Taconic basal thrust," which brought continental-rise sediments up above the former shelf (**SNT** in New York City) and (2) and **CL**, a major dislocation within the Taconic Sequence along which deep-ocean sediments were transported above the continental-rise sediments. According to us, only a small part of the rocks formerly assigned to the Manhattan Schist represent the metamorphosed clastics belonging to the Tippecanoe Sequence, the former foreland-basin filling material. The main body of the schistose and gneissic rocks exposed on Manhattan consists of two thrust sheets consisting of "Taconic" rocks: (1) a lower sheet consisting of metamorphosed continental-rise sediments, and, (2) an upper structural sheet, of metamorphosed deep-ocean sediments.

Bedrock Stratigraphy of New York City

The bedrock underlying Manhattan includes the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose and gneissic rocks formerly included in a single formation thought to be younger than the Inwood Marble, the Manhattan Schist. In modern sequence terms, the Manhattan Schist as originally diagnosed would consist entirely of rocks belonging to the Tippecanoe Sequence. These metamorphosed, Lower Paleozoic bedrock units are found west of Cameron's Line, a major tectonic boundary in New England. Together, they are the products of metamorphism of sediments formerly deposited on Proterozoic crust (pꞒ-O in Figure 1). Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Hall 1976; Rodgers and others 1959, Merguerian 1977, 1983a) or Hutchinson River Group (Seyfert and Leveson 1968, 1969; Levesen and Seyfert 1969), or Pelham Bay Member of the Hartland Formation (Baskerville 1982). In contrast to the Sauk and Tippecanoe sequences, the Hartland Formation consists of metamorphosed deep-water sediments formerly deposited on oceanic crust (Ꞓ-Oh in Figure 1) and which became accreted to North America during the middle Ordovician Taconic orogeny (Hall 1980; Merguerian 1979; Merguerian, Mose, and Nagel 1984; Robinson and Hall 1980). To the west of Cameron's Line, in The Bronx and Manhattan, rocks with lithologic affinities transitional between those of the Sauk-Tippecanoe sequences and the Hartland Formation (i.e. - the lower sheet of the Taconic Sequence) crop out.

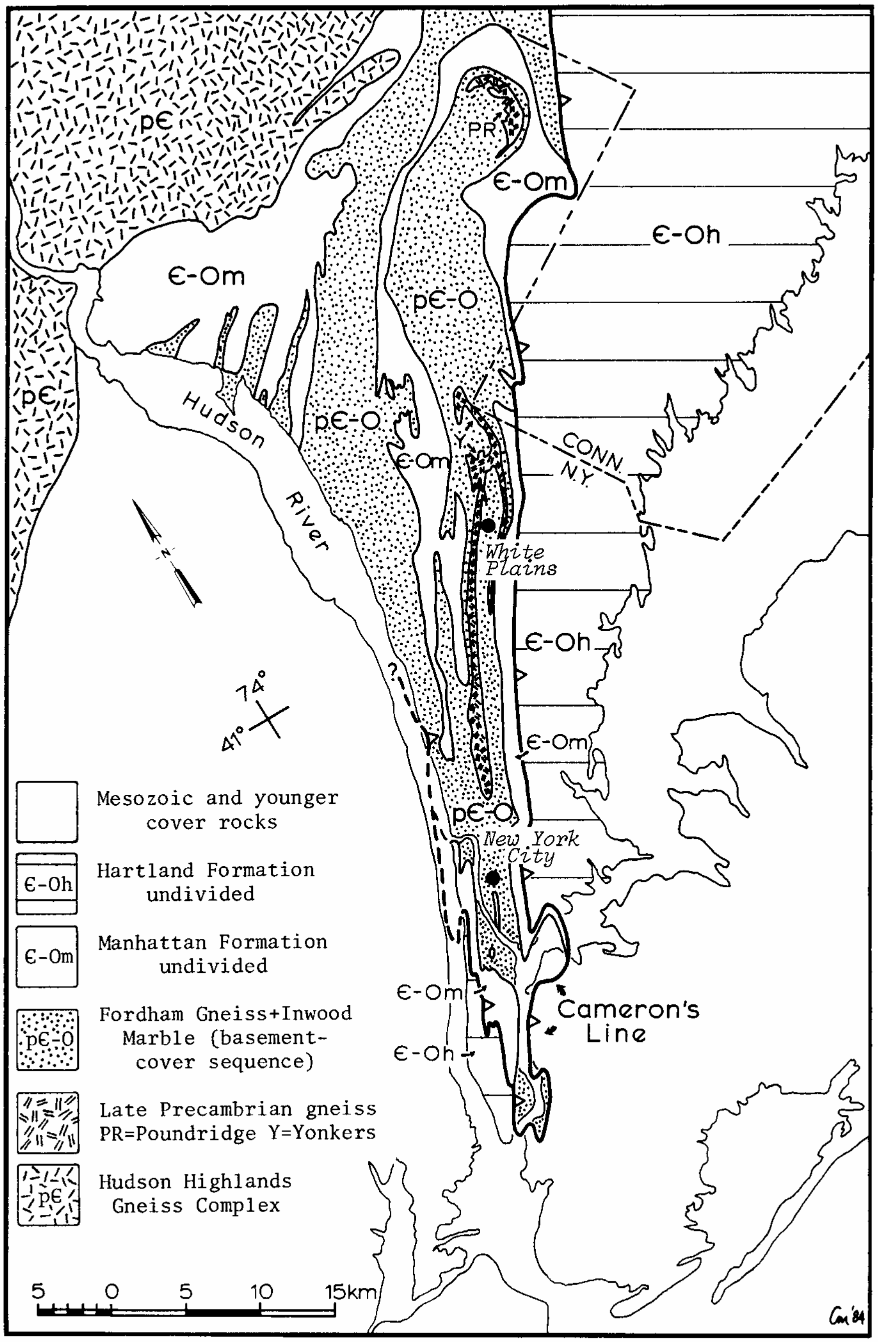

Figure 1 - Simplified geological map of the Manhattan Prong showing the distribution of metamorphosed equivalents of the Sauk and Tippecanoe (included in pЄ-O), and Taconic (Є-Om and Є-Oh) sequences in the vicinity of New York City. Both Cameron's Line (solid traingles) and the Saint Nicholas thrust (open triangles) are shown but brittle faults and intrusive rocks have been omitted. (Adapted from Mose and Merguerian, 1985, fig. 1, p. 21.)

Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. Hall's (1968a, b, c) mapping in White Plains established subdivisions of the

Manhattan Schist into two basic units: (1) the autochthonous Manhattan A, which was originally deposited as part of the Tippecanoe Sequence overlying the basal Tippecanoe limestone that forms the topmost unit of the Inwood marble, and, (2) the allochthonous Manhattan B and C members. Hall (1976) suggested that the Manhattan C (schist) and B (interlayered amphibolite unit) were Early Cambrian (or possibly older) in age, and thus are parts of the Taconic Sequence and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 1, Manhattan A is included in the Tippecanoe Sequence (pꞒ-O) and Manhattan B and C are designated Ꞓ-Om. Merguerian (1983a, 1996) interprets the Manhattan B an C as slope-rise sediments that were deposited continentward of the sedimentary protoliths of the Hartland Formation and are now separated from them by Cameron's Line. Thus, in contrast to Hall's (1976, 1980) views, CM regards the Manhattan B and C and the Hartland as being essentially coeval tectonostratigraphic units.

Strong evidence for three subdivisions and possibly allochthony within the Lower Paleozoic schists exists in New York City (Merguerian 1983b; Mose and Merguerian 1985). On the basis of lithostratigraphic- and structural evidence, most of the exposed schist on Manhattan Island and The Bronx (Figure 2) are interpreted as the metamorphosed part of a transitional slope-rise sequence (Ꞓ-Om) and as the deep-water oceanic Hartland Formation (Ꞓ-Oh), not as the metamorphosed stratigraphically youngest unit, the foreland-basin-filling Tippecanoe Sequence, as was suggested in all "pre-plate tectonics" bedrock interpretations!

Based on his detailed mapping, CM divides the schist on Manhattan Island and The Bronx into three, lithologically distinct, structually imbricated, lithostratigraphic units of kyanite- to sillimanite metamorphic grade that plunge toward the south. (See Figure 2). The structurally lowest unit (Om), crops out in northern Manhattan and the west Bronx (including the new excavation at the New York Botanical Garden). This unit is composed of brown- to rusty-weathering, fine- to medium-textured, typically massive, biotite-plagioclase-quartz-muscovite-garnet-kyanite-sillimanite-garnet schist containing interlayers centimeters- to meters thick of biotite±hornblende+plagioclase+quartz granofels and calcite+diopside+plagioclase+mica marble. *(NOTE - Minerals are listed in order of decreasing relative abundance).* This lower unit is lithologically correlative with the Middle Ordovician Manhattan member A of Hall (1968a) because it "looks like it" and is found interlayered with the underlying Inwood at two localities (1) at Inwood Hill Park and (2) Grand Concourse and I-95, The Bronx. Near the schist-Inwood contact, the carbonate rocks contains layers of calcite marble (probably metamorphosed Balmville, the basal limestone of the Tippecanoe Sequence). Because unit Om is interpreted as being autochthonous (depositionally above the Inwood Marble), we assign it a middle Ordovician age and consider it to be a part of the Tippecanoe Sequence.

The lowest schist unit (=Tippecanoe Sequence) and the Inwood Marble are structurally overlain by the middle schist unit (Ꞓ-Om = Taconic Sequence) a vast structural sheet which forms the bulk of the "schist" exposed on the Island of Manhattan and throughout the west Bronx (including the new excavations at the New York Botanical Garden). The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-textured, massive

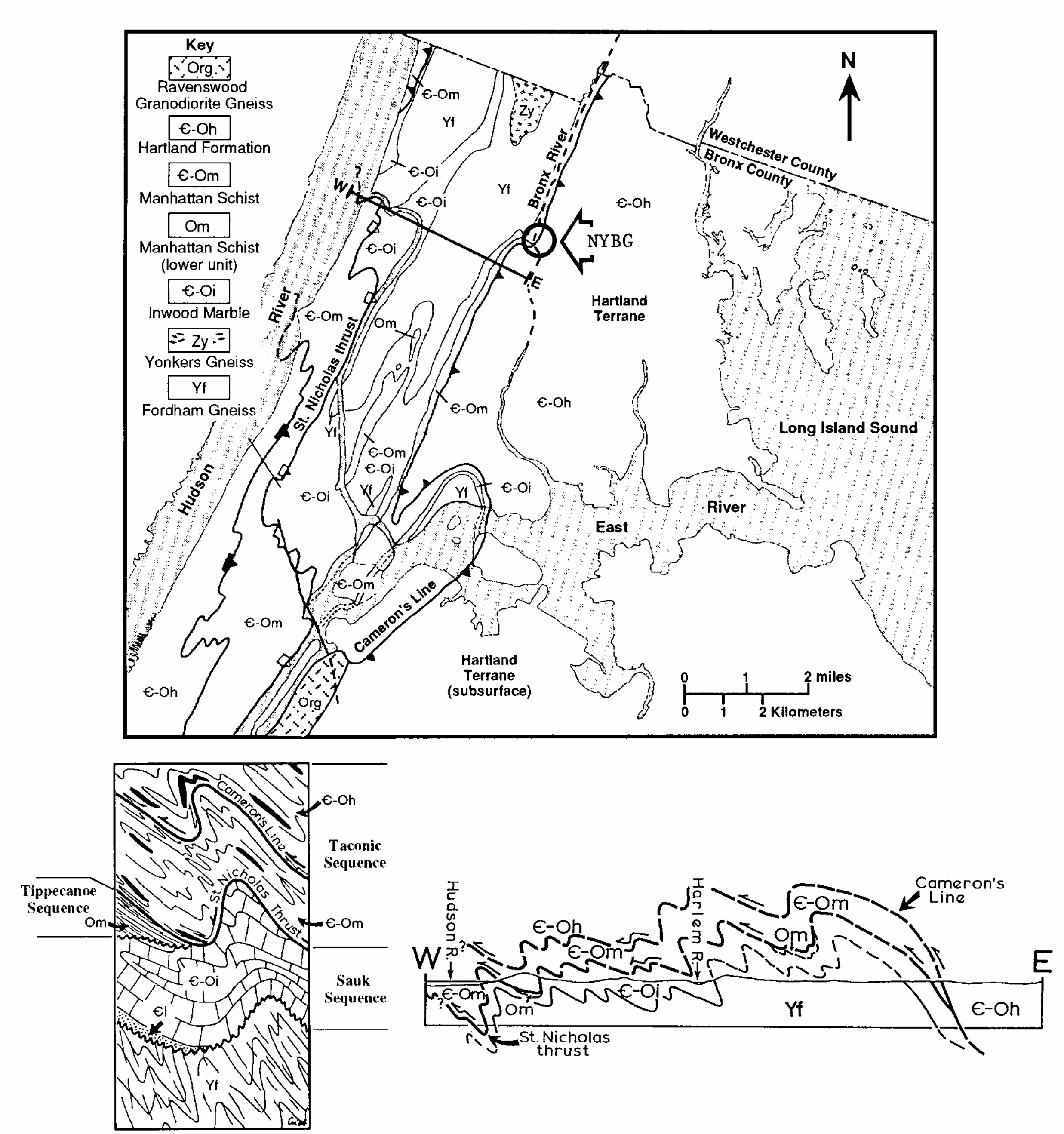

Figure 2 - Geologic map of the south end of the Manhattan Prong showing Cameron's Line, the Saint Nicholas thrust, and bounding metamorphic rock units (as described in text). Inset shows the tectonostratigraphic units of New York City as subdivided into the Sauk, Tippecanoe, and Taconic sequences. Geologic section (keyed to line of section W-E) shows folded Taconian thrusts. The general position of the new excavation at the New York Botanical Gardens (NYBG) is circled.

biotite+quartz+plagioclase+muscovite+garnet+kyanite±sillimanite gneiss and, to a lesser degree, schist. The middle unit is characterized by the presence of kyanite±sillimanite+quartz+magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite, and local quartzose granofels. The middle unit is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Cambrian to Ordovician ages in New England (Hatch and Stanley 1973; Hall 1976; Merguerian 1983a, 1985). These "Taconian" rocks are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks formed in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America.

The structurally highest, uppermost schist unit (Ꞓ-Oh = Taconic Sequence) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and granofels with cm- and m-scale layers of greenish amphibolite $\pm$ garnet and distinctive quartz+garnet+biotite granofels (coticule). The uppermost schist unit, based on Merguerian's study of more than 500 exposures in Manhattan and the Bronx and of a multitude of drill cores and construction excavations, underlies most of the western- and southern third of Manhattan and the eastern half of The Bronx and is lithologically identical to the Cambrian and Ordovican Hartland Formation of western Connecticut and southeastern New York. On this basis, we correlate them with the Hartland and extend the name Hartland into New York City. Accordingly, we infer that together they represent metamorphosed deep-oceanic shales, interstratified graywackes, and volcanic rocks formed adjacent to North America during Early Paleozoic time.

How to sort all this out depends on how one feels about the term "Manhattan Schist." If one adopts the view that the only appropriate basis for continuing to use "Manhattan Schist" is as implied in the original definition (i.e., schists younger than the Inwood Marble and belonging to the Tippecanoe Sequence), then only unit Om merits the designation of "Manhattan Schist." By contrast, if one adheres to the view that all the schists on Manhattan Island are what belong under the term "Manhattan Schist," then continued use of the term "Manhattan" merely serves to perpetuate confusion about the correct ages and structural relationships of the schistose rocks found there. Accordingly, we feel the term "Manhattan Schist" should be discontinued and replaced by three new names: one for the in-situ Tippecanoe-age schists and two others, for the overthrust Taconian schists. You pays your money, and you takes your choice.

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval foreland-basin-fill- (Om), transitional slope/rise- (Ꞓ-Om), and deep-water (Ꞓ-Oh) lithotopes that were juxtaposed when the ancestral North American shelf edge was telescoped in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny. (See geologic section in Figure 2.) Regional correlation suggests, then, that the higher structural slices of the Manhattan Schist are older, or possibly overlap in age with the lower unit (Om). The structural evidence used to define the contacts among the three Manhattan "schists" is described below.

Structural Geology of New York City

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

A ductile shear zone, the Saint Nicholas thrust (open symbol in Figure 2), truncates the base of the middle schist (Ꞓ-Om). This thrust is exposed in Inwood Hill and Isham Parks, in Saint Nicholas Park, and in Mount Morris Park in Manhattan and in Boro Hall Park and in the new excavation in the New York Botanical Garden in The Bronx. The upper schist unit (Ꞓ-Oh) is in ductile-fault contact with the middle schist unit along Cameron's Line (Boro Hall Park exposure in The Bronx and in Manhattan). However, this conclusion is based upon regional stratigraphic evidence; good exposures of Cameron's Line are rare.

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

Although the regional metamorphic grain of the New York City bedrock trends N50°W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25°. (See Figure 2.) 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 and mica overgrowths and annealed mylonitic textures (Merguerian 1988). At least three phases of crenulate- to open folds and numerous brittle faults and joints have been superimposed on the older ductile fabrics. The effects on map contacts of these late features is negligible but the scatter of S_3 is deemed the result of post-D_3 deformation.

New York Botanical Gardens Exposure

In early November 1997, Mr. A. Wayne Cahilly alerted us to the new construction just underway at the New York Botanical Garden (NYBG) Plant Study Center and LuEster T. Mertz Library located immediately north of the existing Museum. On 04 November 1997, we visited the site along with Hofstra University geology major, Mr. Tyrand Fuller. We found about two dozen roughly square 3m-by-3m excavations dug in preparation for reinforced concrete footings for the new building (Figure 3). About a dozen of them were accessible and we were able to map, photograph, and sample the bedrock in detail and take samples which were later thin sectioned. Reconnaissance of all exposed bedrock (along the north edge of the site, freshly blasted bedrock was exposed) enabled us to identify two of the schistose rock sequences we were familiar with in New York City, the **Tippecanoe Sequence** (Unit Om) on the western portion of the site (Stops N540-2B, -3, -4, and -5) and the **Taconic Sequence** (Unit Ꞓ-Om) on the eastern portion of the site (Stops N540-1, -2A, -6, -7, and -8). The field stop numbers are keyed to the site geologic map of Figure 3. Forming the boundary between these units, we identified and sampled distinctive subvertical mylonitic rocks of the Saint Nicholas thrust (SNT) zone (Stops N540-2A and -2B, in particular) which trends roughly N4°E-N12°E through the construction site and shows the effects of F3 folds. (See Figure 3.) Along the eastern wall of the overall excavation, the bedrock was overlain by a brownish till that we sampled for further study (N540-9).

Field Relationships. Within a zone about a 6m wide surrounding the SNT, all rock exposures displayed the megascopic effects of ductile faulting in the form of highly laminated mylonitic textures and an overall reduction of crystal size resulting in predominately dark-colored, fine-textured rocks. Yet, away from the SNT, the rocks showed little obvious textural evidence for mylonitization, an observation borne out by petrographic studies. Within the SNT zone, the rocks are highly laminated, and splintery in appearance; many thin intercalated slices of schistose units Om and Ꞓ-Om, scraps of serpentinized calc-silicate marble, and hornblende+biotite granofels are present. Rocks of unit Ꞓ-Om retain their distinctive massive appearance and exhibit telltale aluminosilicate nodules together with biotite, quartz, magnetite, and large garnet augen and are locally migmatitic, exhibiting the effects of lit-par-lit granitization. By contrast, the rocks of unit Om are slabby in appearance with reddish biotite, plagioclase, and quartz the predominant minerals. Garnet is locally abundant. Local layers and lenses, up to 1 m thick, of pyritiferous calc-silicate calcite marble (= "Balmville") characterize the unit Om. The following paragraphs summarize the results of our petrographic study of eleven samples taken from nine pier sites.

Petrography. Petrographic analysis of rocks indicate the mineralogic distinctions that allow separation of units Om and Ꞓ-Om in the field. Specifically, unit Om is richer in plagioclase and contains red-brown to brown pleochroic biotite. Unit Ꞓ-Om is much richer in quartz than plagioclase and contains typical brown to tan pleochroic biotite. Unit Om contains layers of diopsidic calcite marble and hornblende-biotite granofels, lithologies absent in unit Ꞓ-Om. Garnets are idioblastic to subidioblastic, larger, and more abundant in unit Ꞓ-Om and are smaller, more numerous and subidioblastic to xenoblastic in unit Om. Both units display idioblastic biotite and muscovite and local idioblastic kyanite porphyroblasts as overgrowths on older fabrics, textures formed in response to a post-tectonic regional metamorphic crescendo (Merguerian 1988, 1996). It is this amphibolite facies post-tectonic metamorphic pulse, synchronous with third-generation folds, that resulted in annealing of the former D_2 mylonitic textures formed in response to development of the SNT.

Under the microscope at low magnification both units bounding the SNT show the morphologic effects of mylonitization. At 100X magnification, one could easily overlook these distinctive but somewhat domainal textures. As such, 10X stereoscopic examination of sections on a small polarized light box was found to be most useful as a starting point for detailed

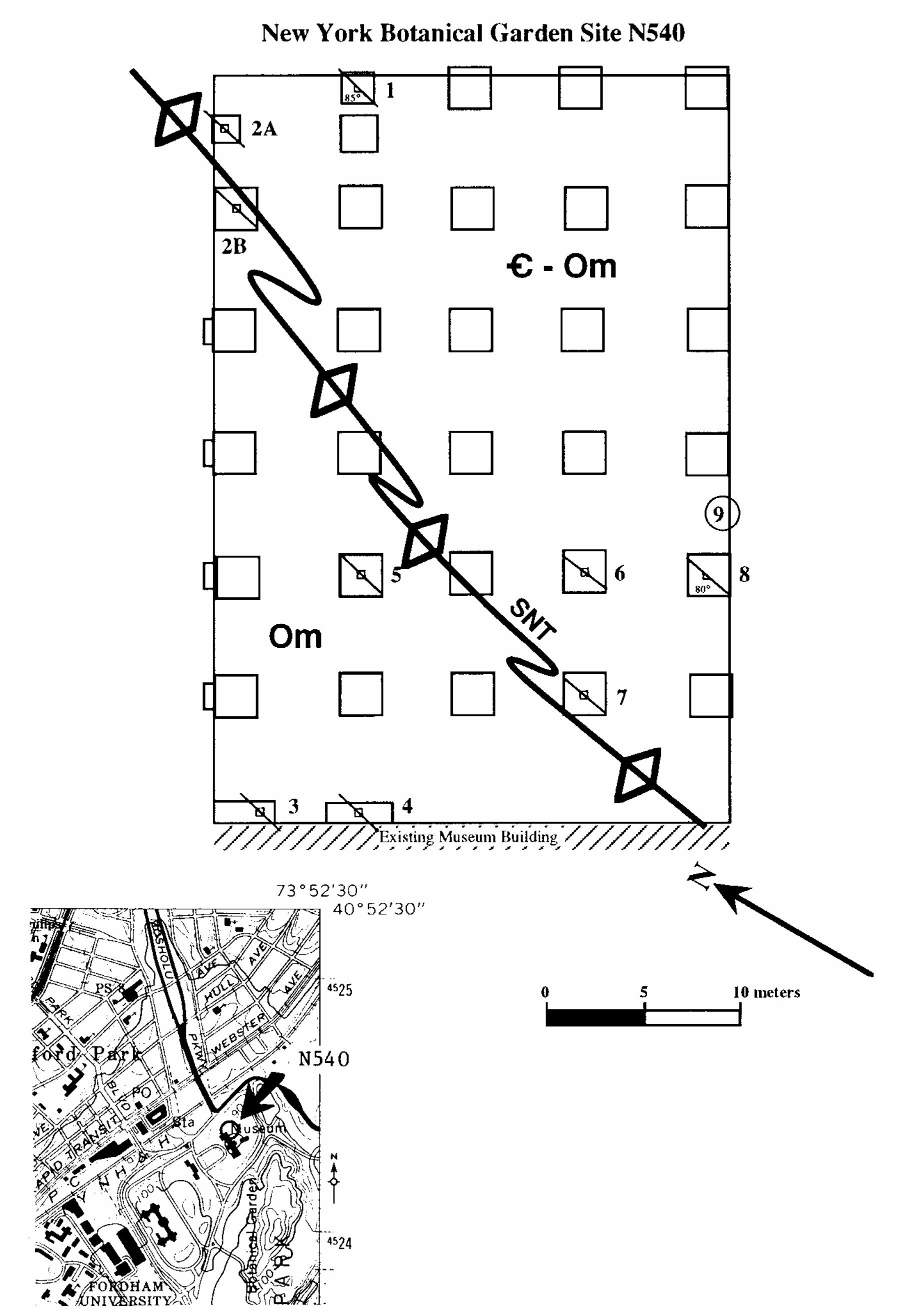

Figure 3 - Geological map of the New York Botanical Garden (NYBG) Plant Study Center and LuEster T. Mertz Library construction site (UTM Grid Coordinates of Site N540 = 594.45E/4524.37N; NE corner of the Central Park quadrangle [inset]) as exposed in November 1997. The Tippecanoe (Om) and Taconic (€-Om) sequences and the folded Saint Nicholas thrust are all exposed within the site. Field stop numbers are keyed to the text.

investigations. The mylonitic textures are characterized by an overall size reduction of all component minerals, strained quartz lentils, and ribbons of polygonized quartz exhibiting sutured boundaries. Micas (particularly biotite) were found to be frayed, shredded, folded and bent; they displayed edge granulation, mica “beards”, and have recrystallized to form a fine-textured penetrative mylonitic foliation. In places, microveins of finely recrystallized biotite have been "intruded" into the quartzose ribbons. This produces a mosaic structure wherein subgrains of quartz have been forcibly separated by through going trains of acicular fine-textured mica.

In calc-silicate layers and lenses of unit Om, serpentinization and replacement of plagioclase to a mosaic of fine white mica are distinctive. Recrystallization resulted in subidioblastic diopside and in sieve-textured, late porphyroblastic crystals of white mica and calcite which overgrows altered plagioclase.

Conclusions

A new excavation in the New York Botanical Gardens has provided petrographic data that corroborate the field identification of mylonitic fabrics at the Saint Nicholas thrust zone. This regionally important Taconian frontal thrust separates the Tippecanoe and Taconic Sequences in the core zone of the Appalachians, as exposed in other parts of New York City. As has been noted elsewhere in the city, the thrust zone is characterized by distinctive mylonitic textures and lithologic differences in rocks on both sides of the SNT. These are the result of intense localized shearing under amphibolite-facies metamorphic conditions.

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