STRATIGRAPHY, STRUCTURAL GEOLOGY, AND DUCTILE- AND BRITTLE FAULTS OF NEW YORK CITY

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INTRODUCTION

Long the center of commerce and culture in the United States, Manhattan is an island around which many geologic units and structural features coalesce. Manhattan's underlying lithology and durable crystalline structure have enabled the construction of enormous towering skyscrapers rooted into glacially-sculpted Paleozoic and older crystalline rock. First studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, the bedrock geology of the New York City area was mapped in systematic detail beginning in the mid- to late 1800's by L. D. Gale, W. W. Mather and F. J. H. Merrill. Merrill, the senior author of the United States Geological Survey New York City Folio (#83) published in 1902, outlined the basic stratigraphic- and structural framework that all succeeding geologists would test, promote, and expound upon.

Today's trip examines the Paleozoic bedrock geology and the ductile- and brittle faults of New York City. The trip consists of seven easily accessible localities ("stops") in Manhattan and the Bronx (Figure 1). All of the outcrop areas are located in public parks or roadcuts which may be easily reached by car, bus, or subway. The seven localities are plotted on segments of the Central Park 7-1/2 minute quadrangle (Figure 2) and UTM grid coordinates are supplied with the stop descriptions. Thus, no detailed road log has been made for this trip. The field-trip stops have been chosen to best identify outcrops critical to my new interpretations of the bedrock geology of New York City, including the results of joint studies with J. E. Sanders that have provided evidence for post-Pleistocene uplift along the footwall of the Mosholu Parkway fault in the Bronx.

GEOLOGIC BACKGROUND

New York City is situated at the extreme southern end of the Manhattan Prong (Figure 3), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terranes of New England. Southward from New York City, the rocks of the Manhattan Prong plunge unconformably beneath predominately buried Mesozoic rocks, Cretaceous sediments, and overlying Pleistocene (glacial) sediments that cap Long Island and Staten Island.

West of Manhattan Island, in New Jersey, a series of gently west-dipping sedimentary rocks of Late Triassic to Early Jurassic ages rests depositionally on the deeply eroded bedrock of Manhattan. As indicated in the west-east cross section from New Jersey to the Bronx (Figure 4), the westward tilted Mesozoic sedimentary rocks of the Newark Basin have been intruded by the Palisades Intrusive Sheet whose tilted and eroded edge forms prominent cliffs along the west margin of the Hudson channel. Joint studies by Merguerian and Sanders (1992a, 1994, 1995a, b, and c) suggest that the Palisades sheet is lopolithic in form with a feeder located near Staten Island and was intruded under relatively shallow (~3-4 km) overburden.
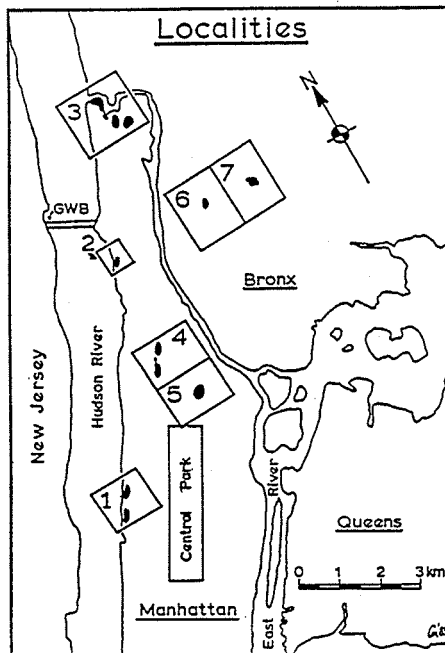
Figure 1 - Locality map of northern Manhattan and adjacent Bronx showing stop-number maps (numbered rectangles), each of which is enlarged on Figure 2.
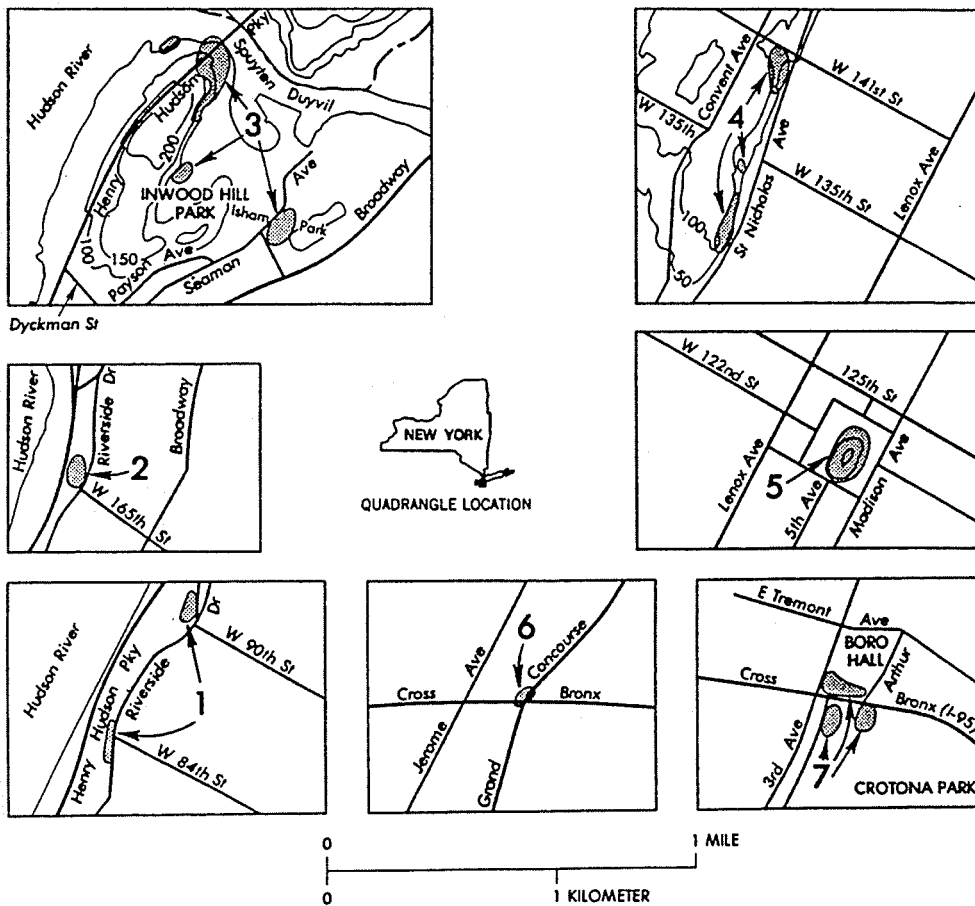

Figure 2 - Outcrop locations for trip stops (shaded areas) shown on segments of Central Park 7.5-minute topogographic quadrangle map of U. S. Geological Survey.

Early Mesozoic and
younger cover rocks

€-Oh Hartland Formation
undivided

€-Om Manhattan Schist
undivided

p€-O Fordham Gneiss+Inwood
Marble+autochthonous
schist (basement+
cover sequence)

Late Proterozoic gneiss
PR=Poundridge Y=Yonkers

p€ Hudson Highlands
Gneiss Complex

Hudson River

Long Island Sound

CONN.
N.Y.

White Plains

New York City

Cameron's Line

€-Oh

€-Om
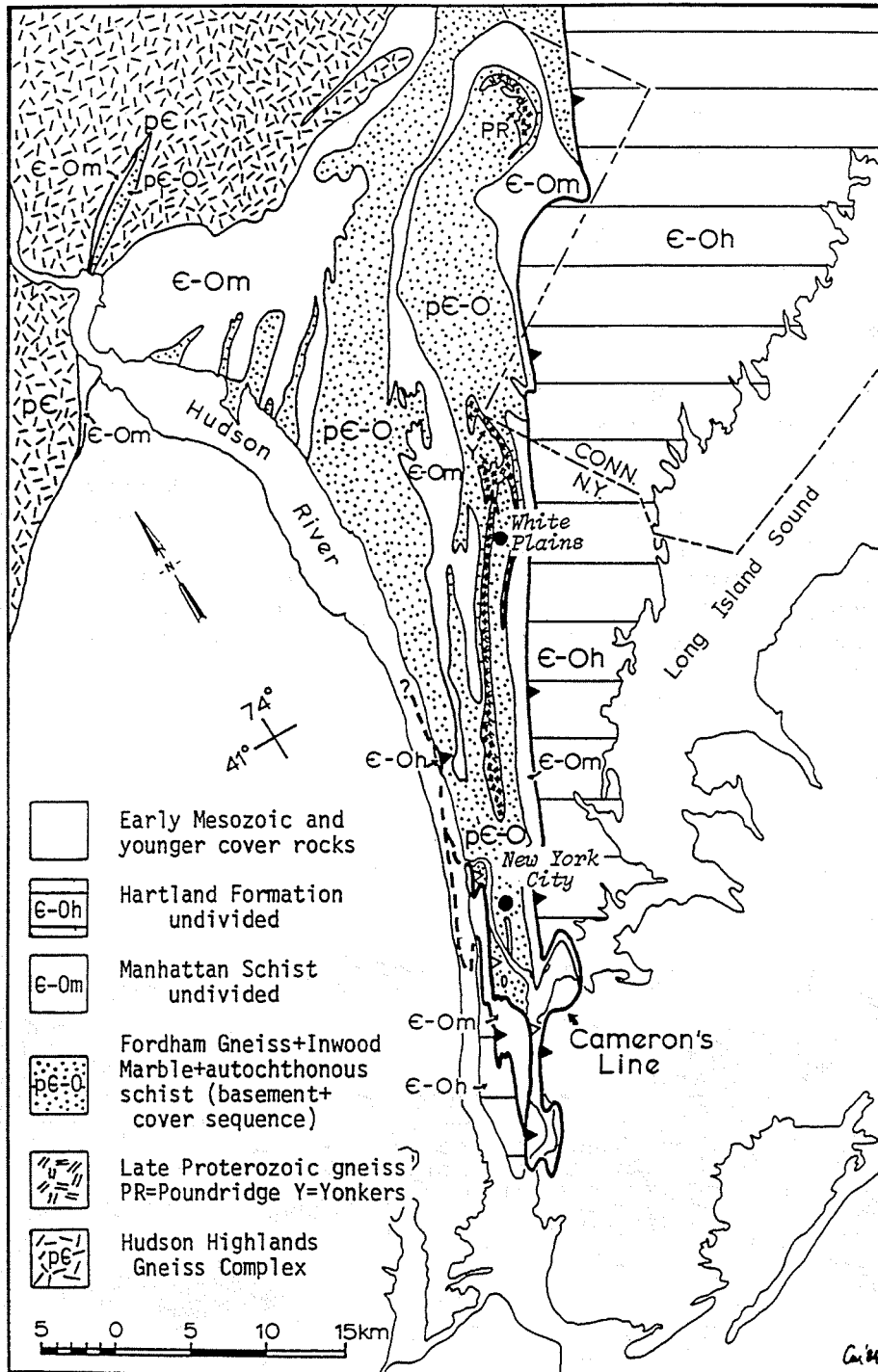
p€-O

PR

5   0   5   10   15km

74°
41°

Figure 3 - Simplified geologic map of the Manhattan Prong showing the distribution of
metamorphic rocks ranging from Proterozoic Y through Early Paleozoic in age. Most faults and
intrusive rocks have been omitted. (Mose and Merguerian, 1985, figure 1, p. 21.)

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STRATIGRAPHY OF THE BEDROCK UNITS OF NEW YORK CITY

History of bedrock geologic investigations. The first geologic map of the New York City area appeared in W. W. Mather's treatise on the Geology of the First District of New York in 1843. Incorporating L. D. Gale's detailed contributions (1839, and in an addenda in Mather (1843)), Mather's map of Manhattan shows the distribution of Primary granite, gneiss, "limestone of New York County", serpentine (on Staten Island), and alluvial sand and marshland. Mather's Plate 3 included two water-colored geologic cross sections that illustrated the structure of New York City in sections parallel- and perpendicular to strike. Issachar Cozzens' (1848) geologic section through Manhattan shows a continuous granite substrate overlain by gneiss, limestone, amphibolite, serpentine, and glacial "diluvial" strata. Before the turn of the century, many geologists were examining the geology of New York City and vicinity as building construction and industrial development grew exponentially. Reports by Merrill (1886a, b; 1890, 1898a, b, and c), Dana (1880, 1881, 1884), Ries (1895), and Kemp (1887, 1895, 1897), provided important information on the bedrock geology of southeastern New York.

In 1890 (p. 390), Merrill named the Manhattan Schists for 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 and others (1902), produced the United States Geological Survey New York City Folio (#83) and following Dana, chose to use the name Hudson (rather than Manhattan) Schist for the schistose rocks of New York City. The *Silurian* Hudson Schist was successively underlain by the *Cambrian to Silurian* Stockbridge dolomite, the *Cambrian* Poughquag quartzite, and finally the *Precambrian* Fordham Gneiss. 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 lithology and structure of New York City bedrock units. A complete literature review appears in Merguerian and Sanders (1991, 1993a, b).
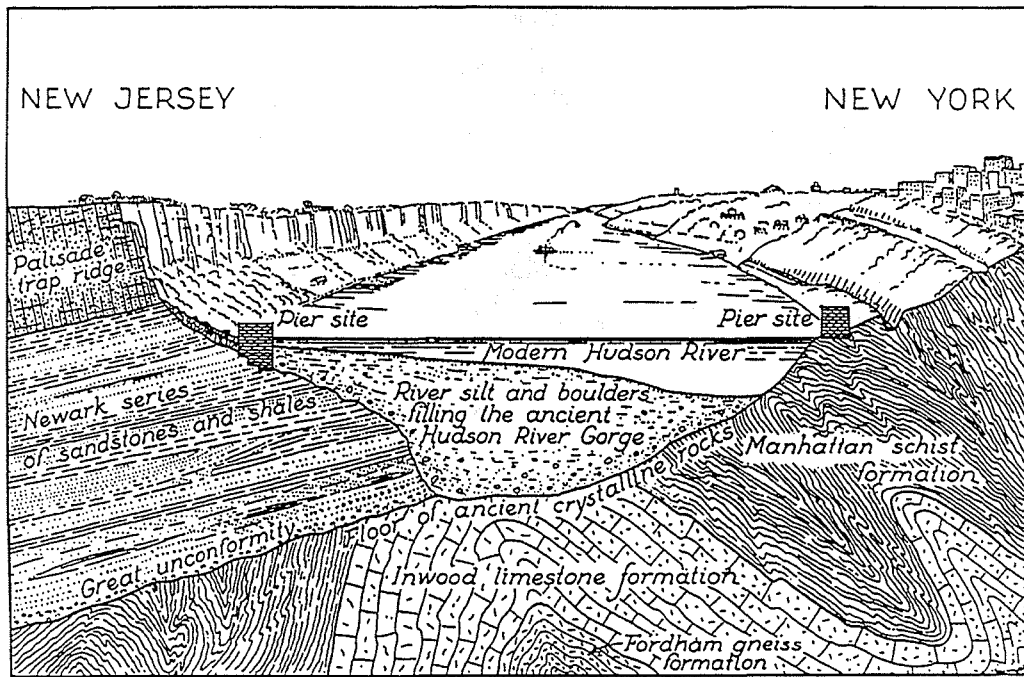

Figure 4 - Interpretive geological section across the Hudson River in the vicinity of the George Washington Bridge. (Berkey, 1948, figure 7, p. 62.)

In 1959, K. E. Lowe edited a series of papers presented at a conference at the New York Academy of Sciences in Manhattan into an annals volume on the geology of New York City (Long, Cobb, and Kulp, 1959; Norton, 1959; and Prucha, 1959). A symposium on the New York City Group of Formations, held at a 1968 meeting of the New York State Geological Association at Queens College, New York, provided discussion for papers by Bowes and Langer (1969), Hall (1968a, b), Paige (1956), Ratcliffe (1968), Ratcliffe and Knowles (1969), and Seyfert and Leveson (1969). Formal "de-Grouping" of the New York City Group of Formations resulted from Leo M. Hall's identification of truncation of subunits of the Fordham Gneiss beneath various members of the Inwood Marble in the Glenville area of Westchester County. Later, a U-Pb age determination by Grauert and Hall (1973) yielded a 1.1 Ga (Proterozoic Y) age for the Fordham gneiss, verifying the field results. The combination of isotopic- and paleontologic evidence proved the Early Paleozoic age of the Inwood Marble. Based on superposition, the Manhattan Schist was considered **younger** than the Inwood but pre-Silurian based on regional relationships and the late medial Ordovician age of the Taconic unconformity.

Based on his work in the Glenville area of Westchester County, Hall (1968a, b, c), proposed subdivisions of the Manhattan Schist into lithically variable members (designated by letters A, B, and C). In Hall's view, the autochthonous Manhattan A, was originally deposited above the Inwood marble and the allochthonous Manhattan B and C (an interlayered amphibolite unit) members were correlated with Cambrian rocks of the Taconic allochthon of eastern New York State. Later, Hall (1976, 1980) suggested that the Manhattan B and C were Early Cambrian (or possibly older) in age, part of the eugeosyncline and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 3, Hall's Manhattan A is included in the basement-cover sequence (p€ - O) and Manhattan B and C are designated € - Om. Merguerian (1983a, b; 1986a, b; 1995) has interpreted the Manhattan B an C as a slope-rise-facies that was formerly deposited continentward of the Hartland Formation and now separated from the Hartland by Cameron's Line. Thus, in contrast to Hall's views, Merguerian interpreted the Manhattan B and C and the Hartland as essentially coeval tectonostratigraphic units, and both a part of the **Taconic Sequence**.

In addition to those cited above, studies by Baskerville (1982a, b; 1989a, b; 1992), Merguerian (1994, 1995, 1996a, b, c), Baskerville and Mose (1989), Merguerian and Baskerville (1987), Merguerian and Sanders (1996a, b), Mose and Merguerian (1985), and Taterka (1987), have demonstrated the extreme stratigraphic- and structural complexity of the Manhattan Prong in New York City. Rather significant differences in stratigraphic- and structural interpretation can be found among these studies.

Sequence Stratigraphy of the New England Appalachians. The Lower Paleozoic strata of what is now the Northern Appalachians accumulated along an ancient passive continental margin. During the Cambrian and Ordovician periods, North America lay astride the Earth's Equator; what is now the eastern part of the continent lay in the Southern Hemisphere tropics. The interior of the continent lay to the north, and an open ocean, to the south. Tropical conditions prevailed throughout the time period and a vast sequence of quartzose sands followed by calcareous sediment was deposited above an eroded- and submerged Proterozoic (Grenville) basement complex. The Cambrian- to Ordovician clastics+carbonate passive-continental-margin sequence is known as the **Sauk Sequence** following Sloss (1963), parts of which thinned outward into the NYC area as the protoliths of the Lowerre Quartzite and Inwood Marble Formations.

Starting in the mid-Ordovician, lithospheric plate convergence brought to an end the passive-margin regime that had prevailed since early in the Cambrian Period. An initial, and particularly conspicuous, product of this episode of plate convergence was the appearance of the Northern Appalachian foreland basin. This basin, which developed with unconformity atop the **Sauk Sequence**, saw the influx of deep-water pelitic sediments and intercalated turbidites. This basin, whose origin has been ascribed to the isostatic effects of thrust loading (Quinlan and

Beaumont, 1984) appeared **after** the demise of the carbonate shelf. In New York and adjacent areas, this mid-Ordovician flysch (known as the Normanskill, Walloomsac, Annsville, and Martinsburg formations) constitutes the **Tippecanoe Sequence.**

The original basis for recognizing Taconian thrusting was the juxtaposition of two suites of Lower Paleozoic strata deposited in contrasting paleogeographic settings. One of these suites consists of **Sauk** carbonate rocks. The other is composed of pelitic rocks, deposited beyond the former shelf edge, subsesquently interpreted as being products of deposition on a continental rise and generally referred to informally as the **Taconic Sequence.** During the Taconic Orogeny, within the Northern Appalachian foreland basin, both the **Sauk** and **Tippecanoe** sequences became imbricated by low-angle thrusts and older, deeper-water pelites of the **Taconic Sequence** were emplaced above them.

Bedrock stratigraphy of New York City. Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. My field- and laboratory investigations of the bedrock geology in NYC since 1972, based on study of over 500 natural exposures and a multitude of drill cores and construction excavations, define a complex structural history and suggests that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, mappable tectonostratigraphic units. My subdivisions agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-unrecognized, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian, 1981, 1983a, 1985, 1987).

The bedrock stratigraphy of NYC is best explained in the context of sequence stratigraphy. The bedrock underlying Manhattan and the Bronx includes, from the base upward, the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose rocks formally lumped together as the Manhattan Schist. As a result of construction as well as of its very local deposition, the Lowerre is no longer exposed on the surface and the underlying Proterozoic Z Ned Mountain Formation of Brock (1989, 1993) has not been recognized. Metamorphosed miogeosynclinal representatives of the **Sauk Sequence** (including the Inwood Marble ($\mathcal{C}$ - Oi) and the Manhattan Schist (Om) and their Proterozoic cratonic basement rocks occur west of Cameron's Line, a major tectonic boundary in New England. Together, they constitute the autochthonous miogeosynclinal basement-cover sequence of the New England Appalachians (p$\mathcal{C}$ - O in Figure 3) and thus represent metamorphosed sedimentary rocks formerly deposited on crystalline Proterozoic crust (Merguerian and Sanders, 1996a).

Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Rodgers and others 1959, Merguerian 1977, 1985) or the Hutchinson River Group (Seyfert and Leveson 1969, Baskerville 1982a). In contrast to the basement-cover sequence, the Hartland Formation (or **Taconic Sequence**) consists of aluminous schists, granofels, and metavolcanic rocks formerly deposited on oceanic crust ($\mathcal{C}$ - Oh in Figure 3) which became accreted to North America during the Medial Ordovician Taconic orogeny (Hall, 1980; Merguerian 1983b; Merguerian and others, 1984; Robinson and Hall, 1980). Other schistose rocks ($\mathcal{C}$ - Om in Figure 3), originally mapped as the Manhattan Schist and found west of Cameron's Line, are here also interpreted as a part of the **Taconic Sequence** as described below.

Will the Real Manhattan Schist Please Stand Up!. Based on detailed mapping in NYC (Figure 5), Merrill's Manhattan Schist has been subdivided into three roughly coeval, structurally complex, ductile-fault bounded, tectonostratigraphic units of kyanite- to sillimanite grade (Merguerian and Baskerville, 1987; Merguerian and Sanders 1996a).

The structurally lowest unit (**Om = Tippecanoe Sequence**) and crops out in northern Manhattan and the west Bronx. (See Figure 5.) This unit is composed of brown-to rusty-

weathering, fine- to medium-grained, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist containing interlayers centimeters to meters thick of calcite+diopside marble (minerals are listed in decreasing order of abundance). The lower unit is lithically correlative with the Middle Ordovician Manhattan member A of Hall (1968a) because it is a direct lithostratigraphic correlative and is found interlayered with the underlying Inwood at two (possibly three) localities (Stops 3, 5?, and 6), often containing interlayers of calcite ("Balmville") marble near its base. Because it is interpreted as being autochthonous (depositionally above the Inwood Marble), Merguerian informally refers to it as "the Good-Old Manhattan Schist" and has assigned a middle Ordovician age.
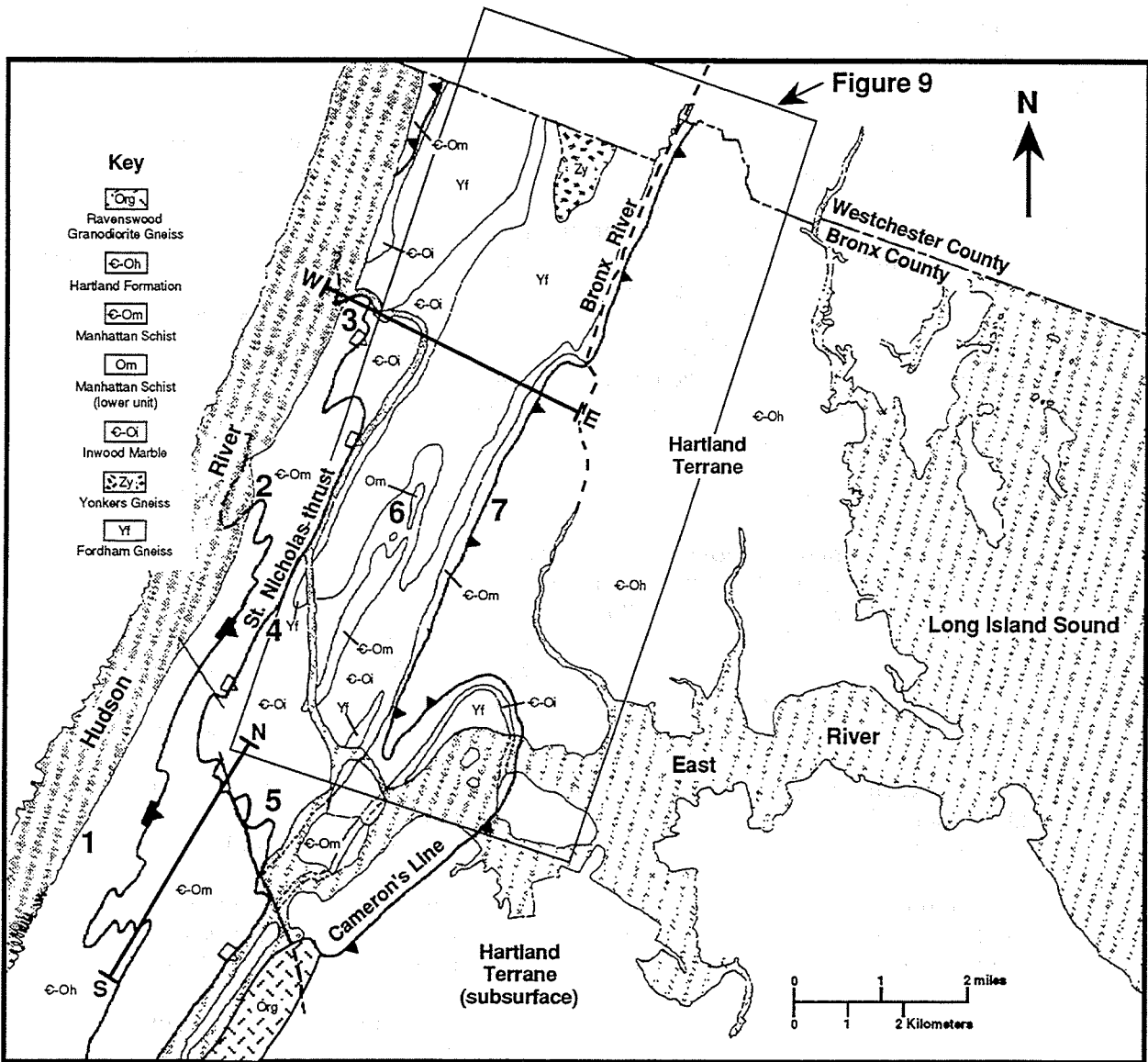

Figure 5 - Geologic map of south end of Manhattan Prong showing Cameron's Line, the St. Nicholas thrust, the Hartland Terrane, and the Ravenswood Granodiorite (Org). Rectangle shows location of Figure 9. Geologic section lines are keyed to Figure 7. The seven field-trip stops are indicated by arabic numerals. (Adapted from Merguerian and Baskerville, 1987, fig. 3, p. 139.)

The lower Manhattan schist unit and the Inwood Marble (**Tippecanoe and Sauk, respectively**) are structurally overlain by the middle Manhattan schist unit (Є - **Om**) which forms the bulk of the "schist" exposed on the Island of Manhattan (Stops 3, 4, 5, 7, and most northern Central Park exposures). (See Figures 1, 2, 5.) The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-grained, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The middle schist unit is characterized by the presence of layers and lenses of kyanite±sillimanite+quartz+ magnetite up to 10 cm thick, cm-to m-scale layers of blackish amphibolite, and subordinate 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 (Hall, 1976; Merguerian, 1983a, 1985). These rocks, which contain calc-silicate interlayers in western Connecticut (Merguerian, 1977) are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America, and are thus considered a part of the **Taconic Sequence.**

The structurally highest, upper schist unit (Є - **Oh**) is dominantly gray-weathering, fine- to coarse-grained, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and thin- to massive granofels and coticule, with cm- and m-scale layers of greenish amphibolite±garnet (Stops 1, 2, 3?, 7 and most construction exposures south of Central Park). Together they represent metamorphosed deep-oceanic shales, interstratified lithic sandstones, chert, and volcanic rocks, all a part of the deep-water facies of the **Taconic Sequence.** The upper schist unit, which underlies most of the western edge and southern half of Manhattan and the eastern Bronx, is lithologically identical to the Cambrian and Ordovican Hartland Formation (Rowe, Moretown, Hawley belt) of western Connecticut and Massachusetts. On this basis, they are considered correlative and, in my opinion, extension of the Hartland Terrane into New York City and southeastern New York is a stratigraphic necessity. (See Figure 3.)

Most of the exposed schist on Manhattan Island can be interpreted as part of a transitional slope-rise sequence (Є - Om) and as the eugeosynclinal deep-water oceanic Hartland Formation (Є - Oh), both a part of the **Taconic Sequence.** Thus, two out of three "Manhattan" schist units, which have been historically lumped together as the Manhattan Schist Formation, need to be seperated from in-situ **Tippecanoe** Manhattan (Om), which is found only locally interlayered with the Inwood Marble. The "good old Manhattan Schist" (Om) is the metamorphosed equivalent of the foreland-basin-filling Normanskill or Walloomsac strata (i. e., that part whose protoliths belong to the **Tippecanoe Sequence,** and were deposited unconformably above the basal Tippecanoe limestones), whereas the overlying schistose rocks are the metamorphosed equivalent of two parts of the **Taconic Sequence** [= the Waramaug (Hoosac) formation (Є - Om) and Hartland Terrane (Є - Oh)], whose protoliths are basically coeval with the Inwood Marble and owe their structural positions above the marble (and also above unit Om of the Manhattan Schist) to displacement along two ductile thrusts (the St. Nicholas thrust and the Cameron's Line thrust).

The Taconic problem in New York City focuses on ductile-fault imbrication of these three amphibolite-grade rock sequences. The St. Nicholas thrust (Taconic frontal thrust) separates lower-plate **Tippecanoe** (Om) and **Sauk** (Є - Oi) rocks from upper-plate gneiss, schist, and amphibolite of the former Cambro-Ordovician slope- and rise (Manhattan Formation; Є - Om). The structurally higher ductile fault known as Cameron's Line, juxtaposes muscovite-rich schist and gneiss, amphibolite, serpentinite, and coticule of a former deep-water realm (Hartland Terrane; Є - Oh) with Є - Om rocks. Combined as the Manhattan Schist Formation by past workers, the subunits Є - Om and Є - Oh are here considered to be allochthonous, ductile-fault-bounded facies of the **Taconic Sequence.**

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 fold phases (D_4-D_{6+}). The synmetamorphic juxtaposition of the various schist units occurred very early in their structural history (D_2) based upon field relationships. The base of the middle schist (€- Om) is truncated by a ductile shear zone, named the St. Nicholas thrust (open symbol in Figure 5). The thrust is exposed at or near Stops 3, 4, and 5. The Hartland (€- Oh) is in probable ductile fault contact with the middle schist unit along Cameron's Line (closed symbol in Figure 5) in the Bronx (Stop 7) and in Manhattan (at Stop 2 and also in Central Park [See Merguerian and Sanders, 1993a, Stop 5]).

Initial deformation and metamorphism of bedrock units occurred during two progressive stages of prograde amphibolite- facies ductile deformation accompanied by isoclinal- and shear folding (F_1 + F_2). The F_1 folds are inferred from a locally preserved S_1 foliation (and parallel S_0 layering) which is truncated by zones of D_2 mylonite. Early metamorphism up to garnet-sillimanite grade is overprinted by metamorphism in the kyanite-staurolite-garnet zone. The two Taconian terrane boundaries (the St. Nicholas thrust and Cameron's Line) now occur as steeply oriented, complexly folded, migmatized zones of commingled mylonitic rocks. Formed at the culmination of D_2, a highly laminated S_2 mylonitic texture formed in the thrust zones producing mylonitic layering, frayed and rotated mica- and feldspar porphyroclasts, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 isoclinal- and shear folds.

During D_2, the bounding lithologies acquired a penetrative foliation (S_2), growth of kyanite, staurolite, and garnet porphyroblasts (which enclose early stage sillimanite) and growth of distinctive lenses and layers of quartz and kyanite+quartz+magnetite (up to 10 cm thick). The quartzose and aluminosilicate lenses and layers formed axial planar to F_2 folds which regionally deformed the bedrock into a large-scale recumbent structure that strikes N50°W and dips 25°SW. Stereograms (Figure 6) show the distribution of 245 poles to S_2, F_2 fold axes and L_2 lineations as measured in the field.

Although the regional S_2 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 Figures 5 and 6.) 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 annealed mylonitic textures (Merguerian, 1988). Stereograms (Figure 6) show the distribution of 238 poles to S_3, F_3 fold axes and L_3 lineations as measured in the field. Note the great-circle distribution of poles to S_2 and how the pole to that great circle corresponds to the concentration of F_3 axes.

At least three phases of open- to crenulate folds and numerous brittle faults and joints are superimposed on the older ductile fabrics. 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 deemed the result of post-D_3 deformation. Retrograde metamorphism and production of muscovite pseudomorphs after kyanite were formed during one or more of these later episodes.
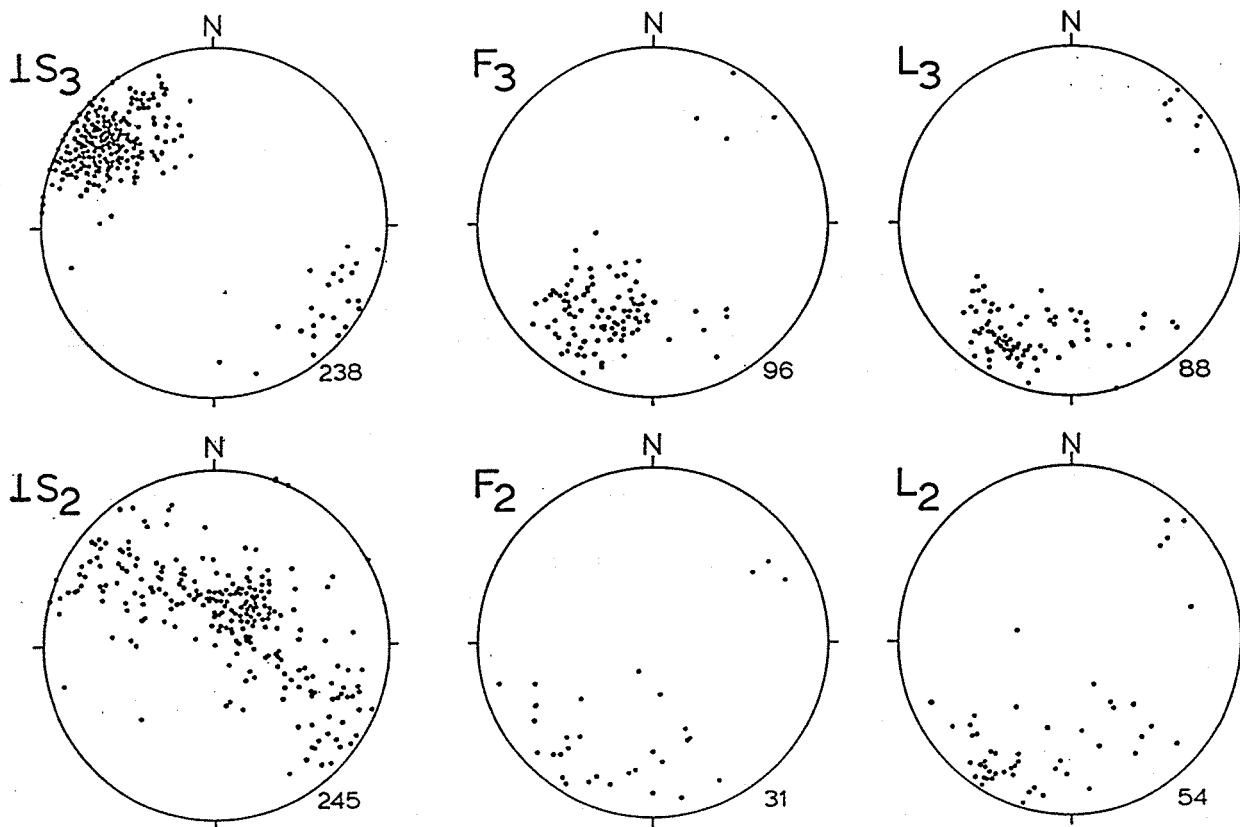
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Figure 6 - Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Merguerian and Sanders, 1991, fig. 26, p. 113.)

Structure Sections. The localities described below offer critical evidence for new structural interpretations of the Paleozoic schists exposed in New York City. Figure 7 presents simplified W-E and N-S structure sections across the New York City area. Keyed to Figure 5, the sections illustrate the complex structural- and stratigraphic interpretation that has emerged over the years. The W-E section shows the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward topping of lithostratigraphic units exposed in central Manhattan and the effects of the late NW-trending upright folds.

Ductile Faults. Synchronous with D_2, foliated rocks of the Sauk, Tippecanoe, and Taconic sequences were imbricated along two major syntectonic ductile thrust faults (Cameron's Line and the St. Nicholas thrust), and intruded by late-syntectonic calc-alkaline plutons (now orthogneisses such as the Ravenswood Granodiorite Gneiss of Zeigler (1911) and the Brooklyn Injection Gneiss of Berkey (1933, 1948) and Blank (1973). These metaplutonic rocks vary from granitoids through diorite and lesser gabbro and are typically foliated indicating a relatively early intrusion age with respect to structural deformation and regional shearing. Isotopic dating of crosscutting igneous rocks along the length of Cameron's Line indicate a pre-late Ordovician age for development of the mylonitic fabrics (Amenta and Mose, 1985; Merguerian and others, 1984; Baskerville and Mose, 1989).
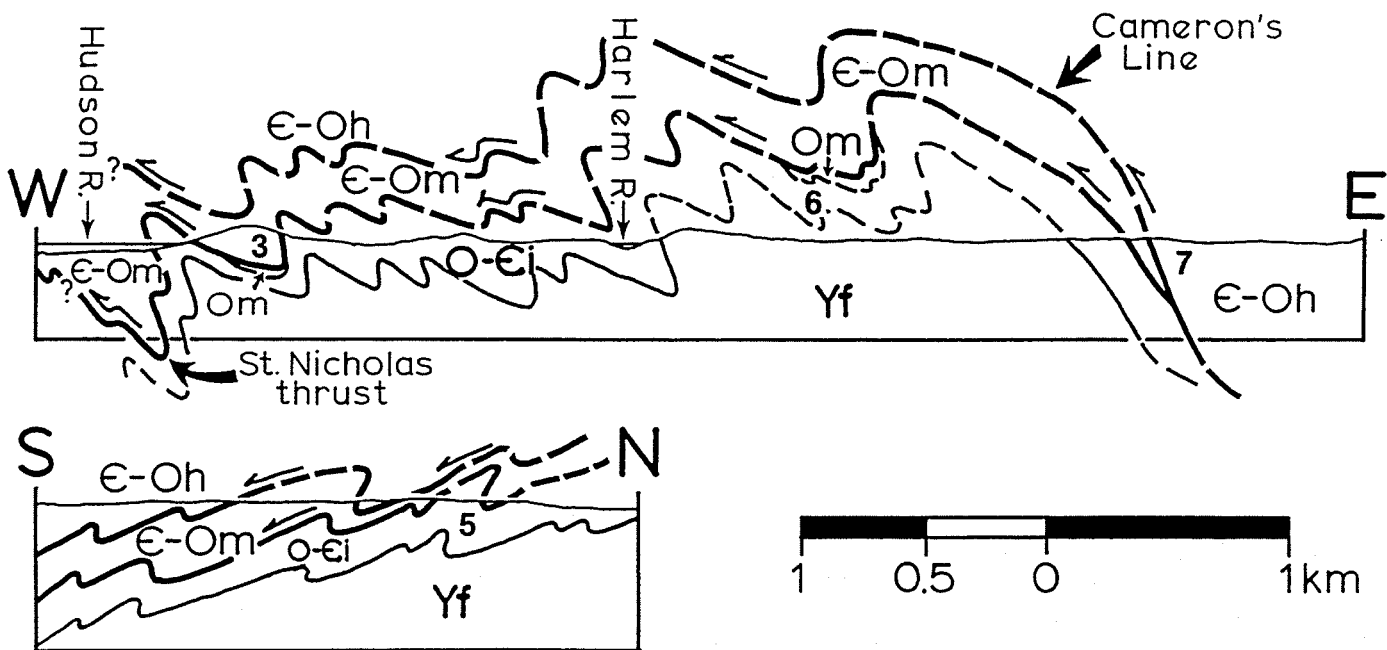
Figure 7 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). Symbols defined on Figure 5. Some field-trip stops are indicated by arabic numerals. (Merguerian and Sanders, 1991, fig. 27, p. 114.)

BRITTLE FAULTS AND SEISMICITY

Geologists and seismologists generally agree that earthquakes produce dislocations known as faults and that preexisting faults tend to localize new earthquakes. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of brittle faults which belong to two contrasting sets oriented NE and NW. These faults cut the New York City area into large fault-bounded blocks. A serious bone of contention among seismologists and geologists revolves around a perceived lack of evidence that surface ground breaks have accompanied historic earthquakes. Many seismologists argue that the bedrock faults that structural geologists map in the field experienced offset at great depth with **no surface connection** and that uplift and erosion have unroofed these structures. Research on the diversion of the Bronx River by Merguerian and Sanders (1996b), summarized below, provides the first demonstration of surface deformation in response to fault motion in geologically recent time.

Two contrasting, near-orthogonal brittle-fault sets cut the isoclinally folded imbricate ductile thrusts (Cameron's Line and the St. Nicholas thrust) and intervening amphibolite-facies metamorphic rocks of New York City. Figure 8A, a stereonet of poles to 118 surface faults, shows a bimodal distribution of moderate- to steep faults although a scattering of gently dipping faults exists. This field evidence and existing subsurface data indicate that the trends of these sets are: 1) approximately N30°E (roughly parallel to the overall trend of lithologic units and the axis of Manhattan Island), and, 2) approximately N45°W (across the NE trend, roughly parallel to the N50°W average S_2 axial surface of the F_2 folds). The trends of brittle faults in the vicinity of New York City are the products of emphatic structural control, as summarized below.
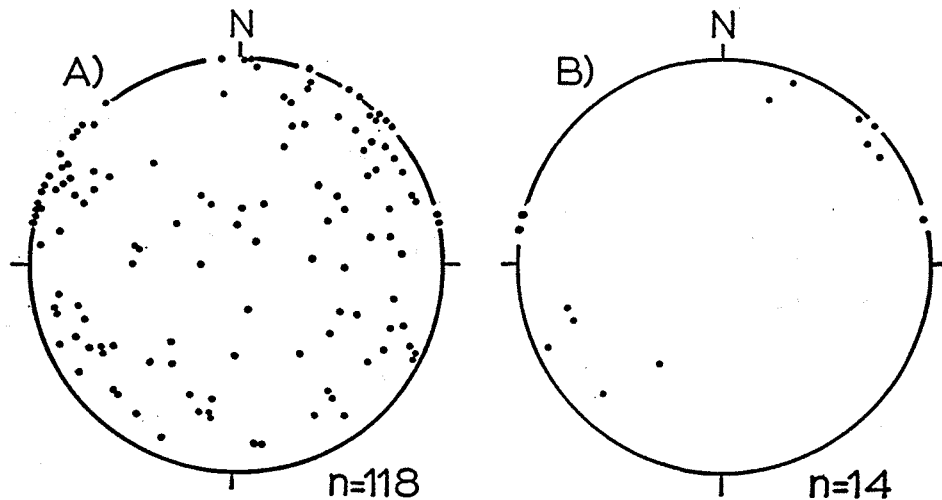
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A) N

B) N

n=118

n=14

Figure 8 - Equal-area stereonets showing poles to mapped surface faults. Northern half of net used for poles to vertical faults.

A) Poles to 118 faults showing bimodal distribution of NE- and NW-trending fault sets. The dips of the NE-trending set (average trend of N30°E, essentially parallel to the long axis of Manhattan) are steep to moderate. The dips of the NW-trending set (average trend of N45°W) are also steep to moderate.

B) Poles to 14 strike-slip faults with a dominantly NW trend.

NE-trending faults. The NE-trending faults dip steeply to moderately and show dominantly dip-slip motion with offset up to 1 m in zones up to 2 m thick. Locally, where they parallel NE-oriented mylonites (Cameron's Line and the St. Nicholas thrusts), they are found to be cataclastic with greenish clay-, calcite-, and zeolite-rich gouge up to 30 cm thick. Invariably, where the ductile faults are oriented northeasterly, they have been reactivated by brittle faults and marked by fresh clay-rich gouge. Elsewhere, the NE-trending faults have commonly been healed by quartz, calcite, or zeolite minerals. Typically, the NE-trending faults are developed parallel to and commonly disrupt an S_3 transposition foliation or spaced schistosity and/or transposed compositional layering and foliation(s) ($S_0 + S_1 + S_2$).

NW-trending faults. The NW-trending faults (See Figure 5 and Lobeck, 1939, figure on p. 568.) also dip steeply to moderately and show complex movement histories dominated both by left- and right-lateral oblique-slip offset often followed by secondary dip-slip or oblique-slip reactivation. The NW-trending faults contain zeolites, calcite, graphite, and sulfides. Composite offsets along the left-lateral faults average a few cm to more than 35 cm but local offset along the right-lateral faults (such as the 125th Street and Mosholu Parkway faults) exceeds 200 meters in brecciated zones. The famous 14th Street fault controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan south of 23rd Street and north of Canal Street. Figure 8B shows the poles to 14 strike-slip faults. Of these, 80% were left-lateral and 20% were right-lateral, with the latter producing map-scale offset of mapped contacts.

Based on geometric relationships and superimposed slickensides, the movement histories of the northwest-trending faults are typically more complex than those of NE trend. A case in point was observed in the water tunnel beneath the east channel of the East River where a NW-trending, steep NE-dipping left-lateral strike-slip fault bearing sub-horizontal slickensides, showed overprint by N- to NE- plunging slickensides indicating a change from strike-slip to oblique-normal slip movement.

The New York City Water Tunnel #3 cuts through the 125th Street fault beneath Amsterdam Avenue in Manhattan. Here, in an abrupt zone of highly fractured Manhattan Schist 40 m wide, the 125th Street fault dips 55° to 75° SW and cuts orthogonally across the tunnel line and the steeply dipping foliation in the schist. In the overhead roof of the tunnel, 2 to 3 m blocks of the Manhattan, which remained internally coherent within the broad zone of cataclastic rock, showed up to 90° of rotation about a vertical axis. Clearly, this observation indicates that along the 125th Street 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.

The NW-trending faults are structurally controlled by an anisotropy produced by A-C joints related to southward-plunging F3 folds and/or by the NW-trending S_1+S_2 regional metamorphic fabric of the bedrock. Thus, the intersection of these two important sets has cut NYC into large, fault-bounded blocks. Of the two, the NW-trending faults show the greatest composite offset but both fault sets are found to cut each other, suggesting that they both harbor potential seismic activity.

DIVERSION OF THE BRONX RIVER IN NEW YORK CITY - EVIDENCE FOR POSTGLACIAL SURFACE FAULTING?

North of the New York Botanical Garden, near the Mosholu Parkway in the Bronx (Figure 9), the NW-SE-trending Mosholu Parkway fault offsets the Bronx River valley (a NNE-SSW-trending strike-valley lowland underlain by the Inwood Marble) from the Webster Avenue lowland (another NNE-SSW valley also underlain by the Inwood Marble). Just at the point of offset of the marble lowland, the Bronx River has abandoned its former wide NNE-SSW-trending strike-valley lowland and currently occupies a narrow N-S-trending gorge, here named the Snuff Mill gorge, cut across the more-resistant Hartland Formation.

Joint studies by Merguerian and Sanders (1996b) suggest that this first-order drainage anomaly was prompted by a blockage induced by postglacial elevation of a bedrock barrier (E. 204th Street Bulge of Figure 9) immediately north of and adjacent to the NW-trending Mosholu Parkway fault. This uplift blocked the marble lowland, dammed the Bronx River, and thus caused a lake to form upstream from the present site of the Mosholu Parkway. Water spilling out of this lake to the south, possibly reoccupying the beginnings of a valley that had been eroded during earlier ice blockage of the Webster Avenue lowland, eroded the N-S-trending Snuff Mill gorge in the New York Botanical Garden, where the Bronx River crosses the Hartland Terrane. Figure 9 shows subsurface contours on the bedrock surface. Note that the Webster Avenue valley is youthful with a narrow, V-shaped profile.

Our studies of subsurface boring records and field examination indicates that the Mosholu Parkway fault is a NW-trending right-lateral oblique-slip fault that projects across the Bronx River channel immmediately below the area (near Webster Avenue and E. 203rd Street in the Bronx) where the Bronx River departs from its previous NNE-SSW-oriented channel and N-S-directed flow begins. (See Figure 9.) A NW-trending bedrock high exists at this point as shown by depth-to-bedrock profiles, topographic maps, and surface exposures. The long axis of this basement high (E. 204th Street Bulge) parallels the Mosholu Parkway fault and may, in fact, have been caused by motion along the footwall of the fault. We've proposed that the northern segment may have moved upward in response to normal oblique-slip motion. Such motion would be identical in orientation and magnitude to offset noted for the subparallel 125th Street fault in Manhattan. In support of post-glacial motion, a broad U-shaped valley, similar to that found along the 125th Street fault in Manhattan, does not exist along the Mosholu Parkway fault.
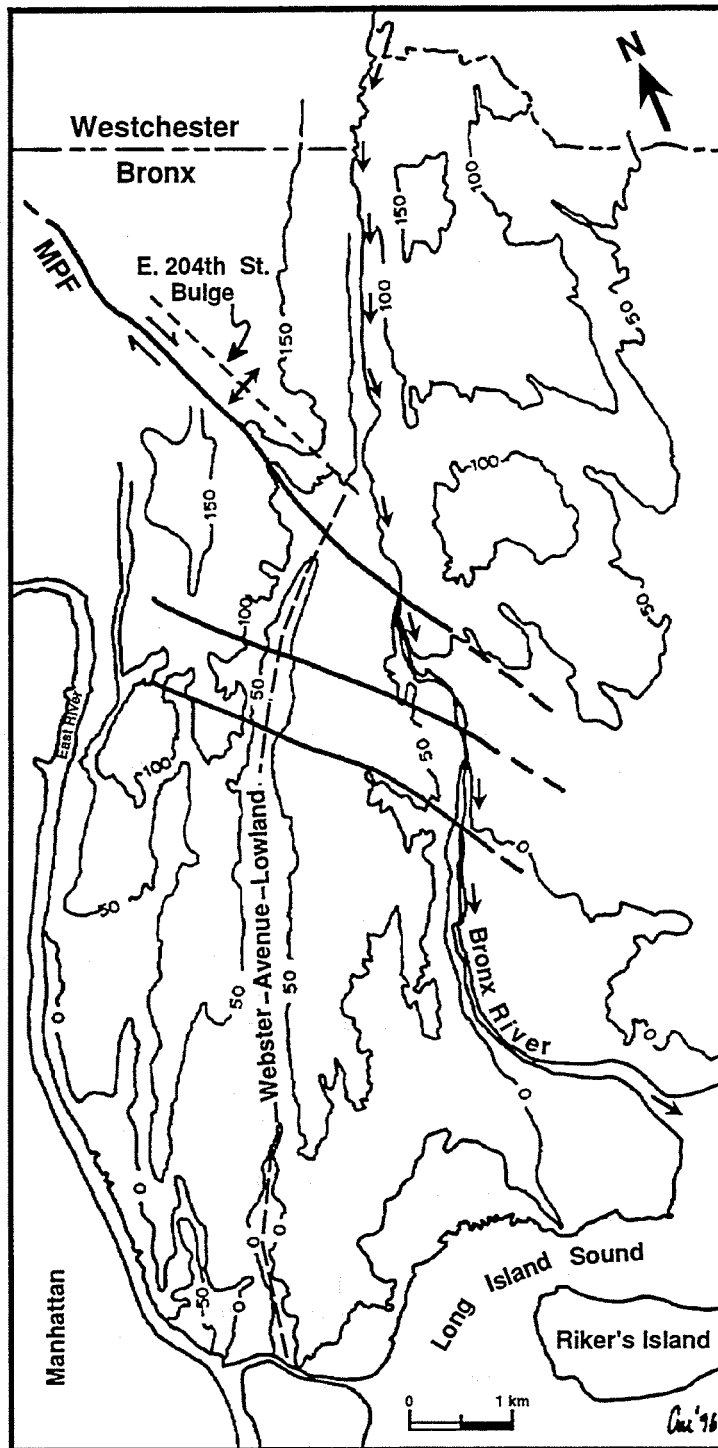
Figure 9 - Index- and bedrock-contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including the Mosholu Parkway fault (MPF), and the 204th Street Bulge. The Webster Avenue Lowland marks the previous course of the Bronx River. Subsurface- and fault data from Baskerville (1992), engineering records of the New York City Subsurface Exploration Section, Hofstra University's Metropolitan New York Drill Core Collection. (Merguerian and Sanders, 1996b, fig. 4, p. 138.)

A postglacial age of diversion is further demonstrated by the absence of glacial polishing and -striae on the jagged walls of the Snuff Mill gorge and by a subsurface unit of clay (lake deposits) that overlies a probable till (glacial deposits) detected north of the bedrock barrier. Significantly, if this explanation for diversion is correct, these data provide the first evidence for induced surface deformation in response to neotectonics in the New York City area. As the well-documented (magnitude ~5) earthquakes of 1737, 1783, and 1884 demonstrate, we live in an area with a recognized history of time-separated seismic events. The potential for a damaging earthquake in the populated areas of New York City **can not** and **should not** be ruled out as earthquakes **have** occurred here, **can** occur here, and **will** occur here. Effective pre-emptive seismic planning is clearly an urban necessity in New York City.

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

The following seven stops (Figures 1, 2) illustrate the evidence for changes in the interpretation of the stratigraphy, structure, and presence of ductile shear zones between the schistose rocks in New York City, as described above.

STOP 1 - HARTLAND FORMATION IN RIVERSIDE PARK *UTM Coordinates: 585.95E/4515.35N northward to 586.35E/4516.10N, Central Park 7-1/2 minute quadrangle.*

The Hartland Formation or upper schist unit ($\in$ - Oh) crops out in Riverside Park from West 75th Street northward to West 116 Street. Described here are exposures near West 90-91 Streets and West 82-85 Streets.

The northernmost outcrops consist of gray-weathering, well-layered and slabby to laminated, lustrous muscovitic schist containing interlayers of quartz-muscovite biotite granofels. Locally, 1 cm thick glassy quartzite interlayers and elliptical pods of recrystallized dark quartz occur. The prominent 2-3 cm scale layering results from original compositional variations and subparallel S_1 + S_2 metamorphic recrystallization. The metamorphic layering is parallel to N48°E, 65°SE axial surfaces of long-limbed F_2 isoclinal folds plunging 60° into S28°E. A strong down-dip stretching lineation (L_2) composed of quartz ribs and streaked mica lies within S_2 and is deformed by F_3 folds. The F_3 folds are tight, south-plunging "s" folds with abundant shearing along their axial surfaces (S_3 = N37°E, 78°SE). L_3 intersection lineations and stretching lineations are parallel to F_3 hingelines which plunge 22° into S29°W and deform the L_2 lineations. S_3 is typically a transposition foliation with oriented mica and migmatite overprinting the older folds and related fabrics. Pre-, syn-, and post-D_3 pegmatites are found throughout the area.

The southern outcrops of the upper schist unit are lithologically identical to the above except the layering is thicker (6-8 cm) and a laminated black-weathering, greenish-black biotite-amphibolite layer (1 m thick) occurs near West 82 Street. Together these outcrops illustrate the penetrative nature of F_3 isoclinal folds with their shallow southward plunges. Apparently the NW-trending, shallow SW-dipping enveloping S_2 metamorphic layering exerted a strong control on the orientation of F_3 hingelines despite the fact that significant transposition occurred during D_3. The average orientation of S_3 is N55°E, 75°SE with F_3 hingelines and sub-parallel L_3 lineations plunging 20° into S40°W. (See Figure 6.) Late, open folds with axial surfaces trending N47°E, 90° are locally developed.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roches moutonnées. Not only are the rock surfaces rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE, consistent with a multiglacier model

proposed recently by Sanders and Merguerian (1991, 1992, 1994a, b) and Merguerian and Sanders (1996c).

STOP 2 - CAMERON'S LINE AND THE HARTLAND AND MANHATTAN FORMATIONS NEAR WEST 165 STREET. *UTM Coordinates: 588.90E/4521.41N, Central Park 7-1/2 minute quadrangle.*

The Manhattan formation (€ - Om) is exposed here in a large outcrop west of Riverside Drive. The Manhattan formation dominates, consisting of rusty- to gray-weathering, coarse-grained biotite-muscovite-plagioclase-quartz-kyanite-sillimanite-garnet-tourmaline gneiss and schist with 2-15 cm interlayers of quartz-biotite-garnet-kyanite-sillimanite granofels. The rock contains porphyroblasts of kyanite +/- sillimanite and garnet (up to 1 cm). Outcrops 350 m to the north show more typical rusty-weathering colors and abundant aluminosilicates of € - Om, yet in November 1985, subsurface construction exposures to the east of Riverside Drive exposed muscovite-rich Hartland lithologies (€ - Oh) cut by brittle faults. These exposures are typical of Cameron's Line, with intercalated lithologies of both bounding units found in close proximity and clear distinction blurred by D_2 tectonic intercalation.

Structurally, at the south end of the outcrop, there is a clear example of a long-limbed intrafolial F_2 reclined fold refolded by F_3 "z" folds. Here, F_2 folds an S_1 biotite foliation and granitoid pods developed parallel to S_2 (and/or S_1) are folded by F_3. S_2 trends N54°E, 44°SE with F_2 plunging 40° into S19°E and S_3 trends N20°E, 75°SE with F_3 axes plunging 42° into S10°W. Excellent examples of type-3 interference patterns (Ramsay, 1962) are found on the sloping north-facing portion of the outcrop. Cameron's Line passes above our heads as we stand in the core of a south-plunging F_3 fold, exposing € - Om at street level. Hartland rocks crop out to the south and east.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roches moutonnées. This particular rock knoll probably was a splendid example of a roche moutonnée many years ago, but cannot be considered as such any longer. The diamond-drill holes along the rock face by the sidewalk indicate that the SE side of this knoll was blasted away to make way for the street and the sidewalk. Not only has the rock surface been rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE.

STOP 3 - ST. NICHOLAS THRUST AND CAMERON'S LINE, INWOOD HILL AND ISHAM PARKS *UTM Coordinates centered on: 590.50E/4525.00N, Central Park 7-1/2 minute quadrangle.*

Inwood Hill Park is located in the extreme northwest corner of Manhattan Island. 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 214 Streets.

The area of Manhattan north of Dyckman Street is known as the Inwood section. Except for Inwood Hill Park, the region is underlain by the Inwood Marble marking the name-locality (originally called the Inwood Limestone by Merrill 1890). Isham Park contains near continuous exposure of the Inwood Marble (€ - Oi). Several lithologies occur such as coarse-grained dolomitic marble, fine-grained calcite marble, foliated calc-schist, and marble containing siliceous layers and calc-silicate aggregates that stand in relief as knots on the weathered surface. The marble ranges from white- to blue-white to gray-white. Depending on the amount of impurities, it

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weathers gray or tan and produces a sugary-textured surface on outcrops which ultimately develops into a residual calcareous sand. In addition, the outcrops illustrate differential weathering with dolomite-silicate units standing in high relief and calcite marble forming depressions.

The Inwood trends N45°E, 73°SE and forms the eastern overturned limb of a large F_3 synform which is cored to the west by the middle schist unit ($\in$ - Om) of Inwood Hill Park. Tight south-plunging F_3 folds are locally developed. Older structures are not obvious but can be found (especially after, or during, a rain) as long-limbed F_2 isoclinal folds. Abundant examples of boudinage of the siliceous and calc-silicate layers into lenses occur due to the marked ductility contrast between them and the surrounding marble.

Enter Inwood Hill Park following the past past the playground. The first (of two) prominent ridges is composed of kyanite-garnet gneiss and schist of the middle schist unit ($\in$ - Om) which is structurally separated from the Inwood Marble by the St. Nicholas thrust (not exposed here). 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.

Along the path going north (up-slope) along the westernmost ridge, massive, brown-weathering, blackish amphibolite of the middle schist unit crops out. Rocks exposed on the ridge ($\in$ - Om) are massive muscovite-biotite-plagioclase-quartz-garnet-kyanite gneiss and schist with weathered kyanite+quartz+sillimanite nodules. The structure of the ridge is a south-plunging F_3 synform overturned toward the northwest. The S_3 foliation in the middle schist unit is related to F_3 folds with axial surfaces oriented N41°E, 75°SE and south-plunging hingelines. The F_3 structures are superimposed on an older S_2 metamorphic layering which trends N50°W, 25°SW. Atop the ridge, a few exposures of muscovitic schists that are strikingly "Hartland-ish" occur. If they are indeed Hartland rocks and not minor muscovite-rich zones in the Manhattan (which do occur, locally), a case may be made for skirting the top of the ridge with a klippe underlain by Cameron's Line.

Along the N-facing backslope of the western ridge, the contact between the middle ($\in$ - Om) and lower (Om) schist units (the St. Nicholas thrust) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. Structurally beneath the middle schist unit a 0.5 m layer of mylonitic amphibolite is deformed by F_3 folds. Unlike the amphibolite in the middle schist unit above, which contains subidiobastic hornblende, this amphibolite has been retrograded by intense shearing parallel to the S_2 foliation. Green hornblende porphyroclasts are set in an anastomosing S_2 foliation consisting of colorless clinoamphibole, biotite, and quartzose ribbons.

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 a "Balmville" interlayer in the lower schist unit (Om) or a faulted part of the Inwood Marble.

Physically above the marble exposure, the lower schist unit consists of biotite-quartz-plagioclase and kyanite with abundant garnet porphyroblasts. Here the lower schist unit contains an S_2 mylonitic foliation composed of mm-scale ribboned and polygonized quartz with recrystallized reddish pleochroic biotite. Produced in the axial planes of F_2 reclined folds, the S_2 foliation strikes N45°E and dips 55°SE with a strong down-dip lineation plunging 50° in a S34°E direction. The thrust zone is structurally complex consisting of intercalated lithologies of the lower- and middle schist units together with mylonitic amphibolite.

STOP 4 - ST. NICHOLAS THRUST AND MANHATTAN FORMATION IN ST. NICHOLAS PARK *UTM Coordinates: 588.45E/4518.28N northward to 588.75E/4519.15N, Central Park 7-1/2 minute quadrangle.*

The St. Nicholas thrust separates the middle schist unit (Є - Om) from the Inwood Marble (Є - Oi) along the east edge of St. Nicholas Park situated west of St. Nicholas Avenue between West 129 and West 141 Streets. Excellent outcrops of the schist form the steep ridge of the park. The southernmost outcrops consist of rusty-weathering biotite- and muscovite-rich gneiss and schist with abundant aluminosilicate nodules, interlayered biotite-quartz-garnet granofels, and thin amphibolite. The Inwood Marble is not exposed but, based on drill core data and geomorphology, underlies the lowland immediately east of the park.

Outcrops atop the ridge on St. Nicholas Terrace contain flattened aluminosilicate layers folded by F_3 folds. Northward, F_2 isoclinal folds with subhorizontal axial surfaces are also deformed by F_3 folds. S_3 trends N30°E, dipping 70°SE and is locally warped by several generations of late crenulate and open folds.

A penetrative S_2 mylonitic layering occurs at the northeasternmost exposures in the park. Tight- to isoclinal F_3 folds deform and locally transpose the S_2 mylonitic foliation into parallelism with S_3. In addition, the F_3 folds deform pegmatite sills injected sub-parallel to $S_2 + S_1$, thin lit-par-lit foliated syn-D_2 granitoids, aluminosilicate layers, and quartz veins. Because of the combined effects of D_2 and D_3 the rocks are highy recrystallized and locally migmatitic.

The contact between the middle schist unit and the Inwood Marble is never observed but the presence of unusually penetrative S_2 fabrics in the schist at the eastern edge of the park and the apparent absence of the lower schist unit together suggest that the St. Nicholas thrust may be marked by the abrupt break in slope to the east.

STOP 5 - ST. NICHOLAS THRUST AND THE MOUNT MORRIS PARK OUTLIER *UTM Coordinates centered on: 589.13E/4517.25, Central Park 7-1/2 minute quadrangle.*

The Mount Morris Park Outlier, a hill protruding above the Harlem Valley centered at West 122 Street and Fifth Avenue, consists of an erosional remnant of the middle schist unit (Є - Om). The Inwood Marble (Є - Oi) crops out on the Madison Avenue (east) side of the park. The marble is gray- to tan-weathering and contains schistose zones with layers and nodules of diopside+tremolite+ quartz. The middle schist unit is composed of rusty- and locally, maroon-weathering, gray, biotite-muscovite-plagioclase-quartz-kyanite-garnet-sillimanite gneiss and schist with kyanite layers, zones of porphyroblastic kyanite+garnet, and layers of biotite-quartz-plagioclase+garnet granofels.

The overall structure of the park is a south-plunging klippe of the middle schist unit produced by the superposition of an F_3 synform and a late, NW-trending synform. The klippe of Є - Om is terminated along its southern margin by a brittle fault (splay of the 125th Street fault?) exposed at street level trending N69°W, dipping 84°SW. Slickensides in the fault surface are oriented N70°W @ 22° clearly indicating a strike-slip movement sense although a component of reverse motion is suggested by faint dip-slip slicks and the presence of Inwood Marble to the south. Along the east-face of the exposure, the St. Nicholas thrust is found between the Manhattan schist and Inwood Marble and is marked by 10° truncation of lithologic layering and an early S_1 foliation in the marble, extreme flattening, 2-3 cm scale annealed mylonitic layering, shearing and imbrication of lithologic units (including small tectonic slivers and interlayers of schist unit Om?), and quartz veins.

Developed during thrusting and deformed by F₃ folds, the S₂ enveloping surface is variable but on average trends N30°W, 20°SW and marks the axial surface of reclined and isoclinal folds found both above and beneath the St. Nicholas thrust contact. Disharmonic F₃ folds of mylonite developed at the thrust contact are exposed at the northern edge of the klippe. They trend N32°E, 80°NW to 70°SE and plunge 23° into S25°W.

STOP 6 - "BALMVILLE" MARBLE AND LOWER MANHATTAN SCHIST UNIT - GRAND CONCOURSE AND THE CROSS BRONX EXPRESSWAY, BRONX. *UTM Coordinates: 591.65E/4521.95N, Central Park 7-1/2 minute quadrangle.*

An excellent exposure of the lower schist unit (Om) occurs west of the Grand Concourse in an overpass above the Cross Bronx Expressway (I-95). Here, fine- to medium-grained, massive but locally friable, tan- to brown-weathering muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist and granofels is found interlayered on the scale of 3-4 m with calcite and dolomite marble containing 2-3 cm diopside+tremolite calc-silicate and siliceous layers. Massive Inwood Marble (Ꞓ - Oi) occurs in the roadcut forming the south wall of I-95 beneath the overpass. This locality, together with exposures described earlier in Inwood Hill Park (Stop 3) and a few other outcrops south of I-95 paralleling the Grand Concourse (C. A. Baskerville, personal communication), are interpreted as the autochthonous portions of the "Tippecanoe" Manhattan Schist.

STOP 7 - CAMERON'S LINE - BORO HALL AND CROTONA PARKS, CROSS BRONX EXPRESSWAY. *UTM Coordinates centered on: 593.00E/4521.80N, Central Park 7-1/2 minute quadrangle.*

Boro Hall Park in the Bronx is surrounded by East Tremont Avenue on the north, Third Avenue on the west, Arthur Avenue on the east, and East 175th Street on the south. The last-named also serves as the westbound service road for the Cross Bronx Expressway (I-95). This park is situated on an important subdivision of the metamorphic schistose rocks of the Bronx. On the 1971 edition of the Geologic Map of New York (New York State Museum and Science Service) places a queried dashed line through the center of the park as the contact between the New York City Group on the west from the Hutchinson River Group on the east. Seyfert and Leveson (1969) discuss the contact as a thrust fault and argue that it is on strike with Cameron's Line. Based on lithologic correlations, Baskerville (1982a, b, 1992) first identified the contact as Cameron's Line; Merguerian and Baskerville (1987) defined the structural relationships discussed below.

Along East 175th Street the outcrop nearest Third Avenue is a brown- to rusty-weathering, medium-textured, gray, biotite-muscovite schist of the middle schist unit (Ꞓ - Om) containing several pegmatite dikes. The foliation strikes N40°E, and dips 70°SE. Test borings for the I-95 overpass near this locality indicate that marble occupies the Third Avenue valley to the west. East of the middle schist unit is a soil-covered shallow swale, 30- to 40 m wide, that trends N40°E. The Hartland Formation (Ꞓ - Oh) crops out to the east of the swale and also south of the expressway in Crotona Park (described below). The Hartland rocks are brown- to tan-weathering, gray muscovite-biotite-quartz-plagioclase-garnet schist and gneiss with granitoid sills and thick layers of greenish amphibolite.

The contact between the middle schist unit (Ꞓ - Om) on the west and the Hartland Formation (Ꞓ - Oh) is never exposed but presumably occupies the swale between the outcrops. Rocks on either side of the contact are highly flattened; as a result of recrystallization during D₃, the microscope shows little evidence for mylonitization. Microscopically, brittle fractures are well-developed in the minerals, suggesting the contact may be a brittle fault reactivating an older ductile

contact. The contact between these units is known as Cameron's Line, a ductile fault separating allochthonous sequences of the Taconian Hartland and Manhattan formations.

Dr. Patrick W. G. Brock of Queens College, who took a class to this stop, collected specimens, and examined the rocks petrographically, detected a corroded grain of corundum that had been highly retrograded by higher-crustal-level metamorphic overprinting. Although it was not in contact with quartz and clearly had undergone retrograde reactions, the corundum discovery suggests that the rocks in this region had initially experienced metamorphism at least up to K-feldspar-sillimanite grade.

To the south of the Cross Bronx Expressway, in Crotona Park, Cameron's Line again separates schist, gneiss, and amphibolite of the Hartland Formation (€ - Oh) on the east from westerly exposures of schist and gneiss of the middle unit of the Manhattan Schist Formation (€ - Om). The rocks are not found in direct contact but, similar to exposures to the north, are separated by a soil-covered interval. The Manhattan exposures are mylonitized, however, with shear folds and laminated textures well displayed.

ACKNOWLEDGEMENTS

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