# STRATIGRAPHY, STRUCTURE, AND TECTONICS OF NEW YORK CITY AS VIEWED THROUGH ITS PARKS

**CHARLES MERGUERIAN**
*Professor Emeritus, Geology Department, Hofstra University, Hempstead, NY 11549, Research Fellow, Yale University, New Haven CT 06520 and Principal,* Duke Geological Laboratory, Stone Ridge, NY 12484

**J. MICKEY MERGUERIAN**
Geologist, Duke Geological Laboratory, Stone Ridge, NY 12484

## INTRODUCTION

### Geological Setting

NYC is situated at the extreme southern end of the Manhattan Prong (Figure 1), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terrains of New England. Southward from NYC, the rocks of the Manhattan Prong plunge nonconformably beneath predominately buried Mesozoic rocks, younger Cretaceous strata, and the overlying Pleistocene drift found capping much of the region including all of Long Island and much of Staten Island. This NYSGA paper and allied Trip A-5 field guide are intended to prepare and expose participants to our subdivisions of the venerable Manhattan Schist into three separable units by utilizing exposures in NYC parks including Isham, Inwood Hill and Central parks.

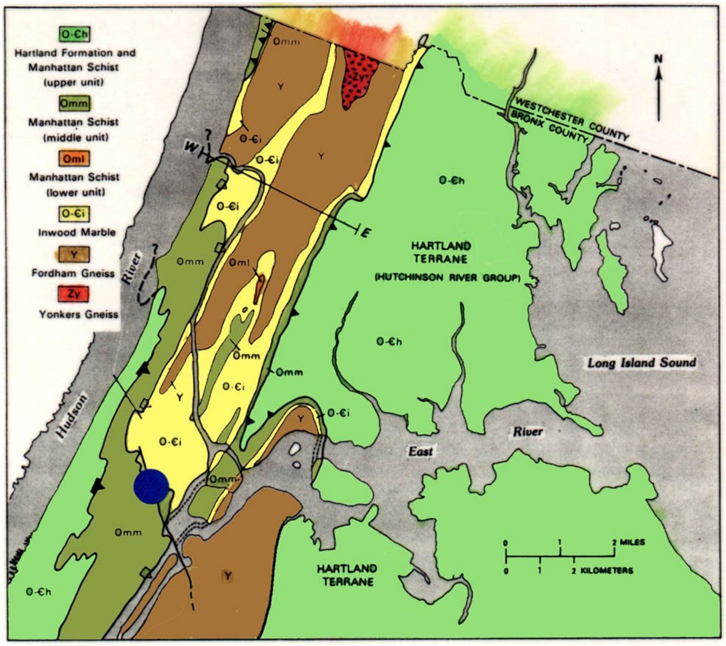


**Figure 1** – Geological map of New York City showing the generalized structural geology of the region using older terminology of upper, middle, and lower units of the Manhattan Schist of Merguerian and Baskerville (1987) and Merguerian and Merguerian (2004). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most faults and intrusive rocks have been omitted. Blue dot is epicenter of 21 January 2001 magnitude 2.4 earthquake that occurred along Manhattanville fault.

## Previous Investigations

A detailed history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991) so the following is simply a brief excerpt and overview. In 1890 (p. 390), Merrill named the Manhattan Schist 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 lower Paleozoic strata of southern Dutchess County, New York. Merrill (1890) confides that "the name Manhattan Group was proposed by naturalist R. P. Stevens, Esq., to include the rocks of New York Island".

Despite this acknowledgement, Merrill and others (1902) produced the United States Geological Survey New York City Folio (#83) and following Dana chose to use the name Hudson Schist (rather than Manhattan Schist) for the schistose rocks of NYC. This pioneering work by Merrill and coworkers set the stage for a series of detailed investigations by many geologists in the 1900's that helped define the details of NYC bedrock units and use of the term Manhattan Schist as the name locality for the unit. Merrill also extended "Group" status to include the Manhattan Schist, the Inwood "limestone" and the Fordham and Yonkers gneisses and correctly correlated the Fordham with Proterozoic sequences of the Hudson Highlands. Formal removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiometric dating techniques and detailed mapping in the 1960's by Leo M. Hall (1968a, b). Formal "de-Grouping" of the "Manhattan Group" took place after spirited debate at a Symposium on the New York City Group of Formations at the 1968 meeting of the New York State Geological Association at Queens College, Queens, New York. Our studies of the metamorphic rocks of NYC since 1972 have benefited from these early works and access to surface and subsurface construction sites.

## NYC BEDROCK STRATIGRAPHY

Based on study of over 1,000 natural exposures and a multitude of drill core and construction excavation geotechnical analyses our joint investigations of the bedrock geology of NYC have portrayed a complex structural history and suggests that the Manhattan Schist formation exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three separable map units now known as the **Hartland, Manhattan, and Walloomsac** formations. (See Figure 1.) These subdivisions agree with designations proposed by Hall (1976, 1980) but suggest the presence of a hitherto unrecognized structurally higher unit that is a direct correlative of the Hartland Formation (= Rowe and Ratlum Mountain schists) of western Connecticut (Merguerian 1983a, 1987, 2016). The three schistose units are juxtaposed along imbricate ductile faults known as the St. Nicholas thrust and Cameron’s Line (Merguerian 1994, 1996a) as indicated in a simplified cross section across the northern tip of Manhattan into the Bronx (Figure 2).

Keyed to Figure 1, the W-E section of Figure 2 shows the general structure of NYC and how the St. Nicholas thrust and Cameron's Line overthrusts position the Manhattan and Hartland formations above the Walloomsac formation and the underlying Inwood- Fordham cover+basement sequence. Late stage regional $F_3$ folds produce digitations of the structural- and stratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward topping of tectonostratigraphic units exposed in central Manhattan and the effects of the yet younger NW-trending asymmetric folds. The structural geology of NYC is detailed in a later section and the proposed new stratigraphic interpretation is diagrammed in Figure 3.

Hartland Formation. The structurally high Hartland formation (OЄh) is dominantly gray-weathering, fine- to coarse-textured, well-layered (cm- and m-scale) muscovite-quartz-biotite-plagioclase-kyanite-garnet-staurolite schist, gneiss, and migmatite with layers of gray quartzose granofels, greenish amphibolite±garnet and scarce coticule. *(Note: Minerals listed in descriptions are in decreasing order of abundance.)* The schistose facies is lustrous and consists of dense, aligned fine- to coarse-textured muscovite and lesser biotite that splits readily along the foliation (Figure 4). The gneiss and granofels lithotypes are massive, commonly more feldspathic, migmatitic and may or may not show pronounced foliation. Gray quartzites are also found as discrete interlayers up to 0.5 m thick. Although typically not exposed at the surface, the Hartland underlies most of the central and southern portions of Manhattan and the eastern half of the Bronx. Because it is lithologically identical to the Cambrian (?) to Ordovician Hartland Formation of western Connecticut and Massachusetts, CM has extended the name Hartland into NYC (Merguerian 1983b) and considers the formation part of the allochthonous **Taconic Sequence**.

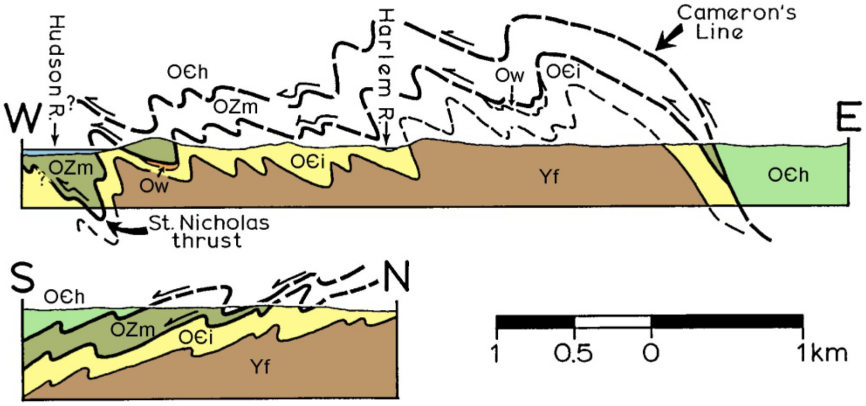
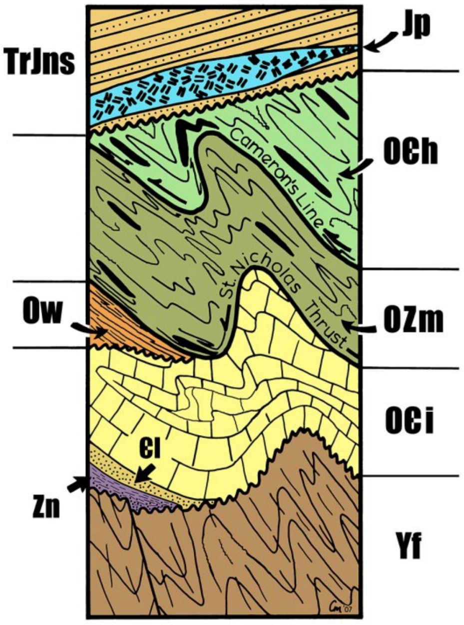


**Figure 2** - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). See Figure 1 for the line of the W-E section. The N-S section runs through the east edge of Central Park.

**Figure 3** - Bedrock stratigraphy of New York City as described in text and noted in figures. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).



Manhattan Formation. The Manhattan formation (OZm) consists of very massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite-magnetite-tourmaline gneiss, migmatite, and to a lesser degree, schist (Figure 5). The unit is characterized by a lack of internal layering except for the presence of kyanite+sillimanite+quartz+ magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite, and scarce thin, quartzose granofels. The unit is a major ridge former in northern Manhattan, a testament to its durability to weathering owing to the lack of layering and presence of resistant minerals quartz, garnet, kyanite, and sillimanite. Owing to the localized concentration of individual crystals and zones of disseminated magnetite some parts of the formation are strongly magnetic.

The Manhattan Formation forms the bulk of the “exposed" Paleozoic metamorphic rocks of northern Manhattan including most northern Central Park exposures and the bulk of the highlands of Inwood Park. The Manhattan is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Late Proterozoic (?) to Ordovician age in New England (Hall 1976; Merguerian 1977, 1983a, 1985, 2016). These rocks, which contain calc-silicate and quartzose interlayers in western Connecticut are inferred to represent metamorphosed sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America. As such they are considered, along with the Hartland Formation, a part of the allochthonous **Taconic Sequence**.

Walloomsac Formation. Found interlayered at the top of the Inwood Marble in New York City, this discontinuous unit (Ow) is composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-pyrite-graphite schist and migmatite. The formation contains interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of (“Balmville”) calcite marble, and hard diopside±tremolite±phlogopite calc-silicate rock. Pinkish garnet occurs as porphyroblasts up to 1 cm in size and amphibolite is absent. As shown in the photomicrograph of Figure 6, strongly pleochroic reddish biotite, pinkish garnet, graphite, and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation.

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

In the Bronx, four areas of Walloomsac rocks have been found; (1) on the Grand Concourse and I-95 overpass (Merguerian and Baskerville 1987), (2) beneath the St. Nicholas thrust in the western part of Boro Hall Park (Fuller, Short, and Merguerian 1999), (3) below the St. Nicholas thrust in the northwest and southeastern part of the New York Botanical Garden (Merguerian and Sanders 1998 and unpublished data), and (4) in the western and northeastern part of Crotona Park (unpublished data). Because it is interpreted as being autochthonous (depositionally above the Inwood Marble and underlying Fordham Gneiss) it is assigned a middle Ordovician age. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels and calc-silicate layers enables the interpretation that the Walloomsac Schist is the metamorphosed equivalent of middle Ordovician carbonaceous shale and interlayered greywacke and calcareous strata of the Tippecanoe Sequence and is therefore considered correlative with parts of the Annsville and Normanskill formations of SE New York and the Martinsburg formation of eastern Pennsylvania.

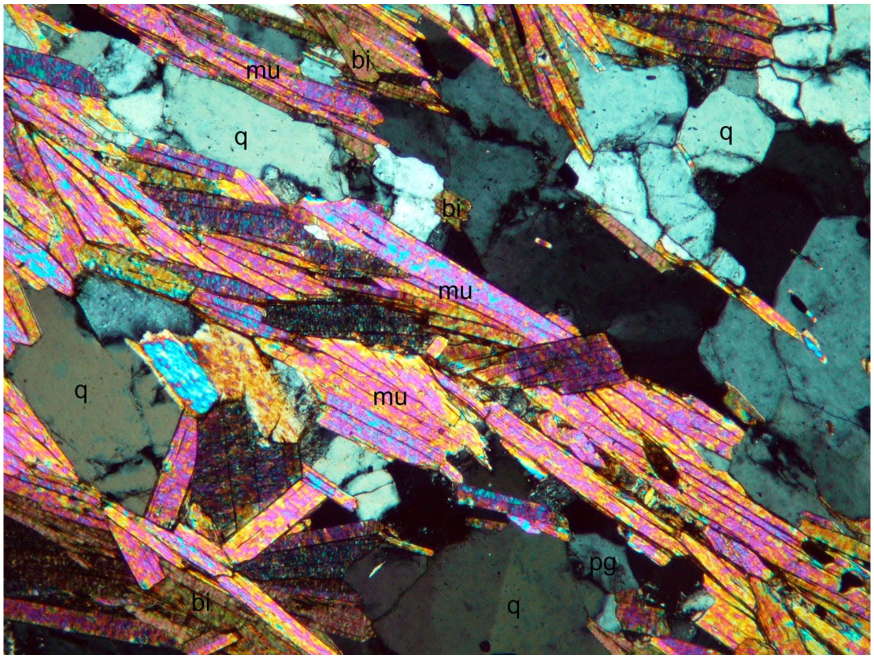


**Figure 4** - Photomicrograph in cross-polarized light of Hartland schist (Ꞓ-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the high mica content and prevalence of muscovite and quartz, diagnostic mineralogical characteristics of the Hartland. (CM Sample N125; 112th Street and Riverside Drive, Manhattan; 2 mm field of view.)

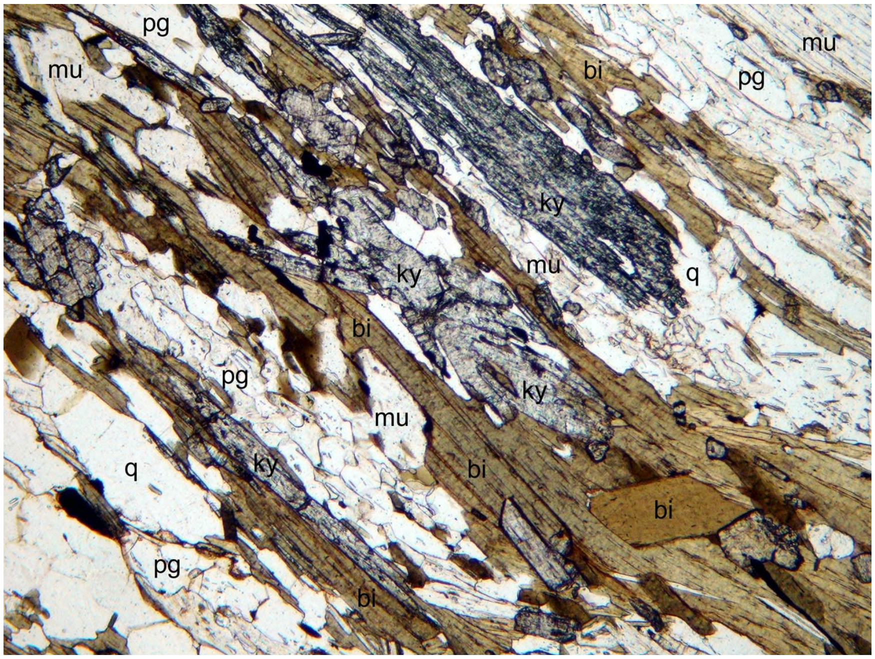


**Figure 5** - Photomicrograph in plane-polarized light of the Manhattan Schist (OZm) showing an aligned intergrowth of biotite (bi), kyanite (ky), and muscovite (mu) in a fine-textured matrix of intergrown plagioclase (pg) and quartz (q). The penetrative foliation in this view, which consists of aligned micas and kyanite as well as flattened quartz and feldspar, is diagonal across the image and marks a structural discontinuity that may split readily. (CM Sample N217; South of George Washington Bridge approach, Manhattan; 2 mm field of view.)

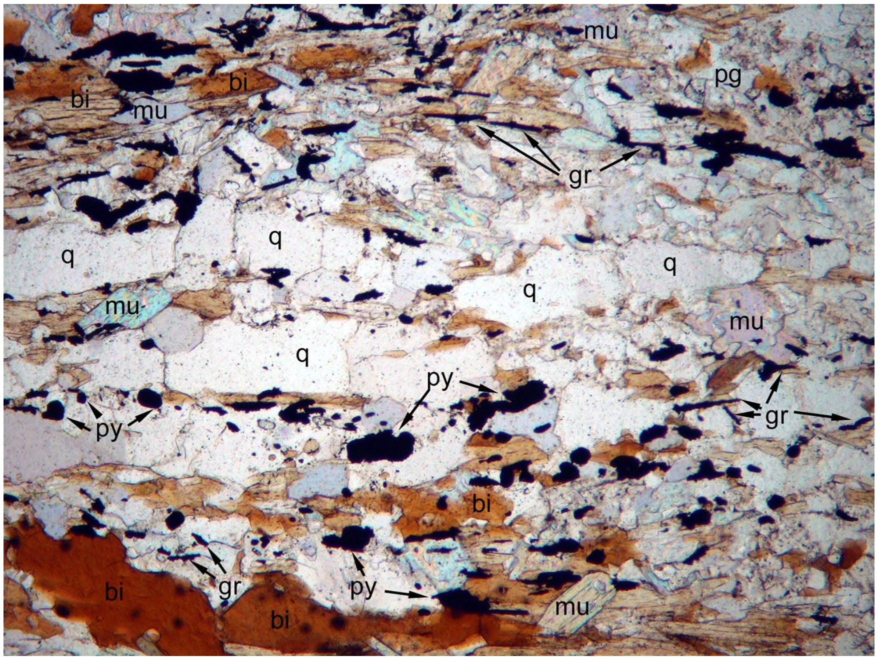


**Figure 6** - Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal) defined by aligned biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals overgrow the foliation. Diagnostic petrographic characteristics of the Walloomsac include the presence of graphite and pyrite and strongly pleochroic red-brown biotite. (CM Sample N113-3L; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

## Origins of the Hartland, Manhattan, and Walloomsac Formations

Metamorphosed to amphibolite facies grade and then retrograded to biotite facies grade the exposed metamorphic cover rocks of NYC (Hartland, Manhattan, and Walloomsac formations) were originally deposited as sediment and intercalated clastic, volcanic and volcaniclastic materials, though in vastly different depositional environments (Figure 7). The Hartland Formation was originally deposited in a deep ocean basin floored by oceanic lithosphere and fringed by offshore volcanic islands. The marginal ocean basin was the receptor of a huge influx of terrigenous and volcanogenic material. This produced a thick well-layered sequence of clay, silt, sand, and interlayered volcanogenic strata which resulted in a variable lithologic sequence. Even after protracted Paleozoic deformation and metamorphism, compositional layering was preserved in the Hartland, forming a dominantly well-layered metamorphic rock mass consisting of interlayered and locally migmatitic schist, gneiss, granofels, and amphibolite.

The Manhattan Formation originated along the edge of the former North American continental margin as thick clay-rich sediment with occasional sand interlayers and mafic igneous injection or flows. (See Figure 7.) As a result, the Manhattan is often more massive in character than the Hartland although some subunits appear similar. By contrast, the Walloomsac Formation is mineralogically unique since it originated under restricted oceanic conditions and consisted of thick accumulations of carbonaceous, sulphidic, and clay-rich sediment with occasional sandy and calcareous interlayers. This has resulted in a mineralogically distinct schistose rock enriched in biotite, graphite, garnet and pyrite together with layers of calcite marble and calc-silicate rock. The contrast in internal compositional layering and mineralogy allows for separation of the three units in the field and also during routine core examination and petrographic analysis.

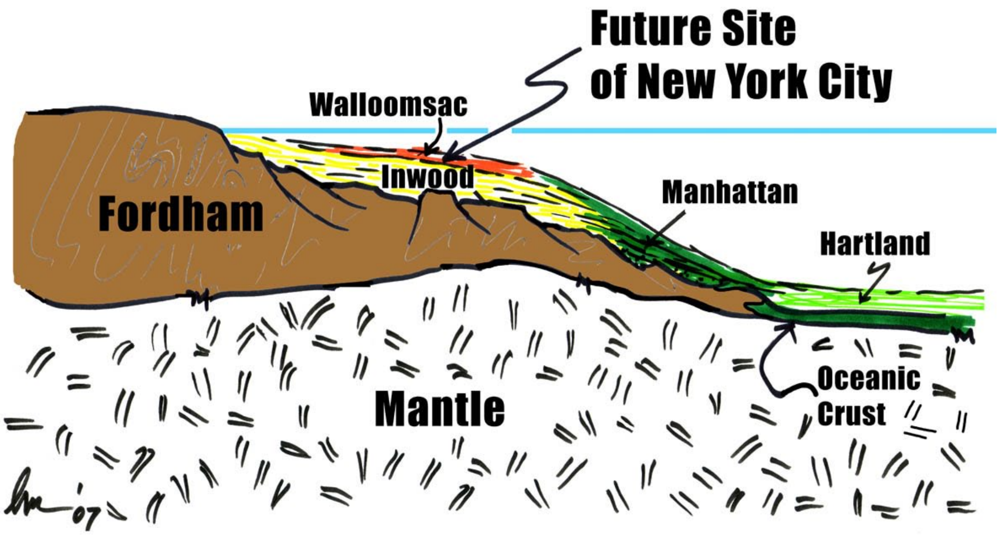


**Figure 7 -** Diagrammatic cartoon of eastern North America after rifting from Rodinia and during deposition of the Paleozoic strata that are to become the Hartland, Manhattan, and Walloomsac formations. Note the correlation of units and their relationships to the underlying units of the partly coeval Inwood and older Fordham.

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

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

Inwood Marble. The Inwood Marble (OꞒi in Figures 1-3) consists of white to bluish-gray fine- to coarse-textured dolomitic and lesser calcitic marble locally with siliceous interlayers containing diopside, tremolite, phlogopite, muscovite (white mica) and quartz (Figure 8) together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite according to our investigations (Merguerian, Merguerian and Cherukupalli 2011). Layers of calc-schist, calc-silicate rock and fine grained gray quartzite with a cherty appearance are also locally present. The unit is exposed in the Inwood section of northern Manhattan, the Harlem lowland NE of Central Park, in thin belts in the East River channel, in the subsurface of southeastern Manhattan, and also crops out in the Bronx and Westchester County. The Inwood is correlative with a continuous outcrop belt of non-metamorphosed Cambro-Ordovician carbonate rocks (Sauk Sequence) found along the entire Appalachian chain of North America.

Fordham Gneiss. The Fordham Gneiss (Yf in Figures 1-3) constitutes the oldest underpinning of rock formations in NYC and consists of a complex assemblage of Proterozoic Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks. In NYC, only a few attempts have been made to decipher the internal stratigraphic relationships, hence, the three-dimensional structural relationships remain obscure. Based on detailed studies in the Queens and Brooklyn NYC water tunnels (Merguerian 2000; Merguerian, Brock, and Brock 2001; Brock, Brock, and Merguerian 2001) the Fordham consists of predominately massive mesocratic, leucocratic, and melanocratic orthogneiss with subordinate schistose rocks. They test Grenvillian in age (1.1 Ga) and were then metamorphosed to the high pressure granulite facies which has produced a tough, anhydrous interlocking mineral texture consisting of primary clino- and lesser orthopyroxene, plagioclase, and garnet that has partially resisted Paleozoic hornblende and biotite grade retrograde regional metamorphism (Figure 9).

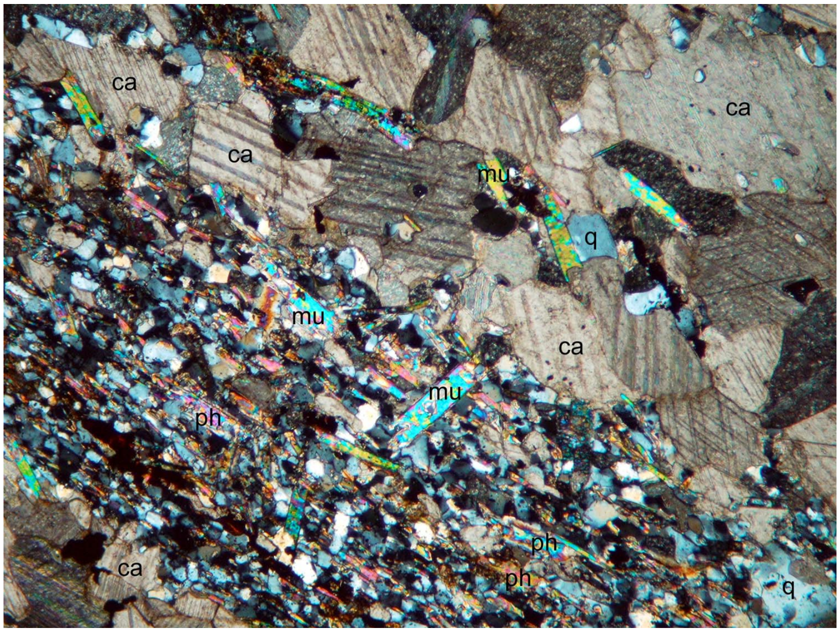


**Figure 8 -** Photomicrograph in cross-polarized light of the Inwood Marble near the contact with the Walloomsac showing the granoblastic texture produced by recrystallized twinned calcite (ca). A fine-textured mica-rich zone cutting diagonally across the slide defines a foliation which here consists of aligned muscovite (mu) and phlogopite (ph) in a matrix of recrystallized quartz (q), calcite, and biotite (bi). Normally the Inwood is quite pure and consists of coarse textured granoblastic calcite or dolomite. (CM Sample N113-4; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

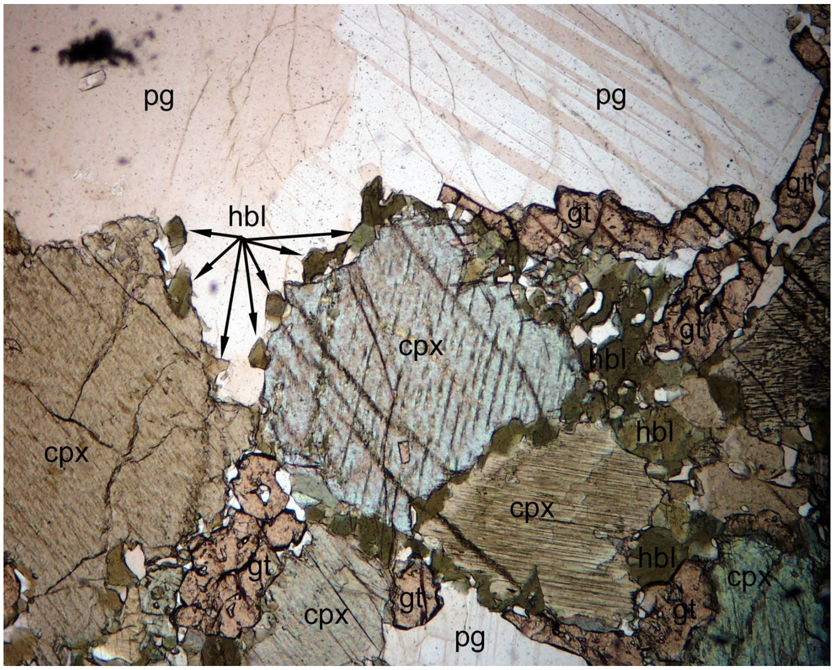


**Figure 9 -** Photomicrograph in plane-polarized light of Proterozoic mafic orthogneiss showing a coarse-textured granular intergrowth of clinopyroxene (cpx), plagioclase (pg), and garnet (gt) produced during Grenvillian metamorphic recrystallization of a former mafic igneous rock. Granular hornblende (hbl) was produced during a secondary Paleozoic metamorphism but the older interlocking granoblastic metamorphic texture has prevailed. (CM Sample Q114; Queens Tunnel Station 015+90; 2 mm field of view.)

The Fordham is exposed in the Bronx, in the subsurface of SE Manhattan, the East River channel, and western Queens and Brooklyn (City Water Tunnel #3, Stage 2) and presumably underlies most the region at greater depth. (See Figure 7.) Occurring locally between the Inwood and Fordham are two minor units that are poorly understood and somewhat controversial. One is the very local Lowerre Quartzite (unit Ꞓl in Figure 3) of Norton (1959) and the other a late Proterozoic unit known as the Ned Mountain Formation (unit Zn in Figure 3) of Brock (1989, 1993). The Ned Mountain is correlative with Proterozoic Z rocks mapped as the Yonkers Gneiss (Scotford 1956) and the Ravenswood Granodiorite Gneiss (Ziegler 1911) found in Westchester County and in western Queens, respectively. They have little bearing on the primary focus of this paper and field trip and are here referenced for sake of completion.

## Other Rocks Associated with the Bedrock Series

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

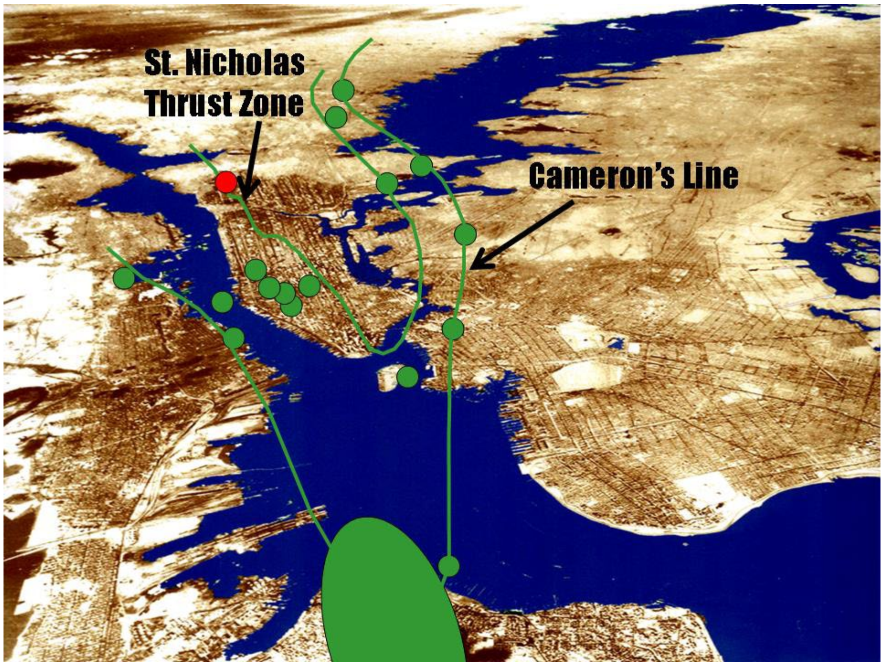


**Figure 10 -** Cartoon showing distribution of 18 known areas of serpentinite in the New York City area. The green lines surround areas of serpentinite defining a zone of sheared rock broadly coincident with the St. Nicholas thrust and Cameron's Line, two important elements of the Taconian suture zone in New York City. The red dot shows the location of a serpentinite in northern Manhattan described by Merguerian and Moss (2007).

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

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

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

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

## STRUCTURAL GEOLOGY

### Deformational Episodes

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

The obvious map scale folds in NYC are those with steep N- to NE-trending axial surfaces ($S_3$) and variable but typically shallow plunges toward the S and SW. (See Figures 1 and 2.) The folds are typically overturned to the NW with a steep SE-dipping schistosity (Figure 11). Shearing along $S_3$ axial surfaces typically creates a transposition foliation of $S_1$, $S_2$, and $S_3$ that is commonly invaded by granitoids to produce migmatite both during the $D_2$ and subsequent $D_3$ events. The third-generation structures deform two earlier structural fabrics ($S_1$ and $S_2$). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of overturned $F_3$ folds). We suspect that all of these structures ($D_1$, $D_2$, and $D_3$) are products of the protracted middle Ordovician Taconic orogeny.

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 with and without fine-textured tails, 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 dominantly L-tectonism, smeared the previously flattened kyanite+quartz layers and lenses into elongate shapes stretched parallel to $F_3$ axes. In addition, porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to $F_3$ hingelines in the bounding Inwood Marble (Merguerian and Merguerian 2012).

Although the regional $S_2$ metamorphic grain of the NYC bedrock trends N50˚W, the appearances of map contacts are regulated by $F_3$ isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25˚. (See Figure 11.) $S_3$ is oriented N30˚E and dips 75˚SE and varies from a spaced schistosity to a transposition foliation often with shearing near $F_3$ hinges. The $F_3$ folds and related $L_3$ lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz and kyanite lenses and layers into elongate shapes. Metamorphism was of identical grade with $D_2$ which resulted in kyanite overgrowths and annealing of former mylonitic textures (Merguerian 1988).

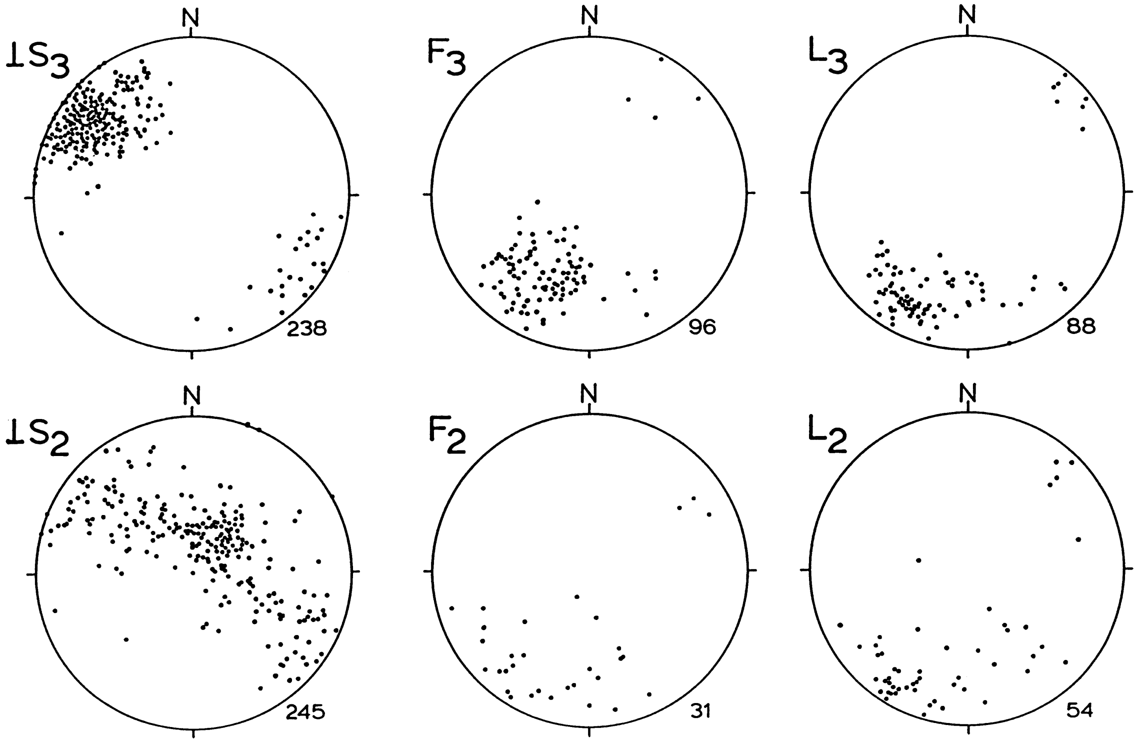


**Figure 11 -** Equal area stereograms showing the distribution of poles to $S_2$ and $S_3$, the orientation of $F_2$ and $F_3$ fold hingelines, and the orientation of $L_2$ and $L_3$ lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, Figure 26, p. 113.)

## Second Ave Subway Mapping

The long-delayed Second Avenue Subway project in NYC has provided us an opportunity for a thorough three-dimensional study of the stratigraphy, structure, and metamorphism of the Hartland formation in NYC. Between 83rd and 87th streets on Second Avenue twin TBM-bored tunnels and ground-down ancillary station complex excavations indicate that the Hartland in this part of NYC is a migmatitic amphibolite facies rock mass that is well-layered at the scale of 0.5 cm to 1.0 m. The project exposes a schistose to gneissic rock consisting of the assemblage muscovite-quartz-plagioclase-biotite±kyanite± staurolite±garnet with interlayers of quartz-plagioclase-mica granofels, greenish amphibolite±biotite± garnet, subordinate gray quartzite and coticule. The schistose facies is lustrous and consists primarily of aligned fine- to coarse-textured muscovite and thus splits readily along the foliation and lithologic contacts. The mica gneiss, granofels, amphibolite, and quartzite interlayers are typically massive and hard, contain much less mica than the schist and may not show pronounced foliation.

In 2012-13 we had the opportunity to observe and record the $F_2$ recumbent fold phase in large-scale fresh exposures during our site inspections and mapping of the 86th street station complex of the Second Avenue subway excavation (Merguerian and Merguerian 2014). Figure 12 provides a south facing view of the main station cavern excavated below 86th street in NYC. The cavern was advanced by traditional drill and blast technology using access shafts at 87th and 83rd streets and by excavating in a series of top down slashes to open the cavern down to the level of existing TBM-bored north and southbound tunnels mined earlier.

**Figure 12** - View from north of west (R) and center (L) slashes of North Cavern excavation at $86^{th}$ Street Station for Second Avenue Subway. West (southbound) TBM tunnel crown at +77.2' exposed in right center of image below area of intersecting joints, faults and resulting overbreak. The center (wet. blackish area) and western (right of center) slashes are discussed in text. (Digital image taken 19 December 2012.)

Center Slash. Exposed in late 2012, the center slash of the 86th street north main station cavern for the Second Avenue Subway project in the vicinity of Station 1205+00 (below 85th street) exposed highly fractured and jointed Harland schist, granofels, and amphibolite in a series of top down excavations that ultimately breached through existing TBM-bored tunnels. The map and image of the center slash (Figure 13) shows SE-plunging $F_2$ reclined isoclinal recumbent folds of early SE-dipping gently inclined penetrative foliation and deformed grantoid sill (g). Another foliated granitoid is injected along a moderately inclined reverse shear showing 0.5 m of offset. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 10.) that has formed parallel to compositional layering and the $S_2$ axial surface. Gently inclined foliation joints are prominent discontinuities ($J_1$) that formed parallel to the foliation and parallel compositional layering. Listed below Figure 13, these are intersected by steep NNE-trending ($J_2$) and NW-trending ($J_3$) joints and faults producing overbreak seen at top of image.

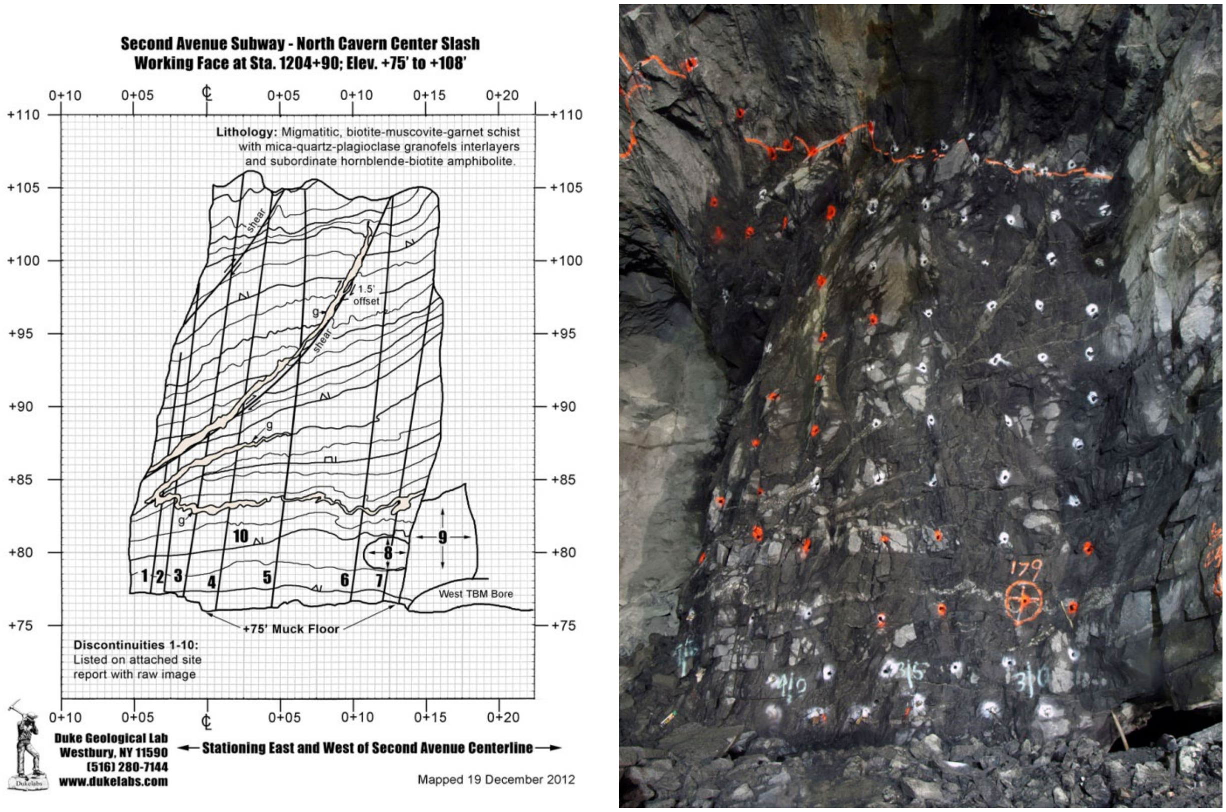


**Figure 13** - Isoclinal recumbent folds of early SE-dipping foliation in Hartland formation (OꞒh) outlined by grantoid sills (g) with gently inclined penetrative foliation. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 10.) that has formed parallel to compositional layering. Gently inclined foliation joints are prominent discontinuities ($J_1$) and have formed parallel to the foliation and parallel compositional layering. These are intersected by steep NE-trending ($J_2$) and NW-trending ($J_3$) joints and faults producing overbreak seen at top of image. (Digital image taken 19 December 2012.)

Discontinuities of Center Slash

NNE-trending Set ($J_2$) – Associated with NNE-trending fault system
1 – N32°E, 76°SE, planar, rough joint (one of 11 joints measured in easternmost 5' of rock face)
2 – N34°E, 82°SE, planar, rough joint (one of 11 joints measured in easternmost 5' of rock face)

3 – N30°E, 81°SE, planar, rough joint (one of 11 joints measured in easternmost 5’ of rock face)
4 – N30°E, 78°SE, planar, rough joint (one of 15 joints measured in easternmost 10’ of rock face)
5 – N19°E, 84°SE to N23°E, 86°NW planar, smooth joints
6 – N31°E, 90° planar, smooth joint
7 – N37°E, 77°SE planar, rough joint

NW-trending Set ($J_3$) – Associated with NW-trending fault system
8 – N41°W, 51°NE undulating, rough joint
9 – N29°W, 82°NE planar, smooth joint face with trace of K-feldspar and microcrystalline epidote

Foliation and Layering Joints ($J_1$)
10 – Foliation, layering and parallel $J_1$ joints are ~ N70°E, 20°SE

West Slash. Also exposed in late 2012, the west slash of the 86th street north main station cavern exposed highly fractured and jointed Harland schist, granofels, and amphibolite. The map and image of the west slash (Figure 14) shows SE-plunging $F_2$ isoclinal reclined recumbent folds of early SE-dipping gently inclined penetrative foliation. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 13.) that has formed parallel to compositional layering and the $S_2$ axial surface.

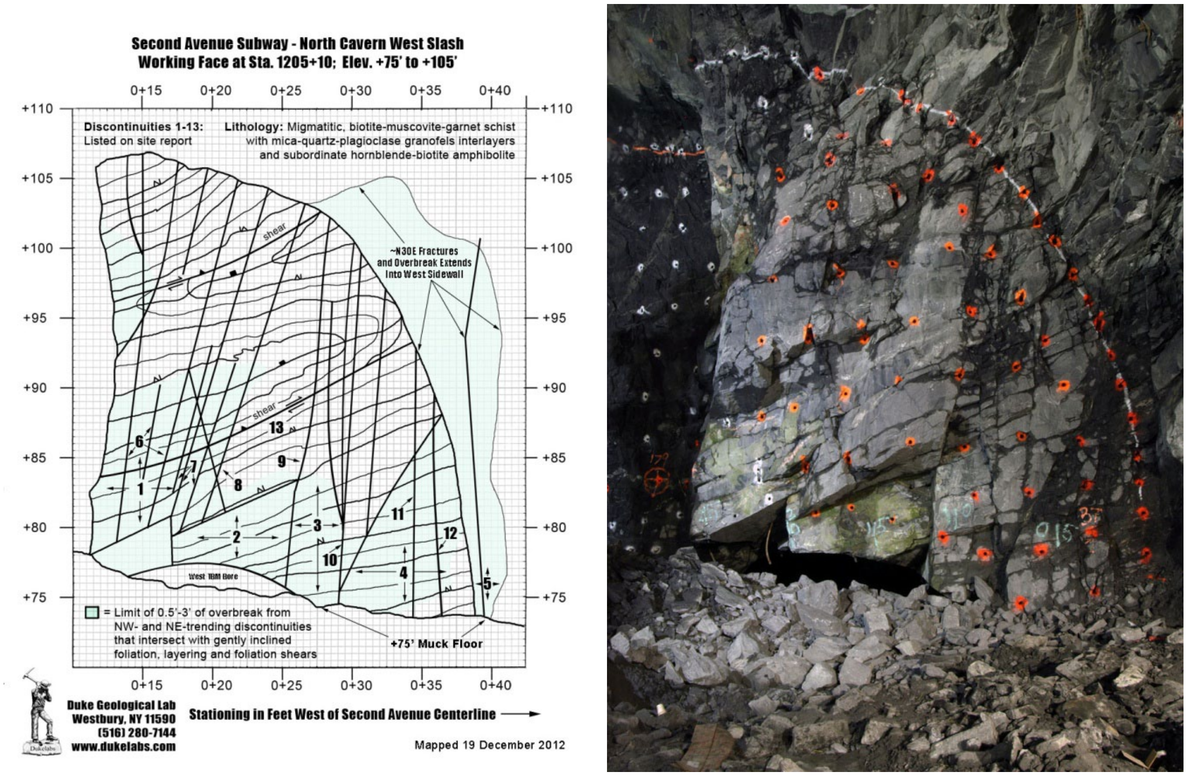


**Figure 14** - Geological map and southward view digital image of west slash of North Cavern below 85th street in NYC. Note the internal structure dominated by internally sheared gentle SE-plunging isoclinal recumbent folds of early SE-dipping gently inclined foliation in Hartland formation (OЄh). Recrystallization during folding and shearing produced penetrative mica foliation (Feature 13.) that formed parallel to transposed compositional layering. Gently inclined foliation joints are prominent discontinuities ($J_1$) and have formed parallel to the foliation and parallel compositional layering. These are intersected by steep NNE-trending ($J_2$) and NW-trending ($J_3$) joints and faults producing overbreak (light green shading). (Digital image taken 19 December 2012.)

Gently inclined foliation joints are prominent discontinuities ($J_1$) that formed parallel to the foliation and parallel compositional layering. Listed below Figure 14, these are intersected by steep NNE-trending ($J_2$) and NW-trending ($J_3$) joints and faults producing overbreak (green shading in Figure 14). Figure 15 shows the mineralized coatings on the prominent NW-trending $J_3$ joints.

Discontinuities of West Slash

NW-trending Set ($J_3$) – Associated with NW fault system
1 – N37°W, 81°SW, planar, smooth joint filled with K-feldspar and microcrystalline epidote
2 – N50°W, 77°SW, planar, smooth fault filled with K-feldspar and microcrystalline epidote
3 – N40°W, 88°NE, undulating, smooth joint filled with K-feldspar and microcrystalline epidote
4 – N27°W, 88°NE, planar, smooth joint filled with K-feldspar and microcrystalline epidote
5 – N20°W, 87°NE planar, smooth joint filled with K-feldspar and microcrystalline epidote

NNE-trending Set ($J_2$) – Associated with NNE fault system
6 – N35°E, 86°SE, planar, rough joints (3)
7 – Same as 6 (3 joints)
8 – N41°E, 77°SE, undulating, rough joint
9 – N25°E, 87°SE, slickensides of clay, steep down-dip slicks, planar, rough dip-slip fault
10 – N41°E, 62°SE to 90° at base of wall, undulating, rough reverse fault, seamy with 1.5” stilbite infilling and associated splays/joints (3)
11 – N37°E, 87°SE, undulating, stepped joint
12 – Same as 11

Foliation and Layering Joints ($J_1$)
13 – Foliation, layering and parallel $J_1$ joints vary from N66°E, 17°SE to N71°E, 20°SE

**Figure 15** - View of microcrystalline epidote (green) and overgrown K-feldspar mineral coating on NW-trending joints cutting Hartland rocks above southbound TBM tunnel. (Digital image taken 19 December 2012.)

To summarize, field studies prior to 1983 (See Figure 11.) and the new views provided by the Second Avenue Subway excavation prove that the internal structure of NYC is dominated by gentle SSW- to SE-plunging recumbent isoclinal long-limbed reclined $F_2$ folds of an earlier $S_1$ foliation. This has resulted in a gently inclined (<30°) southward dipping composite penetrative regional foliation ($S_1$ x $S_2$) striking NW to ENE that formed mostly parallel to compositional layering ($S_0$) and includes sill-like masses and thin veins of foliated granitoid. Steeper dips are found in $F_2$ hinge areas and along the transposed limbs of upright southward plunging $F_3$ folds where the earlier $S_1$ x $S_2$ regional foliation and compositional layering are locally oversteepened. In NYC, the superposed ductile structures are cut by foliation joints ($J_1$) produced parallel to the regional foliation and by steep NNE- to NE-trending ($J_2$) joints and dip-slip faults infilled by stilbite+calcite, by younger steep NW-trending ($J_3$) joints and strike-slip faults infilled by K-feldspar, microcrystalline epidote, quartz and pyrite, and by moderately dipping $J_4$ joints.

## Younger Folds

A geological map of Central Park (Merguerian and Merguerian 2004 and Figure 18 in our allied 2016 NYSGA field guide) shows the $F_4$ folds as a series of warps and open folds with axial traces that strike roughly N30°W and exhibit dominantly steep dips to the SW. The effects on map contacts of these late features is negligible but the scatter of poles to $S_3$ and localized northward plunges of $F_3$ fold axes and $L_3$ lineations are the result of post-$D_3$ deformation. (See Figure 11.) Brittle $S_4$ cleavages in the bedrock may have helped localize the late stage brittle NW-trending faults that cut the region. Idioblastic muscovite pseudomorphs after $D_3$ kyanite are common throughout Central Park and many other places throughout NYC. Their abundance suggests a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of wet granitoids throughout the Manhattan Prong (Brock and Brock 2001).

## Brittle Faults and Joints

Five generations of brittle faults and joints cut polydeformed bedrock units of the NYC area (Merguerian 2002, 2015). The brittle faults include NW-trending gently SW-dipping faults **(Group A)**, younger ENE-trending faults with moderate to steep dips **(Group B)**, subhorizontal faults and fractures **(Group C)**, and a steep dip-slip NNE-trending fault set **(Group D)** with thick clay- and zeolite-rich gouge zones. These are cut by NW- to NNW-trending strike-slip faults of the "Manhattanville" fault set **(Group E)**. Reactivation of older faults is quite common. The two youngest brittle fault sets (Groups D and E) cross cut all metamorphic structures in NYC and cut the Permian (295 Ma) glassy rhyodacite dikes.

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

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

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

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

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

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

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

## TECTONICS

Modern studies of the Appalachian orogen indicate that an arc-continent collision during the Taconic orogeny produced the imbrication of the oceanward facing passive continental margin of proto North America, development of primary penetrative metamorphic fabrics, $F_1$ though $F_3$ folding and the $D_2$ development of the St. Nicholas and Cameron's Line thrusts. Thus, the deformed Paleozoic bedrock of NYC may have originated within the deep-seated convergent walls of a subduction zone formerly situated off shore from proto-North America. The $D_1$ to $D_3$ folds and crosscutting fabrics that presumably formed during the Taconic orogeny are overprinted by two- and possibly three fold phases that, based on their style and general lack of attendant foliation, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics and are responsible for retrograde fabrics and mica growth. As such, the younger fold phases record the effects of the Acadian- and terminal-stage Appalachian (Alleghenian) orogenesis.

## FIELD TRIP GUIDE

Enough about the general geological background for NYSGA field trip A-5 slated for 01 October 2016. In the associated field guide, participants will find more specific details on the geology of our trip to Isham, Inwood, and Central parks with individual stop descriptions for each of our planned stops. Naturally, we will try to visit all of the intended stops and will also endeavor to fit in additional stops as the mood strikes. So pay attention, get your digital cameras ready and for heaven’s sake leave the iPods, iPhones, and other distractions in your bags as they are strictly forbidden during the day on our trip! Public humiliation and post-trip drive-by insults at your homes will be a deterrent. Remember that hammering and rock collecting in NYC parks is strictly forbidden.

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