Stratigraphy, structural geology and metamorphism of the Inwood Marble Formation, northern Manhattan, NYC, NY

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Introduction

Field studies of the Inwood Marble in the type locality together with field data from nearby engineering construction projects have afforded fresh sampling and petrographic study of the Inwood lithofacies in NYC. Consisting predominately of recrystallized dolomite and subordinate calcite marble the Inwood Marble was used for quarrying and mineral collecting yet the bland carbonate mineralogy and paucity of indicator minerals has impeded the use of the Inwood Marble to establish metamorphic conditions during tectonism in NYC.

Our allied studies of the Inwood Marble formation come from field mapping conducted on all of the natural exposures in the Inwood section of Manhattan starting in the mid-1970s, subsurface data collected during a mapping program in the East River section of NYC Water Tunnel #3 in 1985-86, and core examination combined with detailed mapping of a utility tunnel during 2009. In addition to collections made during field mapping, samples were studied from Isham Park, Inwood Hill Park and from other natural exposures in northern Manhattan and The Bronx (Figure 1).

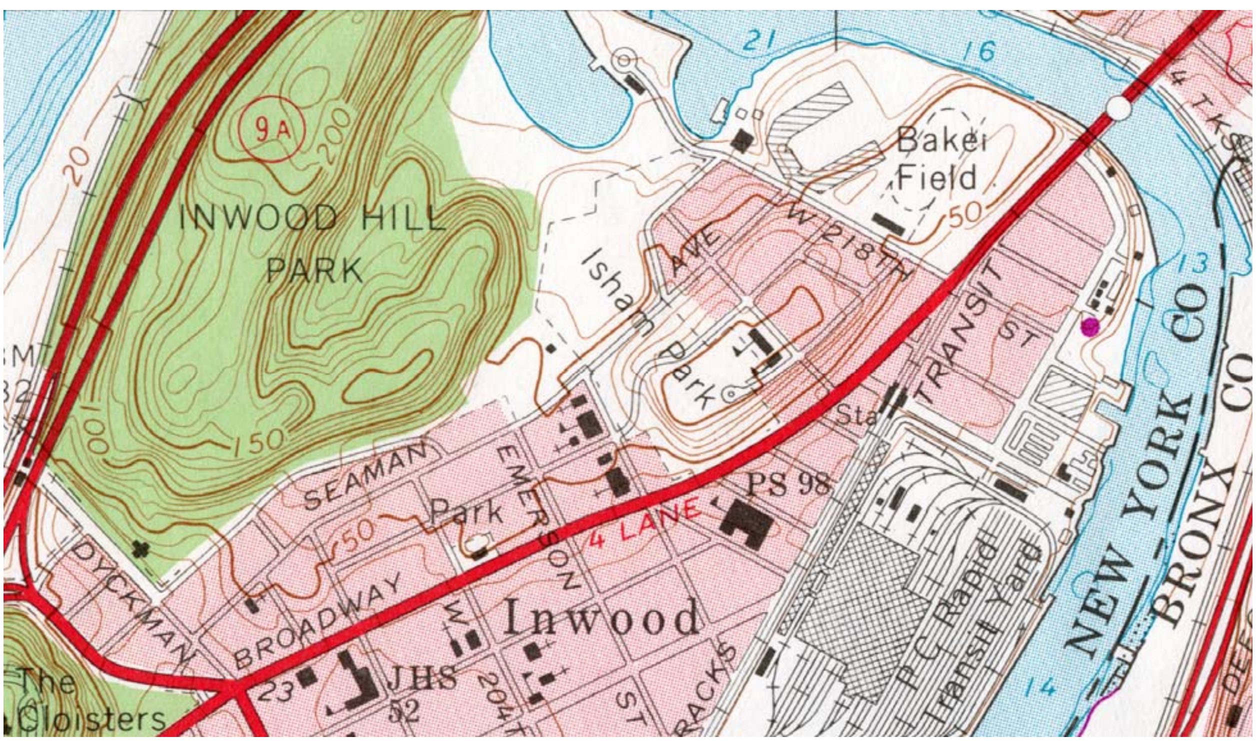

Figure 1 – Index map showing the street names and locations of Inwood Hill Park, Isham Park, Broadway, and Baker Field in northern Manhattan. (Portion of USGS Central Park quadrangle.)

The bulk of the samples used in this study were collected from the roughly 150’ deep excavation for a recently constructed utility tunnel which extends from the northeastern tip of Manhattan across to The Bronx and the allied shafts on either end. Samples were stained with HCl and Alizarin Red S stain using the technique described by Hutchison (1974) and roughly 45 thin sections were prepared for petrographic analysis. We are now in the midst of preparing samples for microprobe analysis. As such, the results presented here must be considered prime for near-term revision, a common side effect of scientific inquiry.

As this joint extended abstract is also a summary of our mutual examinations of the lithology, petrography and mineralogy of the Inwood Marble, to this end we provide a new geological map of Isham Park a geological section across northern Manhattan and a profile view of the bedrock mapped in the utility tunnel.

Previous Work

Utilization of the Inwood Marble began by the second half of the 17th century by early settlers of northern Manhattan and by the late 1700s commercial quarries were in full operation. This work continued until 1840 when mining ceased (Conklin, 1997). Mineral collectors were alerted before 1809 that the Kingsbridge locality, as it was known at the time (Dana, 1850, p. 651), was yielding crystal specimens of diopside, pyrite, pyrrhotite, rutile, titanite (sphene), tourmaline, along with other minor phases. By 1819, widening of the Spuyten Duyvil Creek provided power for the local marble industry. Construction of the Harlem Ship Canal (1885-1895) at Spuyten Duyvil and use of the excavated material as fill at Baker Field and along the shoreline of Manhattan still provides opportunities for avid mineral collectors. Manchester (1931; Plate 118) provides a wonderful photo dated 1887 of about 30 mineral collectors young and old from the New York Mineralogical Club in front of a “limestone” waste pile. Summarized below, excellent reports on the minerals collected from the Inwood Marble can be found in Beck (1842), Chamberlin (1888), Gratacap (1909), Manchester (1931), Conklin (1997), and Betts (2009).

The name **Inwood Limestone** was first proposed by Merrill (1890; p. 390) for roughly 600’-800’ of magnesian crystalline “limestone” extending from the Inwood section of northern Manhattan to the Morrisania section of The Bronx. Naturalists and geologists both before and after the official naming in 1890 have referred to the rock unit in various ways.

L. D. Gale's contributions (1839, and in an addenda in Mather [1843]), together provide a thorough account of the bedrock glacial geology of Manhattan in the format of a street-by-street diary before many buildings were constructed that obscured the terrain. Gale's diary, in Mather (1843, p. 581-604), provided the first detailed report on the orientation of structure and lithology of Manhattan Island including boring data and construction costs, but without a map. Gale describes (on p. 600 of Mather 1843) that the marble consists of “two varieties, coarse granular white or yellowish white, and compact white or bluish”.

Lewis C. Beck (1842), then professor of Chemistry at Rutgers College, reported on the mineralogy of New York State in Part III of the 5-volume Natural History of New York set published by the New York State Geological Survey. He refers to the Kingsbridge quarries and describes the rock found there as a foliated, granular dolomitic marble used primarily for burning into lime (p. 68). He compared the marble in New York City to those known from Westchester County (p. 254). Aside from the common minerals found in marble, Beck describes white crystallized pyroxene in association with the dolomitic marble. Crystals are up to several inches in size and are described as "eight-sided prisms, with two opposite sides often much larger than the other six, so as to present a tabulated form" as depicted in Figure 2.

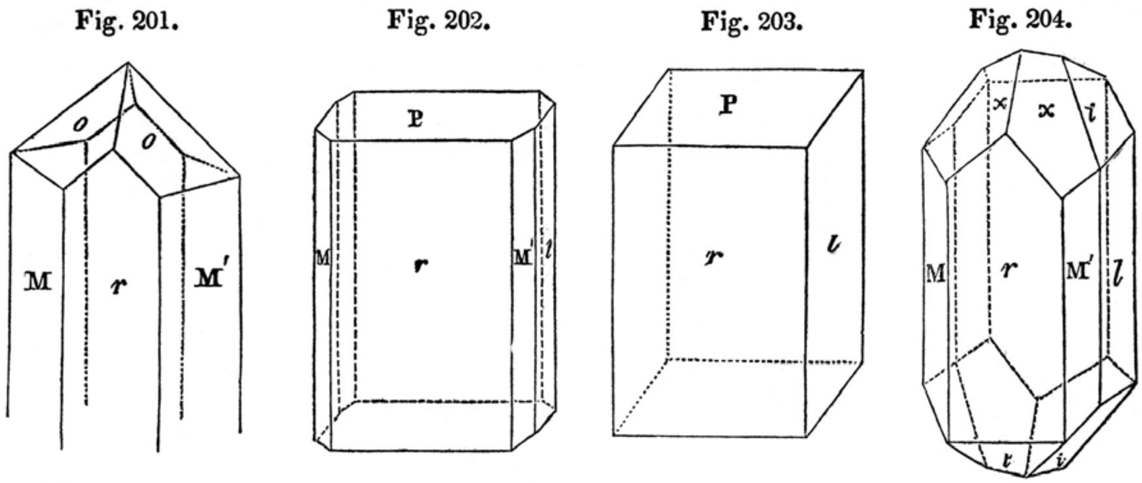

Figure 2 – Various crystal habits of white pyroxene (diopside) found by mineralogists in the Kingsbridge area, NYC as described on p. 291 in Beck (1842). Reproduced figures are found compiled on p. 487.)

Beck describes "white and bluish white tremolite" up to nine inches (22 cm) in length occurring in broad laminated masses cut by transverse seams (p. 300) with some specimens exhibiting "fasciculated groups of minute, diverging or interlacing fibres". Beck states that is "not unusual … to find the tremolite passing into pyroxene" and that the silicate minerals react to HCl as a result of inclusions of marble trapped in the crystal overgrowths. We will revisit this observation below under the section heading Metamorphism.

Beck also describes brown, yellowish or reddish brown crystals of tourmaline associated with reddish-brown mica in dolomitic marble from the Kingsbridge area (p. 358) with many fine specimens recovered during construction of the Harlem railroad line. The habit of the tourmaline is sometimes in the form of six-sided prisms (Beck 1842; figure 358, p. 358) with three terminal faces; many others tourmaline prisms show nine sides with various terminations.

The first detailed geologic map of the New York City area with a longitudinal profile section was published in Mather's treatise on the Geology of the First District of New York in 1843. Drawing heavily from Gale's investigations published in 1839, Mather's map of Manhattan (Figure 3) showed the distribution of Primary granite, gneiss, "limestone of New York County", serpentine (on Staten Island) and alluvial sand and marshland. Figure 3 also shows other marble quarries or areas underlain by marble (blue lensoidal areas in Figure 3) extending along strike to the northeast of NYC, following Maclure's and Dana's attempts at lithostratigraphic correlation.

Figure 3 – A portion of the first geological map of New York County and vicinity showing the extent of "Primitive" limestone (blue lenses) and crystalline rocks (pink). (From Mather, 1843.)

A north-south geological section of Manhattan or New York Island accompanied a 114-page report by Issachar Cozzens in 1843. Cozzens' profile section shows a continuous granite substrate overlain by Primitive granite, syenite, gneiss, hornblende slate, quartz rock, serpentine, limestone (colorized yellow in Figure 4), and glacial "diluvium".

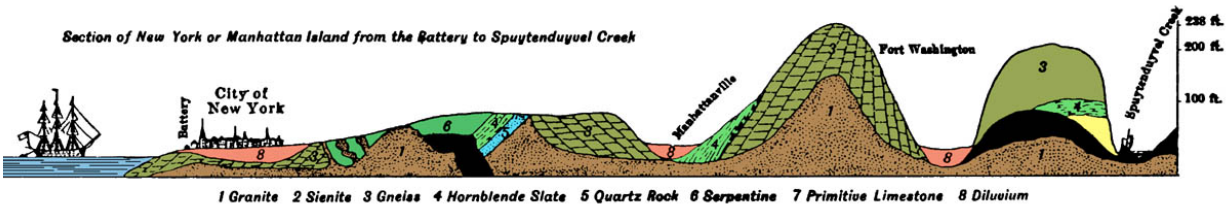

Figure 4 – S to N profile of Manhattan, from Battery (L) to Spuyten Duyvel Creek (R), showing shape of land surface (shaded, below) and inferred geological relationships as determined by Issachar Cozzens. (Adapted from G. P. Merrill, 1924, fig. 43, p. 238; after Cozzens, 1843).

His amusing descriptions are worthy of note as are his field identification of “white, gray and light blue, granular, coarse marble” from the Kingsbridge area. The mineral catalogue identifies quartz, feldspar (“in veins of Primitive Limestone”), tourmaline (both black and brown varieties), tremolite, white augite (diopside of the modern usage), titanium (rutile?), and chalcopyrite in association with the marble.

Merrill et al. (1902) published the first comprehensive geologic map of New York City in their United States Geological Survey New York City Folio (#83). In keeping with the stratigraphy proposed by J. D. Dana for Dutchess County, Merrill and coworkers chose to use the name Hudson Schist for the schistose rocks of New York City and considered them to be of Silurian age. The stratigraphy for New York City by 1902 was, from the top down, the Hudson Schist successively underlain by the Stockbridge Dolomite (Cambrian to Silurian), the Poughquag Quartzite (Cambrian), and finally the Fordham Gneiss (Precambrian). The pioneering work by Merrill and coworkers set the stage for a series of detailed investigations in the early 1900's by many geologists that helped define the lithology and structure of New York City bedrock units and enabled the development of massive engineering construction projects including power generation, water supply, transportation and sewage disposal.

Professor Charles P. Berkey of Columbia University, having been hired as a consulting geologist for the New York City aqueduct project, published a great amount of data on the region’s geology including a view of a proposed Harlem River crossing of City Water Tunnel #1. Berkey (1911, 1948) also detected Inwood “limestone” in SE Manhattan where it showed up in borings as two parallel belts but detailed descriptions of the stratigraphy and mineralogy were absent. These belts are southward continuations of the two thin marble belts detected earlier by J. F. Kemp (1887, 1895) in the East River channels.

Following the pioneering work of E. F. B. Knopf (1962) on her descriptions of the Wappinger Group carbonates from Stissing Mountain in Dutchess County, five subunits or “facies” of the Inwood Marble in Westchester County have been proposed by Hall (1968a, b) based upon his work in White Plains, NY. Baskerville (1992) did not adopt Hall’s proposed subdivisions and describes four Inwood Marble facies in NYC. Baskerville's maps of Bronx County (1992) and New York County (1994) have compiled knowledge on the extent of the Inwood Marble in New York City. Subsequent new construction in NYC since the 1990s indicates that Inwood is more extensive than shown on his maps.

Here, we present the stratigraphy mapped in northern Manhattan as we view it (an attenuated, thin formation – the result of intense folding and shearing) and make little attempt in this report to provide sweeping correlations with Hall. This will become a topic of our continued work in this area.

Mineralogy of the Inwood Marble in New York City

The mineralogy of the Inwood Marble has been studied by amateur and professional mineralogists for over two hundred years as discussed in an earlier section. Adding new details learned from our hand sample and petrographic analysis we present the following compilation of minerals associated with the Inwood Marble of Manhattan with the understanding that not all of the historically reported phases have been identified in our preliminary study. The phases found in our study are indicated by an asterisk [*] and those found in this study but not reported by anyone else are indicated in bold. (After Beck 1842, Chamberlin 1888, Gratacap 1909, Manchester 1932, Dana 1850, Conklin 1997, and Betts 2009.)

Actinolite (acc. Baskerville, 1992).
Apatite [*]
Calcite [*]
Chalcopyrite [*]
Chlorite [*]
Chondrodite
Diopside [*]
Dolomite [*]
Fosterite
Graphite [*]
Garnet (var. Grossular) [*]
Microcline [*]
Phlogopite [*]
Plagioclase [*]
Pyrite [*]
Pyrrhotite [*]
Quartz (milky and smoky varieties) [*]
Rutile (acicular xls in mica acc. Gratacap 1909)
Sericite [*]
Sphalerite
Sphene [*]
Talc
Tourmaline (Dravite-uvite acc. Betts 2009) [*]
Tremolite [*]
Vesuvianite/Idocrase [*]
Wollastonite
Zoisite [*]

Geology of the Inwood Marble Formation of Northern Manhattan

General

Formed from metamorphosed lower Paleozoic (~550 million year old) shallow water marine carbonate and clastic sediment, the Inwood Marble now consists of dolomitic and lesser calcitic marble. It underlies the Inwood section (type locality) of northern Manhattan, the Harlem lowland NE of Central Park, occurs as thin belts in the East River channel and in the subsurface of southeastern Manhattan and also crops out in The Bronx and Westchester County. These exposures are correlative with a laterally continuous outcrop belt of Cambrian to Ordovician carbonate rocks formed along the entire Appalachian chain along the east coast of North America during an open ocean stage of Appalachian mountain building.

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

A cut-away cross-sectional view of northern Manhattan has been drawn on a Google basemap below in Figure 5. Note the interpretation of the structure based on our field work over the years suggesting that the rocky ridges of northern Manhattan are overturned synforms of Manhattan Schist rooted by a major shear zone known as the St. Nicholas thrust (Merguerian 1983) that cuts both the Inwood Marble and locally, the Walloomsac Schist. Below the flat plains of northeastern Manhattan, the Inwood is folded upward to the earth’s surface along the eroded cores of two F_3 antiforms and an intervening F_3 synform overturned toward the NW.

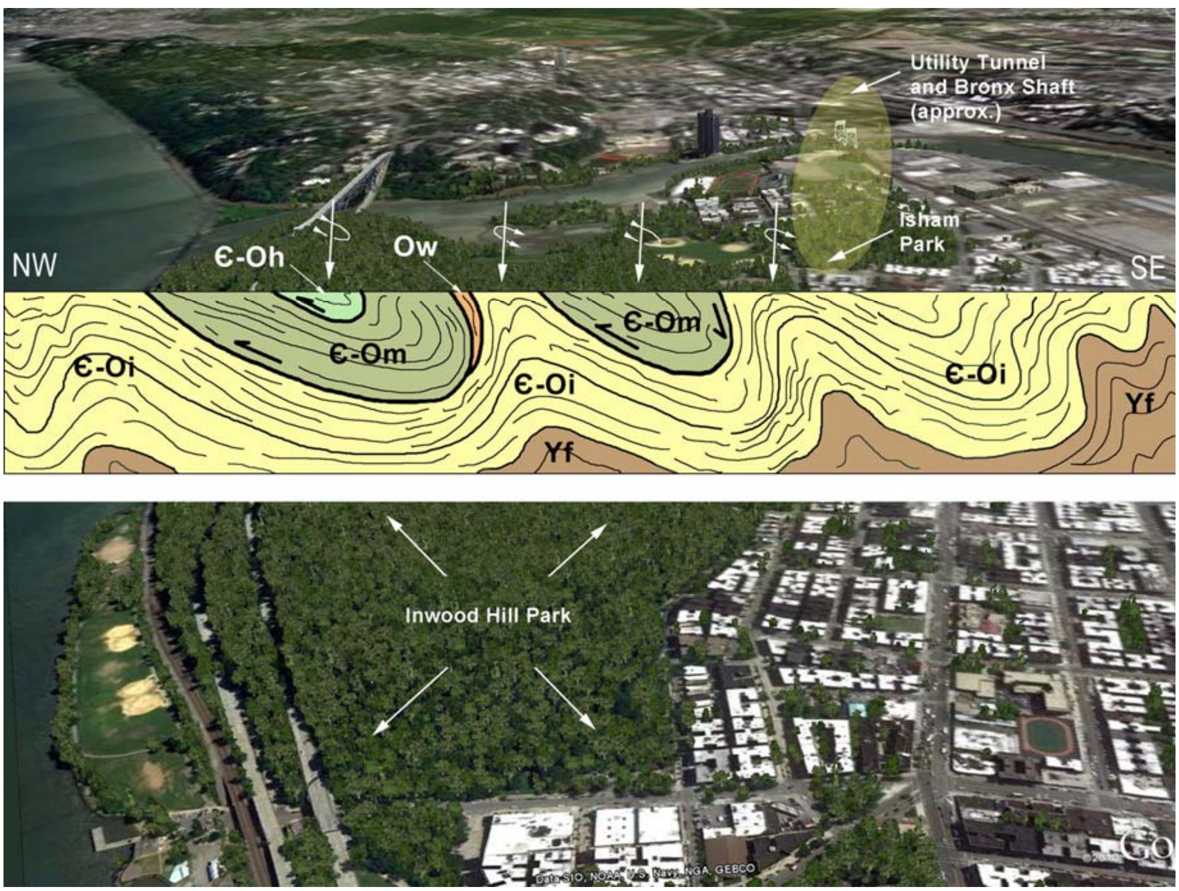

Figure 5 – Oblique northeastward Google Earth terrain view of northern Manhattan and The Bronx with Dyckman Street near the edge of the lower section. Interpretive geological section in cut-away slice roughly across Isham Street in Manhattan. Proposed along-strike correlation between Isham Park and the Bronx Shaft of the a utility tunnel (approximately located for security reasons) shown in yellow shading marks the along strike extension of the SE-dipping limb of an overturned SW-plunging F_3 antiform. Note the positions of major overturned F_3 antiforms and synforms (shown in white), the folding of sheared lithologic contacts, and the position of a thin slice of Waloomsac Schist (Ow) in Inwood Hill Park.

Inwood Hill Park

The geology of Inwood Hill Park is published elsewhere (Merguerian and Sanders 1991) but a brief summary is in order. Inwood Hill Park is located in the extreme northwest corner of Manhattan Island. (See Figure 1.) The park is bordered by Dyckman Street on the south, the Hudson River on the west, Spuyten Duyvil (Harlem Ship Canal) on the north, and Payson and Seaman Avenues on the east. Isham Park occupies the flat area northeast of Inwood Hill Park extending eastward to Broadway between Isham and West 214th Streets.

By entering Inwood Hill Park and following the path westward past the playground and ball fields the first prominent ridge encountered is composed of kyanite-garnet gneiss and schist of the Manhattan Schist (Ꞓ-Om). 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 Manhattan Schist (Ꞓ-Om) crops out. Rocks exposed on the ridge are massive muscovite-biotite-plagioclase-quartz-garnet-kyanite gneiss and schist with weathered kyanite+sillimanite nodules. The structure of the ridge is a south-plunging F_3 synform overturned toward the northwest. (See Figure 5.) The S_3 foliation in the schist is related to F_3 folds with axial surfaces oriented N4l°E, 75°SE and south-plunging hingelines. The F_3 structures are superimposed on an older gently inclined S_2 metamorphic layering which trends across Manhattan at roughly N50°W, 25°SW (Merguerian, 1983, 1996).

The contact between the Manhattan and Inwood Marble or Walloomsac Schist (the St. Nicholas thrust) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. At the base of the Manhattan Schist a 0.5 m layer of mylonitic amphibolite is deformed by F_3 folds. Unlike the amphibolite in the schist above this zone which contains subidiobastic hornblende this amphibolite has been affected by intense shearing in the S_2 foliation. Green hornblende porphyroclasts are set in an anastomosing S_2 foliation consisting of colorless clinoamphibole, biotite and quartz ribbons.

Directly beneath the Henry Hudson Bridge where a dirt trail leads down to the river, a coarse-grained gray-white calcitic marble with differentially eroded calc-silicate nodules is exposed at low tide. It is suspected that the calcite marble exposed at the low-tide mark is an interlayer (Balmville equivalent) in the Walloomsac Schist (Ow). Here the Walloomsac consists of biotite-quartz-plagioclase-graphite and kyanite with abundant garnet porphyroblasts and exhibits an S_2 mylonitic foliation composed of mm-scale ribboned and polygonized quartz with recrystallized reddish pleochroic biotite. The S_2 foliation strikes N45°E, and dips 55°SE with a strong down-dip lineation plunging 50° into S34°E. The thrust zone is structurally complex consisting of intercalated lithologies of the Walloomsac and Manhattan together with mylonitic amphibolite. Muscovitic Hartland rocks can be found along strike to the south at the highest point in the ridgeline, presumably locating Cameron's Line.

Isham Park

Isham Park contains near continuous exposure of white to blue-white Inwood Marble cut by high-angle conjugate joints which have facilitated the weathering process by allowing aqueous solutions to permeate the rocks (Figure 6). Several lithologies occur such as dolomitic marble, calcite marble, foliated calc-schist, and dolomitic marble containing siliceous layers and calc-silicate aggregates that stand in relief as knots on the weathered surface (Figure 7).

Figure 6 – Northward view of highly jointed east-dipping Inwood Marble exposed in Isham Park in Manhattan. Although well-foliated, the obvious compositional layering preserves ancient bedding in the rock mass. (CM digital image taken 19 August 2007.)

Figure 7 – View of a cluster of aligned 6-12 cm tremolite porphyroblasts found to overgrow the S_1 x S_2 composite foliation in dark gray marble with interlayered calc-schist. We are convinced that these are pseudomorphs after diopside. Exposed portion of knife is 6 cm long. (Digital Image by C. Merguerian, 16 November 2008.)

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

A recently compiled preliminary geological map of Isham Park is shown below as Figure 8. Four major lithotypes are shown – white, coarse-textured calcite marble, white to gray dolomitic and calcite marble, marble, schist and calc-silicate rock and well-layered white to gray dolomitic marble. Although variable, the Inwood trends roughly N55°E, 73° SE and forms the eastern overturned limb of a large F_3 synform which is cored to the west by the Manhattan Schist in Inwood Hill Park as described earlier. (See Figure 5.)

The marble, schist, and calc-silicate unit is intensely sheared and internally deformed by F_2 tight- to isoclinal and F_3 asymmetric folds producing complex interference patterns, boudinage and internal shearing of schistose boudins over a meter in dimension (Figure 9). Clearly, the marble + schist + calc-silicate sub-unit shows overthickening and repetition of layers however most of the remaining carbonate sequence in Isham Park is homoclinal. Perhaps the overthickening of the sub-unit is the result of the buttressing effect of the massive, well-layered marble that surrounds it. Asymmetric south-plunging F_3 folds are locally developed in the Inwood of Isham Park (Figure 10). Abundant examples of boudinage of the quartzite and calc-silicate layers into lenses occur presumably the result of ductility contrast between the more competent siliceous rocks and the surrounding marble (Figure 11).

The broad outcrop-scale folding and warping of the S_1 x S_2 fabric is controlled not only by regional F_3 folds but also are affected by open 2m-wavelength SE-plunging F_4 folds (~ 55° plunge) with axial planar slip cleavage (S_4), solution cleavage and joints trending ~ N-S with moderate to steep dips. (See Figure 8.)

Some, but not all of the stratigraphic units found at Isham Park were also found in the utility tunnel as described below.

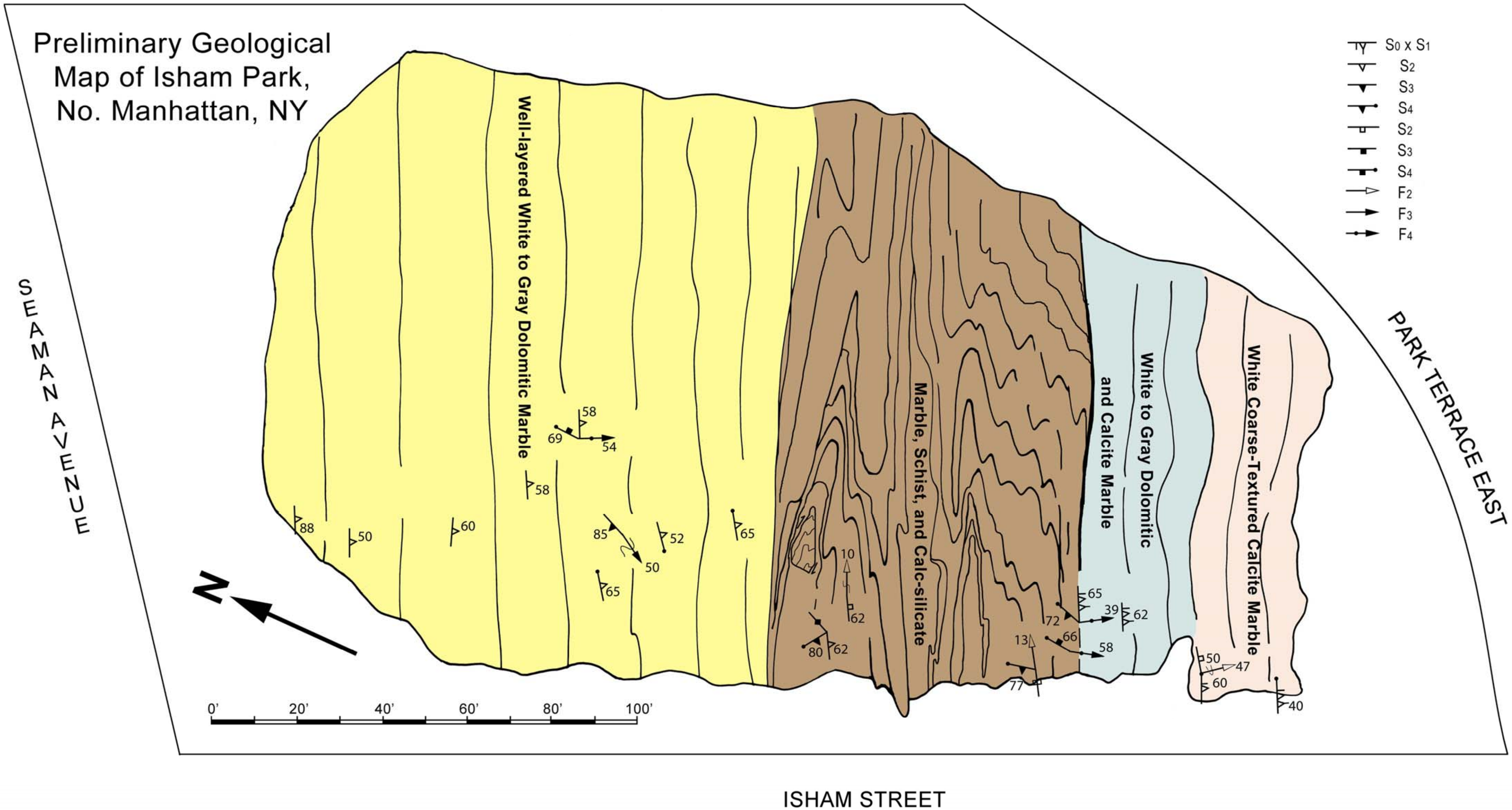

Figure 8 – Preliminary geological map of Isham Park showing the four major lithologic varieties and the form lines of the composite S_1 x S_2 foliation and parallel compositional layering. Discussion in text.

Figure 9 – View on internal deformation in the Inwood Marble of Isham Park in Manhattan showing shearing and disarticulation of resistant quartzite and calc-silicate interlayers and meter-scale blocks of marble and the overall complex patterns produced by gently plunging upright F_2 isoclinal folds. (CM digital image 08 Sept 2007.)

Figure 10 – View of a south-plunging asymmetric F_3 z-fold of layering and foliation in the Inwood Marble of Isham Park in northern Manhattan. Pen points in plunge direction. (CM digital image taken 08 Sept 2007.)

Figure 11 – View of disarticulated boudin of quartzite (former chert?) in differentially weathered Inwood Marble exposed in Isham Park in northern Manhattan. Such features result from the mechanical differences between the competent quartzite and the less competent marble which undoubtedly flowed around the resilient quartzite layers and lenses. Note 9-cm long black pocket knife to left of boudin for scale. (CM digital image taken 19 August 2007.)

Utility Tunnel

For security reasons we will not identify the exact position of the utility tunnel and its two shafts. Suffice to say that the tunnel connects Manhattan and The Bronx near the northeastern tip of Manhattan Island. (See Figures 1 and 5.) In 2009 the Merguerians were retained to perform mapping of the tunnel and the Bronx shaft and the results of these investigations are summarized below.

Texture

Inwood Marble textures vary from foliated to granoblastic with individual crystals ranging from <0.1mm to ~ 1.0 cm in the coarse-textured calcite marble sub-units. The primary foliation (S_1 x S_2) is a composite fabric found parallel to compositional layering in most of Isham Park and also in the utility tunnel and shafts. It is principally defined by major color changes controlled by compositional variations at the outcrop scale and by aligned phlogopite and graphite flakes and by flattened and lineated brown tourmaline with a hand lens. Late porphyroblasts of calcite, diopside, tremolite, and plagioclase overgrow the S_1 x S_2 foliation and are typically a few cms in size but the tremolite can range up to 12 cm in long dimension as also found at the east end of Isham Park. (See Figure 7). [***Remember - No Hammering or Rock or Mineral Collecting Allowed in NYC parks!***]

Stratigraphy

Based on our investigations at the utility tunnel site, the Inwood Marble of northern Manhattan and The Bronx is highly variable in mineralogy and lithology often with quartzose and micaceous layers and lenses. We have identified massive whitish dolomitic marble, whitish-gray, blue, and brown dolomitic marble and subordinate calcite marble and calc-schist. These primary marble lithotopes are intimately interlayered on scales ranging from centimeters to meters with white coarse-textured marble, brown to tan micaceous marble and calc-schist, calc-silicate layers rich in tremolite and tan- to gray quartzite. Interlayering of all lithotopes has been detected on scales ranging from millimeters to decimeters and the stratigraphy is somewhat confusing as a result of internal shearing and deformation but over 75.5' of stratigraphy has been found in the utility tunnel Bronx shaft as shown in Table 1.

Table 1 - Inwood Marble sub-units – Utility tunnel – Bronx Shaft

Sub-unit	Thickness (Feet)
1 - Calc-schist and calcite marble	> 6'; top not exposed
2 - Coarse-textured calcite- and dolomitic marble	4.0
3 - Dark gray marble and calc-schist	3.0
4 - White to buff-colored dolomitic marble	2.0
5 - Dark gray to blue dolomitic marble	5.0
6 - White to buff-colored marble	11.0
7 - Dark gray, blue and brown marble, calc-schist	11.0
8 - Thinly layered whitish-gray and -tan marble and calc-schist	10.5
9 - Brown calc-schist, gray marble, calc-silicate rock and quartzite	11.5
10 - Whitish-tan micaceous marble	>11.5'; base not exposed

Aggregate thickness exposed > 75.5'

The ten sub-units forming the stratigraphy of the Inwood Marble in the Bronx shaft of the utility tunnel is depicted in Figure 12 and described below. Based on our petrographic and hand-sample analysis, the color banding in the marble is the result of concentrations of the following:

Whitish = marble ± sericite
Greenish = marble ± diopside ± chlorite
Whitish to tan = marble ± sericite ± tremolite
Dark gray to blue = marble ± graphite ± pyrite ± rutile(?)
Brown to peach-colored = marble ± phlogopite ± tourmaline (dravite) ± pyrite ± graphite

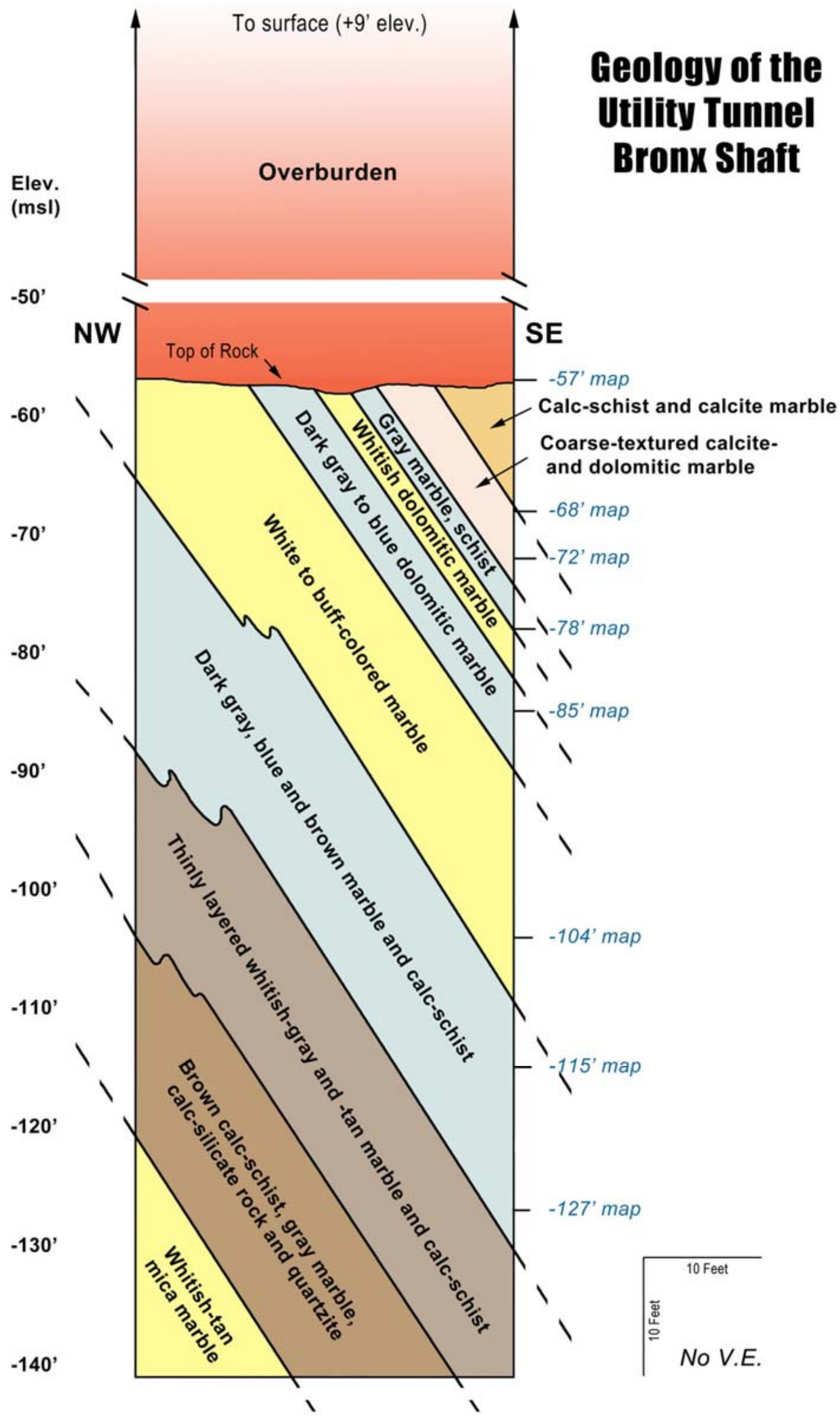

Figure 12 – NW-SE profile section across the Bronx shaft of the utility tunnel showing the homoclinal stratigraphy and the positions of the eight plan view maps (in blue) used to construct the section. (Geological mapping by C.M. and J.M. Merguerian, 2009.)

Brief Descriptions of Inwood Marble Members (Utility Tunnel Bronx Shaft)

1 - Calc-schist and marble – Well-foliated fine- to medium-textured brown phlogopitic calc-schist and interlayered white calcite- and subordinate dolomitic marble. (>6.0'; top of section - unknown thickness.)

2 - Coarse-textured calcite marble and dolomitic marble – Massive, thick- to thinly-layered whitish coarse-textured calcite marble interlayered with medium-textured tan- to peach-colored phlogopitic dolomite marble. (4.0' thick.)

3 - Dark gray marble with tan calc-schist interlayers – Massive, variegated light gray to dark gray to bluish fine- to medium-textured dolomite- and calcite marble with thin to laminated interlayers of tan phlogopitic marble and schist. (3.0' thick.)

4 - White to buff-colored marble – Massive, indistinctly layered whitish to buff-colored fine- to medium-textured dolomite- and subordinate calcite marble. (2.0' thick.)

5 - Dark gray to blue marble – Massive, variegated dark gray to blue medium-textured dolomite- and calcite marble with thin to laminated interlayers of tan phlogopitic marble and schist. (5.0' thick.)

6 – White to buff-colored marble - Massive, indistinctly layered whitish, whitish-green to buff-colored fine- to medium-textured dolomite and subordinate calcite marble. (11.0' thick.)

7 - Dark gray, blue, and brown marble – Massive, whitish-gray to dark gray-blue, brown- and whitish green medium-textured dolomite- and calcite marble with thin interlayers of whitish-tan calc-schist. (11.0' thick.)

8 - Thinly layered whitish-gray and -tan marble and calc-schist – Thinly interlayered whitish-gray, whitish-green, and tan, fine- to medium-textured dolomite- and calcite marble, calc-schist, and quartzite. (10.5' thick.)

9 - Brown calc-schist, whitish gray marble, calc-silicate roc k and quartzite - Well-foliated brown calc-schist with interlayered medium-textured whitish-gray marble, calc-silicate rock and tan-gray quartzite. (11.5' thick.)

10 - Whitish-tan micaceous marble – Massive, fine- to medium textured whitish to whitish-tan micaceous marble. (> 11.5'; base not exposed - unknown thickness.)

Geological Structure

Foliation in the utility tunnel and associated Bronx shaft was parallel everywhere to compositional layering. Our interpretation, owing to the similarity in stratigraphy, structure, and orientation is shown in Figure 5 where we correlate both stratigraphic sequences studied in detail (Isham Park and the utility tunnel and shafts) to be on strike and occupy the SE-dipping limb of a

SW-plunging F_3 antiform overturned toward the NW. Furthermore, comparisons of stratigraphic thicknesses and stratigraphy suggest that most if not all of the utility tunnel section of Figure 12 is exposed at Isham Park. We view the Bronx shaft section to correlate with roughly the southern third of exposed Inwood Marble at Isham Park.

Metamorphism

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

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

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

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

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

Thus, Inwood metacarbonate rocks at Isham Park and the utility tunnel site contain minerals that are consistent with metamorphic facies estimates from the kyanite-staurolite-garnet-bearing pelitic rocks surrounding the marble of NYC. Late tremolite pseudomorphic after diopside (See Figure 8.) suggests that retrograde metamorphism has affected the rock mass in the replacement of diopside, a higher grade phase. As this is a work in progress, we continue our efforts in mapping, petrography, and x-ray microprobe studies to better refine this preliminary study.

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