

# **Structural Implications of Walloomsac and Hartland Rocks Displayed by Borings in Southern Manhattan**

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## **INTRODUCTION**

Over the past three years we have been examining drill core that has penetrated bedrock from various construction sites throughout NYC. Careful examination of rock core, sampling, and petrography have been fruitful in extending mapping to southern Manhattan from areas of natural exposures north of 59<sup>th</sup> Street. The outcrop and drill core data support the view that at least three distinctly different and mappable schistose units constitute the formation known as the Manhattan Schist. Separated by ductile faults known as the St. Nicholas thrust and Cameron's Line the schistose rocks, from their structural base upwards, are known as the autochthonous Walloomsac formation and allochthonous Manhattan and Hartland formations.

Drill core examined from eleven separate locations south of Canal Street in Manhattan indicates that the map of Baskerville (1994) is incorrect in that he identifies the region to be underlain by Manhattan Schist. Rather, internally sheared and migmatized units of the Hartland and Walloomsac formations and associated granitoid rocks clearly predominate. This extended abstract outlines the distinction between the various schist units in four of the more interesting sites and offers preliminary views of structural and tectonic implications of our findings.

## **GEOLOGY OF NEW YORK CITY**

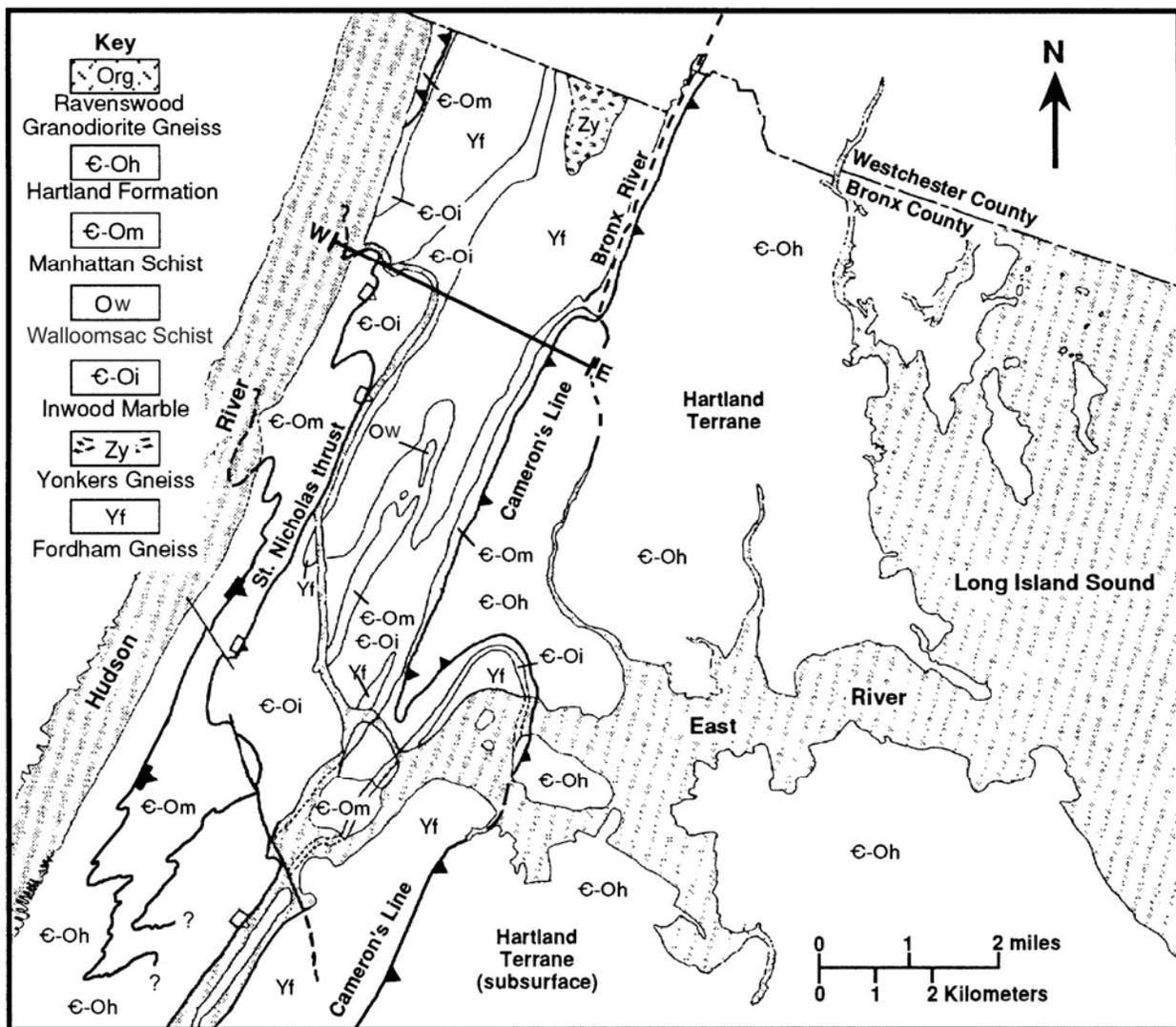
NYC's durable underlying structure consisting of glacially-sculpted Paleozoic and older crystalline rock has enabled the construction of enormous towering skyscrapers and has supported the construction of multiple levels of subsurface engineering. First studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, the bedrock geology of the NYC area was mapped in systematic detail beginning in the mid- to late 1800's by L. D. Gale (1839, 1843), W. W. Mather (1838, 1840, 1843), and F. J. H. Merrill (1890, 1898, 1902). NYC is situated at the extreme southern end of the Manhattan Prong, 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 unconformably beneath predominately buried Mesozoic rocks, Cretaceous strata, and overlying Pleistocene (glacial) sediment that cap Long Island and much of Staten Island.

### **Bedrock Stratigraphy of New York City**

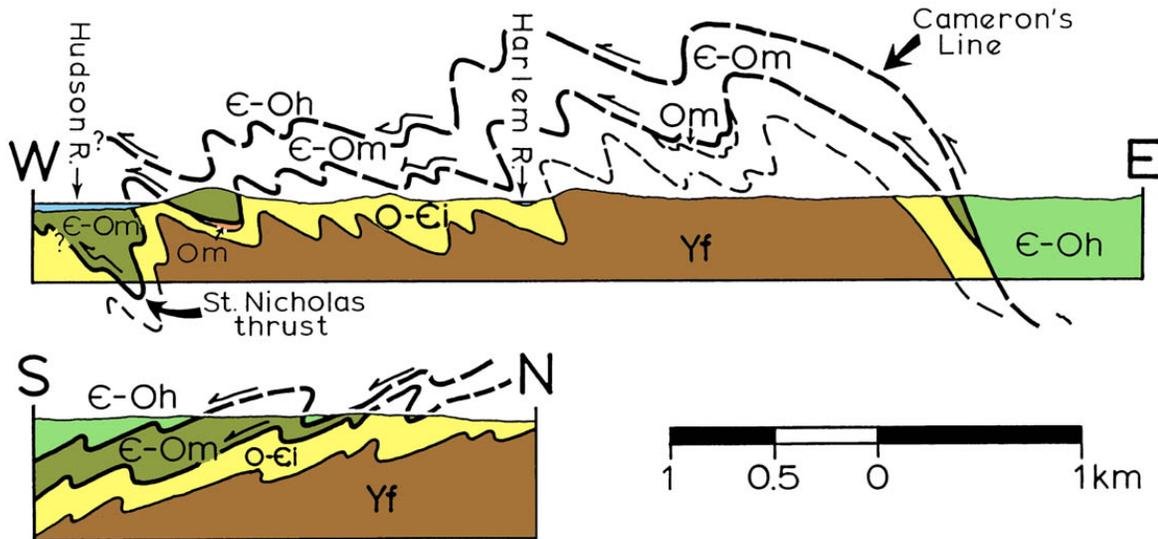
In 1890 (p. 390), Merrill named the Manhattan Schist for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, 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 Schist (rather than Manhattan Schist) for the schistose rocks of NYC.

Over three decades of investigation into the bedrock geology in NYC by the senior author suggests that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three mappable units (Figure 1). These 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 correlative of the Hartland Formation of western Connecticut (Merguerian 1981, 1983, 1985, 1987; Merguerian and Merguerian, 2004). The three schist units are imbricated by regional ductile faults known as the St. Nicholas thrust and Cameron's Line (Merguerian 1983, 1994, 1996, 2005) as indicated in the cross section across the northern tip of Manhattan into the Bronx (Figure 2).



**Figure 1** – Geological map of New York City showing the generalized structural geology of the region. Adapted from 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.



**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.

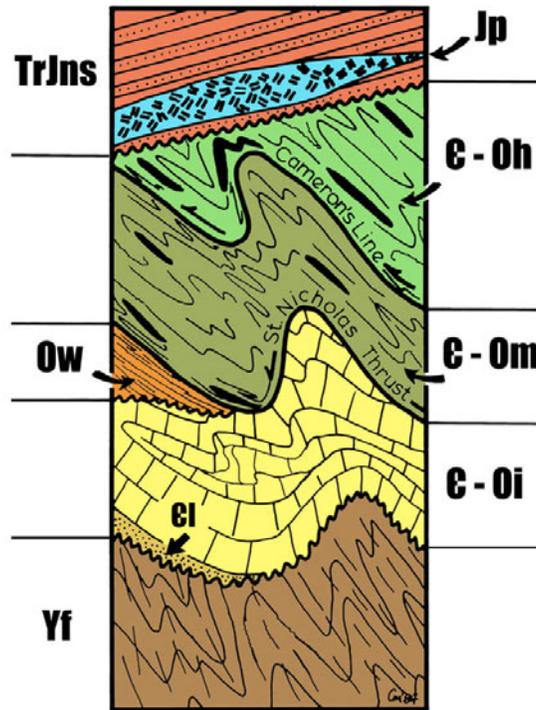
Keyed to Figure 1, the sections in Figure 2 illustrate the complex structural- and stratigraphic interpretation that has emerged over the years. The W-E section shows the general structure of NYC across northern Manhattan and how the St. Nicholas thrust and Cameron's Line overthrusts place the Manhattan Schist and the Hartland Formation above the Fordham-Inwood-Walloomsac basement-cover sequence. The major 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 stratigraphic units exposed in Central Park in central Manhattan and the effects of the late NW-vergent folds.

### Metamorphic Stratigraphy

The three schistose units of NYC are relatively easy to subdivide in the field and in drill core examination. The units are coeval, in part, and range in age from Late Proterozoic through Mid-Ordovician, based on regional correlation. The schistose units are separated by ductile shear zones known as the St. Nicholas thrust and Cameron's Line (Figure 3). Descriptions of the three units follow, starting with the structurally highest rocks of the Hartland formation.

**Hartland Formation.** The structurally high Hartland formation (ε-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-garnet-kyanite-sillimanite schist (Figure 4) with cm- and m-scale layers of gray quartzose granofels, and greenish amphibolite±garnet±biotite. (*Note: Minerals in lithologic descriptions are listed in relative decreasing order of abundance.*) Although typically not exposed at the surface, the Hartland underlies most of the western part and southern half of Manhattan and the eastern half of The Bronx. Merguerian (1983) extended the formation into NYC because they are lithologically identical to and along strike with the Late Proterozoic to Ordovician Hartland

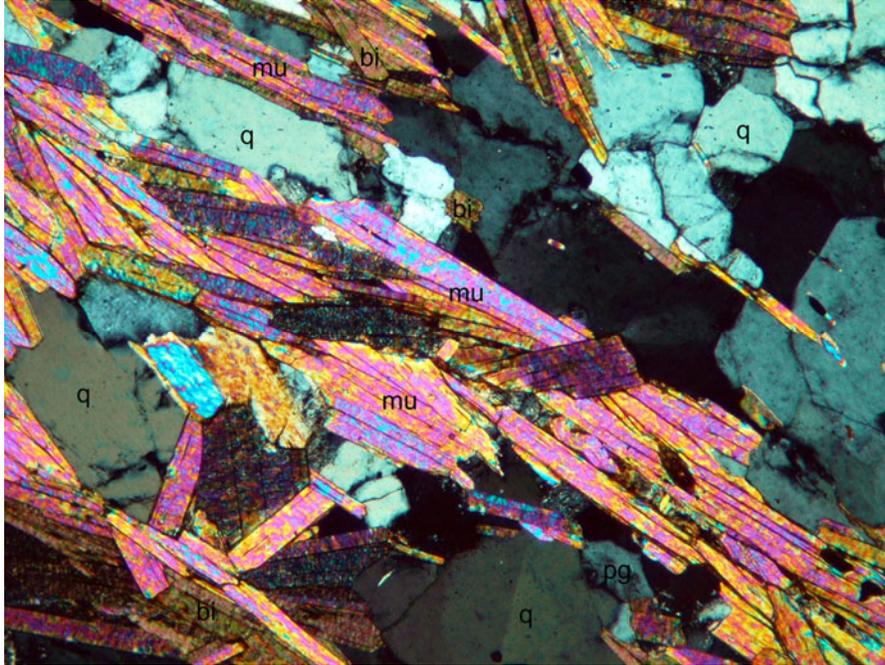
Formation of western Connecticut and Massachusetts. The Hartland represents metamorphosed deep-oceanic shale, interstratified graywacke, and volcanic rocks formed offshore adjacent to North America during Late Proterozoic to Early Paleozoic time.



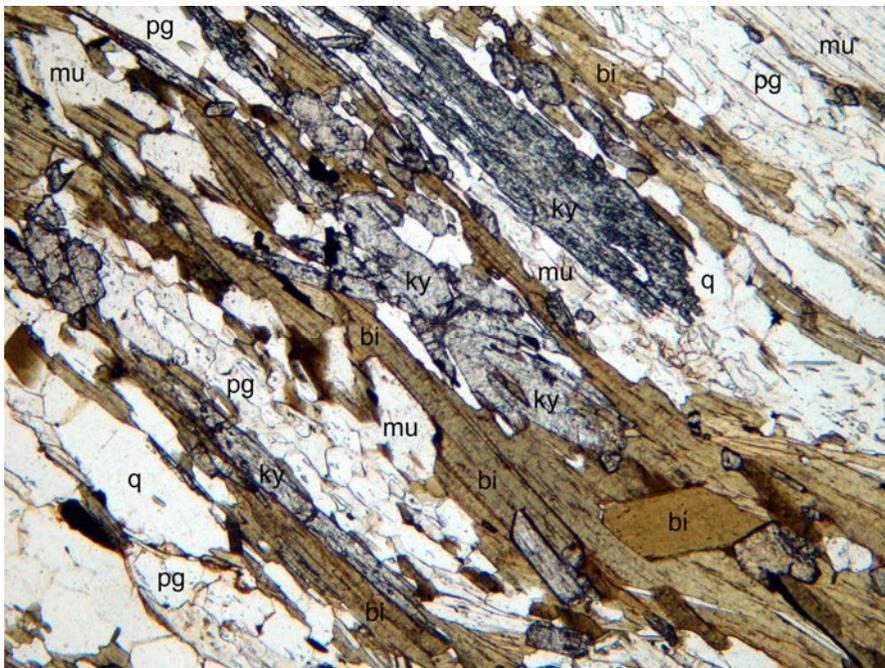
**Figure 3** – Bedrock stratigraphy of New York City as described in text. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades sheet (Jp).

**Manhattan Schist.** The Manhattan consists of very massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist (Figure 5). The unit is characterized by the lack of internal layering, 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 quartzose granofels. The unit is a major ridge former in northern Manhattan, a result of its durability to weathering owing to the lack of layering and presence of wear-resistant garnet, kyanite, and sillimanite.

The Walloomsac Schist and the Inwood Marble are structurally overlain by the Manhattan Schist (E-Om) which forms the bulk of the “exposed” schist on the island of Manhattan and most northern Central Park exposures. The Manhattan Schist is lithologically identical to Hall’s Manhattan B and C and the Waramaug and Hoosac formations of Late Proterozoic to Ordovician ages in New England. These allochthonous rocks, which contain calc-silicate interlayers in western Connecticut, represent displaced metamorphosed sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Late Proterozoic to Early Paleozoic continental margin of ancestral North America (Merguerian, 1977).

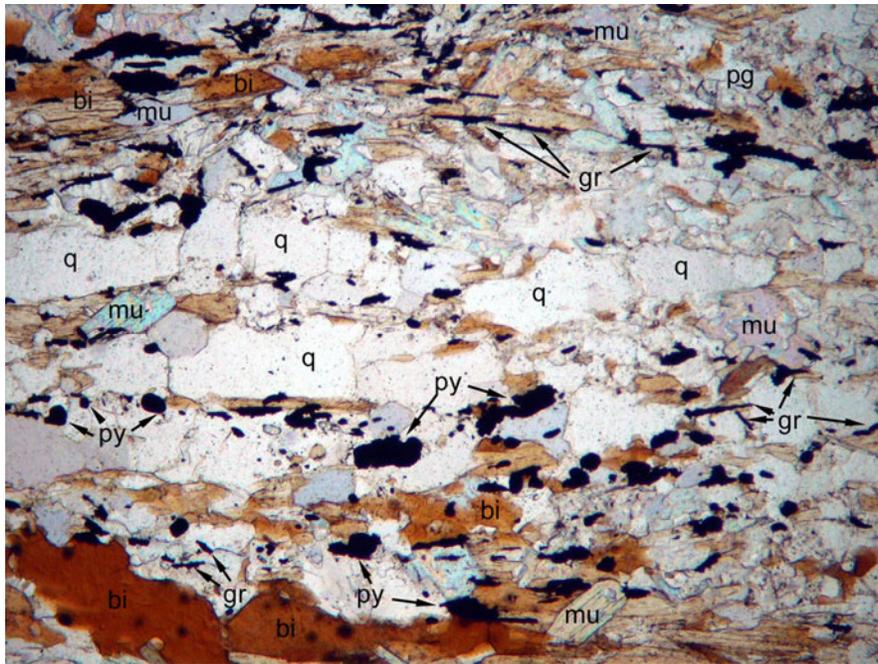


**Figure 4** – Photomicrograph in cross-polarized light of the Hartland Schist (€-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the coarse texture, high mica content and prevalence of muscovite and quartz, diagnostic mineralogical characteristics of the Hartland. (Sample N125; 112<sup>th</sup> Street and Riverside Drive, Manhattan; 1.6 mm field of view.) (From Merguerian, 2005.)



**Figure 5** – Photomicrograph in plane-polarized light of the Manhattan Schist (€-Om) 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 foliation in this view is diagonal across the image. (Sample N217; South of George Washington Bridge approach, Manhattan; 1.6 mm field of view.) (From Merguerian, 2005.)

**Walloomsac Formation.** This discontinuous unit is composed of fine- to medium-textured, fissile brown- to rusty-weathering, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-pyrite-graphite schist and migmatitic schist containing interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels and layers of calcite+diopside±tremolite±biotite ±phlogopite (“Balmville”) calcite marble, calc-schist, and calc-silicate rock. 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-brown biotite, garnet, graphite, and pyrite are diagnostic petrographic features of the formation.



**Figure 6** – Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal in this view) defined by aligned pleochroic biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals locally overgrow the foliation. Diagnostic petrographic characteristics of the Walloomsac include the presence of graphite and pyrite and strongly pleochroic red-brown biotite. (Sample N113-3L; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 1.6 mm field of view.) (From Merguerian, 2005.)

The Walloomsac Formation can be found interlayered with the underlying Inwood at three localities in Manhattan - (1) at the north end 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 northwestern corner of Central Park (Merguerian and Merguerian, 2004). 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 north part of the New York Botanical Garden (Merguerian and Sanders, 1998), and (4) in the northeastern part of Crotona Park (unpublished data). Based on our studies and as discussed below, four new localities in Manhattan south of Canal Street contain Walloomsac rocks.

Because the Walloomsac 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 aids the interpretation that the Walloomsac Schist is the metamorphosed equivalent of carbonaceous shale and interlayered greywacke and is therefore correlative with parts of the middle Ordovician Annsville and Normanskill formations of SE New York and the Martinsburg formation of eastern Pennsylvania (Merguerian and Sanders 1991, 1993a, 1993b).

### **Origin of the Schistose Rocks of New York City**

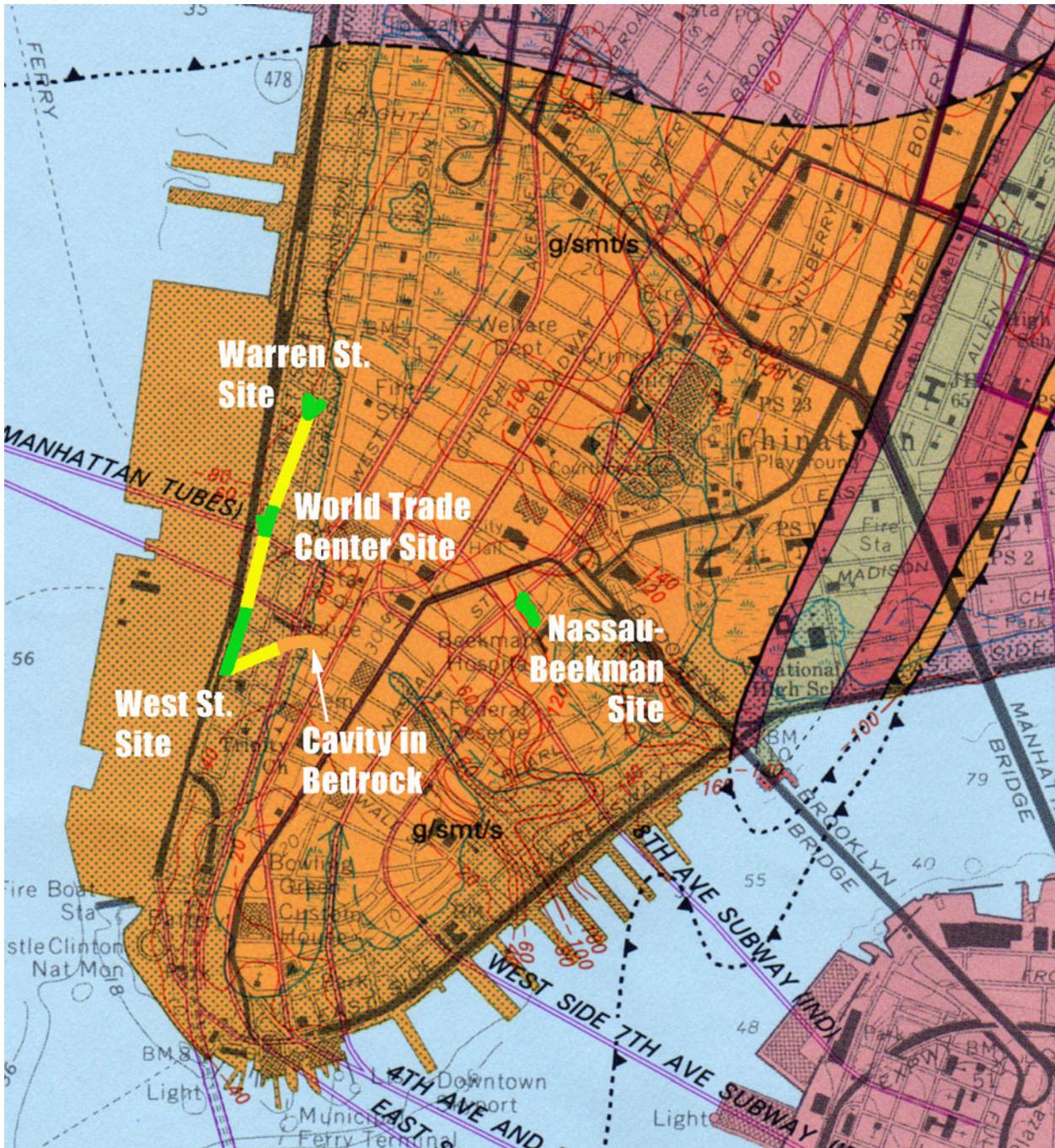
The schistose rocks of NYC (Hartland, Manhattan, and Walloomsac) were originally deposited as sediment, though in vastly different environments. The Hartland was originally deposited in a deep ocean basin fringed by volcanic islands that was the receptor of huge flows of granular sediment from time to time. This produced a thick sequence of interlayered clay, sand, and volcanogenic strata. Compositional layering was preserved in the Hartland, forming a well-layered metamorphic rock mass consisting of schist, granofels, and amphibolite.

The Manhattan Schist, on the other hand, presumably originated along the edge of the former continental margin as thick clay-rich sediment with occasional sand and volcanic interlayers. As a result, the Manhattan Schist is much more massive in character than the Hartland. The lack of internal compositional layering as well as mineralogical differences allows for separation of the two units in the field and also during core analysis. The Walloomsac Schist is mineralogically unique since it originated under restricted oceanic conditions and consisted of thick accumulations of carbonaceous and sulphidic clay-rich sediment with occasional sandy and calcareous interlayers. This has resulted in mineralogically distinct schist, calc-schist, and calc-silicate rock enriched in biotite, graphite, and pyrite.

### **Schistose Rocks South of Canal Street in Manhattan**

The Baskerville (1994) geological map of Manhattan shows the entire area south of Canal Street underlain by rocks of the Manhattan Schist formation and shows that Hartland rocks occupy the region north of Canal. Four localities south of Canal Street exhibit a significant number of borings containing well layered Hartland rocks as well as graphitic schistose and calcareous rocks of the Walloomsac Formation. Only a few borings from one of the sites showed Manhattan Schist. Schistose and calc-silicate units are found in ductile fault contact with the Hartland formation at the Warren Street, West Street, and the Nassau-Beekman sites (Figure 7). Although the exact structural relationships are unknown, the presence of Walloomsac and Hartland rocks changes our view of the bedrock pattern of the region.

**Warren Street Site** – Out of fifty-six boxes of core (~16' of core/box on average) examined for this locality, six of the core boxes penetrate the Walloomsac and the rest were in the Hartland or pegmatitic granitoid intrusives. The transition from biotite schist to diopsidic calc-silicate marble was detected at this locality (Figure 8). Here, steep to subvertically foliated Hartland rocks surround a thin east-west trending belt of Walloomsac schist, marble, and calc-silicate rock that extends across and through the eastern portion of the site.



**Figure 7** – Index map of localities (approximately plotted for reasons of client confidentiality) in southern Manhattan that show Walloomsac calcareous rock and graphitic schist based on our study of drill core. Green lines show locations of the borings that contained Walloomsac rocks and the yellow lines show the on-strike continuity of lithologically correlative borings. Study of about ten localities scattered throughout the map area below Canal Street (but not plotted) indicate that mostly steeply oriented Hartland and Walloomsac rocks and granitoids are found throughout the area originally mapped as Manhattan (Unit g/s/mt/s of Baskerville, 1994). Base map from Baskerville (1994).

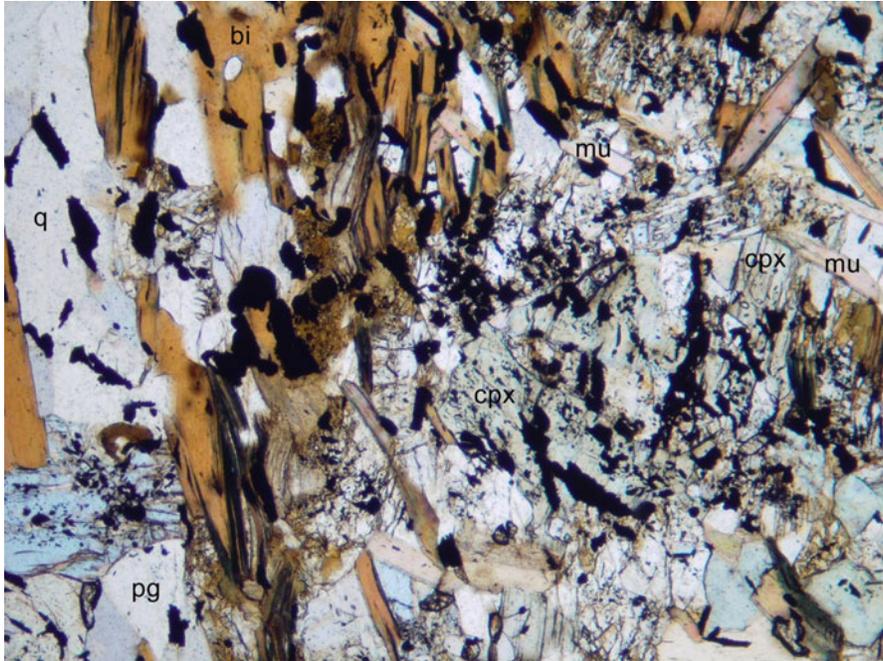


**Figure 8** - Photomicrograph in crossed polars light showing diopsidic calcite “Balmville” marble found interlayered in typical Walloomsac schist. Key: cal = calcite, di = diopside, q = quartz. The small high-order patches are epidote. Field of view 1.6 mm. (Sample N631; Warren Street site.)

**World Trade Center Site** – Over fifty boxes of core were examined at this locality. Most of them consisted of steeply inclined Hartland schist, pegmatite, and foliated granitoid but a few of the borings consisted of Walloomsac-type diopsidic calcite marble and calc-silicate rock, identical in appearance to the Warren locality carbonates.

**West Street Site** – Twenty-two boxes of borings were examined from a site along West Street, to the south and west of the World Trade Center site. Nine of them showed Walloomsac schist, biotite-garnet granofels, calc-silicate and calcite marble and the transitions among them (Figure 9). The remainder of the borings showed steep to vertical lustrous muscovite schist and granofels with smoky quartz stringers (Hartland) and one boring displayed the sheared contact between Hartland and Walloomsac rocks. One of the borings showed a 2’ void in calcite marble, similar to the cavity in bedrock identified by the curved orange line to the east in Figure 7. Most of the rocks are steep to subvertical in inclination, highly flattened, and sheared.

**Nassau-Beekman Street Site** – Twenty-two boxes of core were examined from this locality found well to the east of the others (Figure 7). Most of the core consisted of the Manhattan schist (~9 boxes), six boxes contained Walloomsac schist, and five were Hartland schist. Two boxes consisted of granitoid. The geology of the site is very confusing because all three schist units converge. Yet, the units are not distributed randomly. Based on our study of the borings, a 100’ wide belt of Walloomsac rocks extend from NW to SE across the site and are entirely surrounded by Hartland rocks. Manhattan rocks occur as a sliver between the Walloomsac and Hartland on the SW portion of the site. All of the core exhibit steep to vertical foliation. Local upright folds of the foliation and late crenulate folds have been detected.



**Figure 9** – Photomicrograph in plane polarized light showing transitional facies from red-brown biotite schist to diopsidic calc-silicate. Late idioblastic muscovite obliquely cuts the biotite foliation. Note the abundance of opaques (pyrite and graphite). Key: cpx = diopside, pg = plagioclase, mu = muscovite, q = quartz, bi = biotite. Field of view 1.6 mm. (Sample N681; West Street site.)

## CONCLUSIONS AND IMPLICATIONS

Although work is in progress, our preliminary results indicate that a continuous belt of Walloomsac schistose and calcareous rocks appears south of Canal Street in NYC in two separated areas. (See Figure 7.) The duplication of Walloomsac rocks on either side of the city suggests duplication by folding or faulting. Regional tectonic relationships suggests that in southern Manhattan, Cameron’s Line cuts across the intervening Manhattan schist and places allochthonous Hartland rocks directly in contact with autochthonous rocks of the Walloomsac formation. Thus, a structural window exposes elements of the basement-cover sequence in the shallow subsurface of southern Manhattan, structurally beneath the St. Nicholas thrust and Cameron’s Line.

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