

# **Structural Geology and Metamorphism of the World Trade Center Site**

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## **INTRODUCTION**

In the immediate aftermath of the disaster served up to the World Trade Center (WTC) on 11 September 2001, the engineering community was called upon to stabilize the hydrostatic rise of the west “bathtub” structure of the WTC complex and to help plan for new reconstruction. In this connection, our joint investigations began in 2004 with a careful analysis of new borings taken after site cleanup and continued for over six years through 2010. Mueser Rutledge Consulting Engineers were the geotechnical engineers for numerous projects across the entire site and their geologist Cheryl J. Moss, spent many days at the site during excavation of the glacial drift and bedrock. She arranged for coauthor Charles Merguerian to visit about a dozen times over that interval to jointly map details of the bedrock geology and sample as excavations for new buildings and site improvements expanded and continued. The results of our core studies and subsequent field mapping, sampling and petrographic analysis are presented in this report. We have already reported on the glacial plunge pools and  $^{14}\text{C}$  analysis of 50 Ka wood from a WTC till layer at an earlier Stony Brook conference (Moss and Merguerian, 2009) and briefly on the metamorphism and tectonic implications of the bedrock geology (Merguerian, 2010). Here, we expand on the bedrock geology owing to a continuation of research on samples and data analysis.

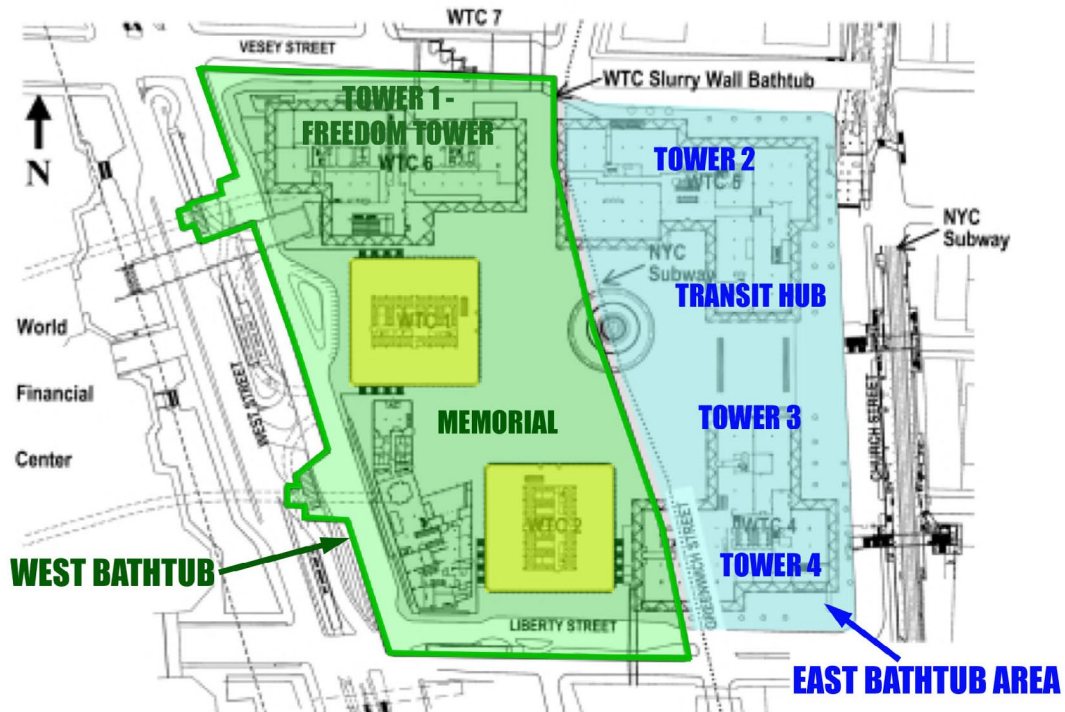
## **SITE LOCATION**

The WTC site encompasses 12 city blocks in lower Manhattan (Figure 1). The original Twin Towers were built within the western 8 blocks that were encircled by a slurry wall socketed into bedrock – the famed west bathtub – to allow their construction. The WTC Memorial and Tower 1 – Freedom Tower were constructed in this western section. In 2007 a second slurry wall was built around the eastern 4 blocks of the site to enable construction of Towers 2, 3 and 4, along with a Transit Hub.

## **SITE GEOLOGY**

Previous published maps of southern Manhattan identify the bedrock in the area of the World Trade Center to consist of Manhattan Schist (Kemp 1887; Mather 1843; Berkey 1910 and 1933) covered by a thin mantle of glacial drift. Baskerville’s 1994 map of Manhattan indicates all Manhattan Schist south of Canal Street, following the published work of all previous workers. Our investigations, based on WTC borings and many construction sites in the vicinity indicate the presence of Walloomsac and Hartland rocks in southern Manhattan at a great number of sites south of Canal Street (Merguerian and Moss 2006; Moss 2010a, b) and deep boulder till--filled glacial plunge-pools beneath the SE corner of the WTC site (Moss and Merguerian 2008, 2009). Micaceous Hartland rocks first were identified by Charles Merguerian and John E. Sanders in

1984 at a site immediately west of the WTC at the World Financial Center (Dukelabs sample of Hartland “Rowe” schist - N403).



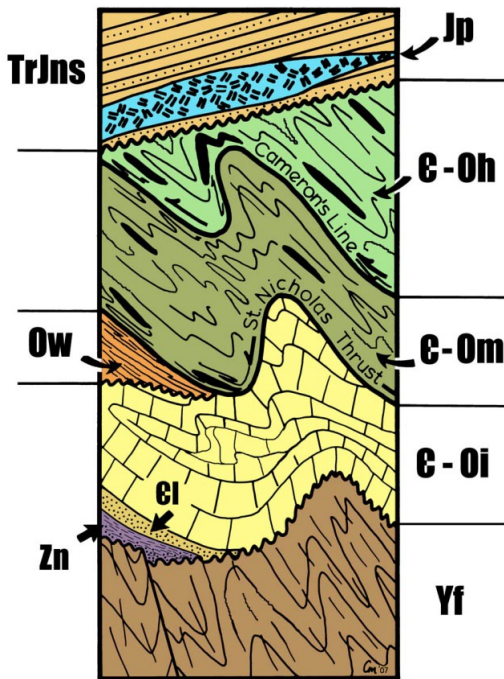
**Figure 1** – World Trade Center site location. The site covers 12 city blocks bounded by Church, Vesey, West and Liberty Streets. The WTC Memorial and Tower 1 (Freedom Tower) are located in the original west bathtub (green shaded area). Located in the east bathtub area (blue shading), Towers 2, 3 4 and the Transit Hub expand the footprint of the original WTC site east of “built over” Greenwich Street.

## BEDROCK STRATIGRAPHY

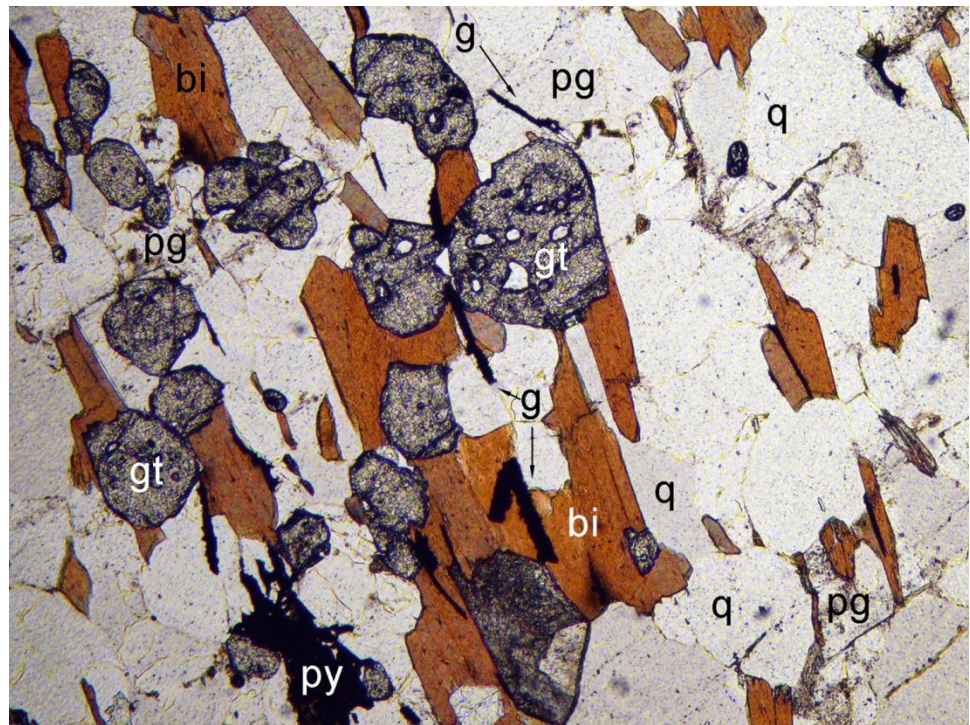
The subdivision of bedrock units in New York City has been fine-tuned and modified over the past two decades in a number of publications and will not be duplicated here (Merguerian 1984, 1994, 1996, 2005, 2008; Merguerian and Merguerian 2004; and Merguerian and Sanders 1991). In a nutshell, the venerable Manhattan Schist formation of former workers has with some degree of reverence been subdivided into three, distinct mappable schistose units known as the Manhattan (*sensu-stricto*), Hartland and Walloomsac formations (Figure 2). Details can be sought in the publications cited above but to summarize, these are the characteristics of the three sub-divisions which show evidence of profound internal folding and shearing and sharp contacts within individual exposures:

**Walloomsac Formation** (Ow) – Former middle Ordovician deep-water sedimentary sequence deposited above Inwood Marble protoliths in an actively subsiding deep restricted basin that supplanted the shallow-water open-ocean platform sequence (Sauk) of proto North America. Originally deposited as interlayered thick black shale, graywacke, and calcareous layers (especially near Sauk contact), metamorphism has produced well-layered to fissile amphibolite facies biotite schist, biotite granofels and calc-silicate rocks grouped together as the Tippecanoe

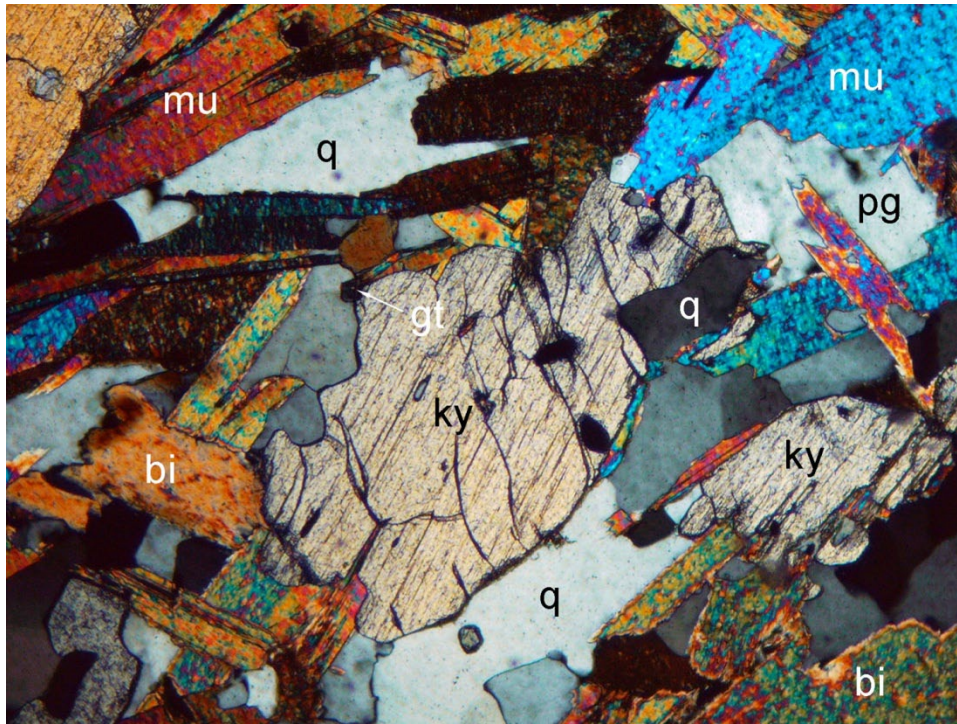
Sequence (Merguerian 1995). Petrographic and geochemical characteristics of the Walloomsac include diagnostic pleochroic reddish-brown titaniferous biotite, graphite, pyrite, and pinkish garnet along with associated muscovite, kyanite, quartz, and plagioclase feldspar (Figures 3, 4).



**Figure 2** - Bedrock stratigraphy of New York City as described in text and references. Designations are Yf = Fordham Gneiss, Zn = Ned Mountain Formation, E-I = Lowerre Quartzite, E-Oi = Inwood Marble, Ow = Walloomsac Formation, E-Om = Manhattan Formation, E-Oh = Hartland Formation. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).



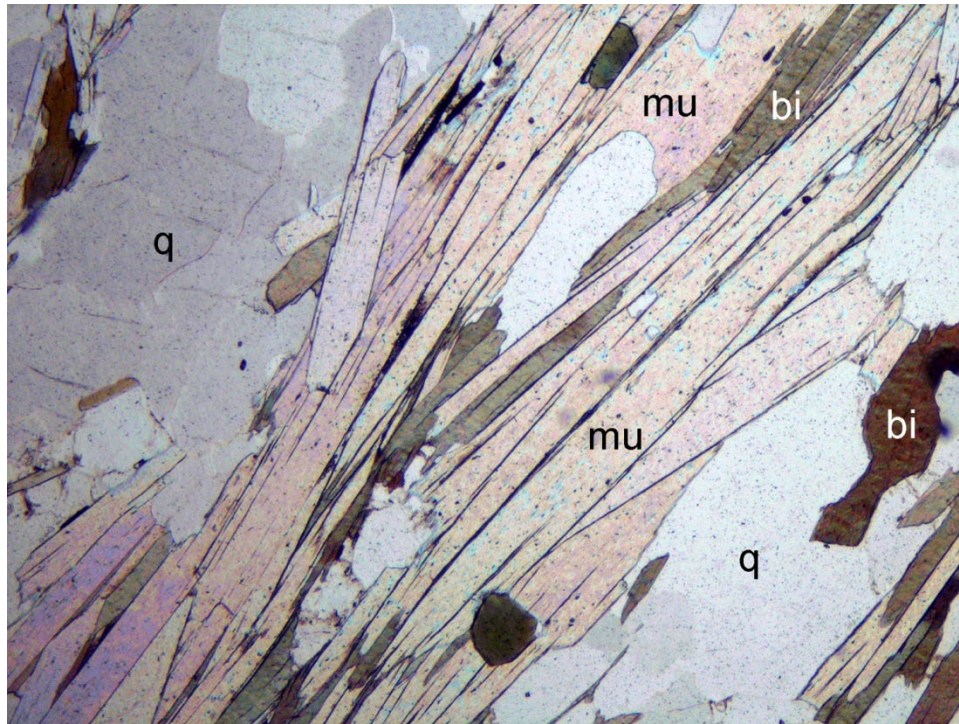
**Figure 3** – Photomicrograph of foliated Walloomsac schist showing typical red-brown pleochroism of titaniferous biotite (bi), along with garnet (gt), graphite (g) and pyrite (py) along with plagioclase (pg) and quartz (q). (Dukelabs Sample N-770; WTC Stop 07; Field of View ~2 mm; plane polarized light.)



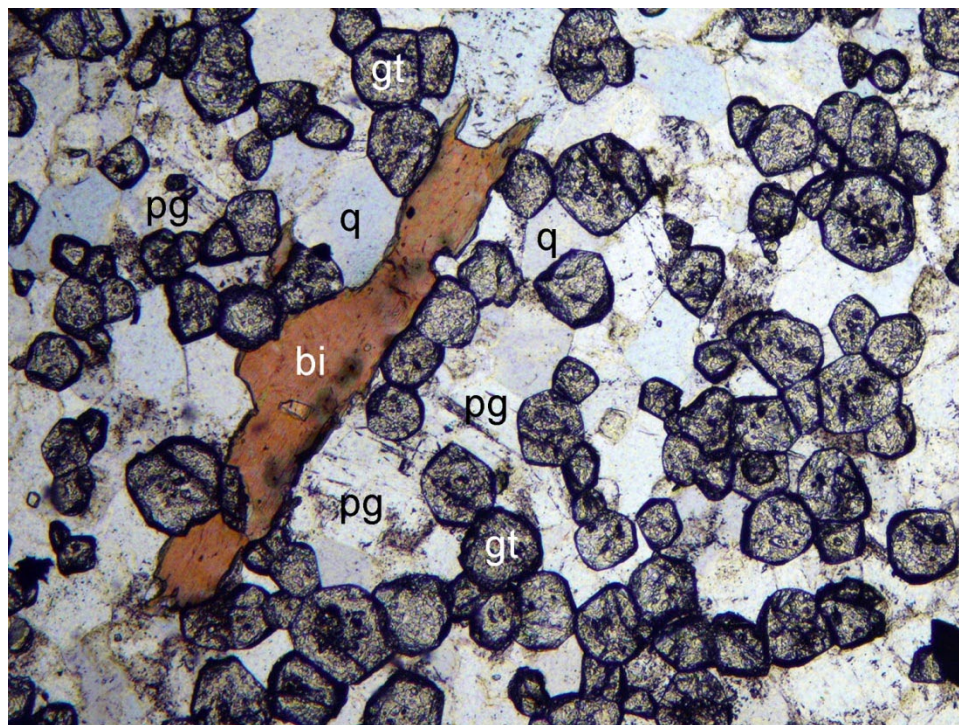
**Figure 4** – Photomicrograph of weakly foliated Walloomsac granofels showing kyanite (ky) along with biotite (bi), garnet (gt), muscovite (mu), quartz (q) and plagioclase (pg). (Dukelabs Sample N-774B; WTC Stop 14; Field of view ~ 2 mm, crossed polars.)

**Hartland** (Є-Oh) – Former late Proterozoic(?) to mid-Ordovician deep-ocean sequence deposited as shale and graywacke on oceanic crust, with subordinate volcanoclastic layers, manganese chert, and metalliferous deposits, now metamorphosed into well-layered amphibolite facies aluminous schist, mica granofels, quartzite, greenish amphibolite, coticule, and itabirite (stratabound specular hematite+pyrite interlayers and laminae associated with coticule rocks). (Figures 5, 6.) These rocks, which contain aluminosilicates and garnet (both red and pink) are grouped together as the Taconic Sequence and are in thrust contact with both Manhattan and Walloomsac rocks at various places in NYC.

**Manhattan** (Є-Om) – Former late Proterozoic(?) to mid-Ordovician slope-rise sequence deposited between the previous two depositional realms. Metamorphism has produced a massive, poorly layered amphibolite facies assemblage of mica gneiss and schist with subordinate interlayers of blackish amphibolite and mica granofels and quartzite. Accessory minerals include red garnet, kyanite, sillimanite, tourmaline, and magnetite. Parts of the formation exhibit a characteristic maroon-colored weathering, especially near magnetite-enriched zones associated with aluminosilicate nodules and lenses. Indeed, the rocks can be quite magnetic in places inhibiting accurate Brunton compass use. Given the distinctive rock mass properties and mineralogy, assignment of formation designations begins in the field and verified using the petrographic microscope. No Manhattan schist was found at the WTC site!



**Figure 5** – Photomicrograph of Hartland schist showing the predominance of muscovite (mu) with minor non-pleochroic biotite (bi) together with quartz (q) and subordinate plagioclase (pg). (Dukelabs Sample N-769A; WTC Stop 06; Field of view ~ 2 mm, plane polarized light.)



**Figure 6** – Hartland coticule (garnet granofels) showing small garnets in high relief in matrix of quartz (q), plagioclase (pg), and scattered biotite (bi). Garnets (gt) are pinkish in hand sample and contain ~12% MnO. (Dukelabs Sample N-757; WTC Stop 33; Field of view ~ 2 mm, plane polarized light.)

Because evidence for shearing and mylonitization is so abundant in NYC bedrock, philosophically one could be led to the conclusion that every intact rock exposure is shear-bounded and that the entire bedrock sequence defines the deep-seated residue of a convergent plate boundary where the three pelitic NYC schists (Walloomsac, Manhattan, Hartland) were isoclinally folded and sheared during protracted plate convergence and metamorphism. Comingling of schistose protoliths may have occurred at various times. As such we use a field distinction of >50% as a rule. That is, if the rocks appear >50% of one lithotype vs. another, we apply that designation and then check for petrographic reinforcement. Duplication of belts of rock by folding vs. shearing is difficult to prove, thus, one's philosophy will have a strong influence on map pattern in areas of discontinuous exposure. We have taken a very conservative approach in the preliminary geological map shown below.

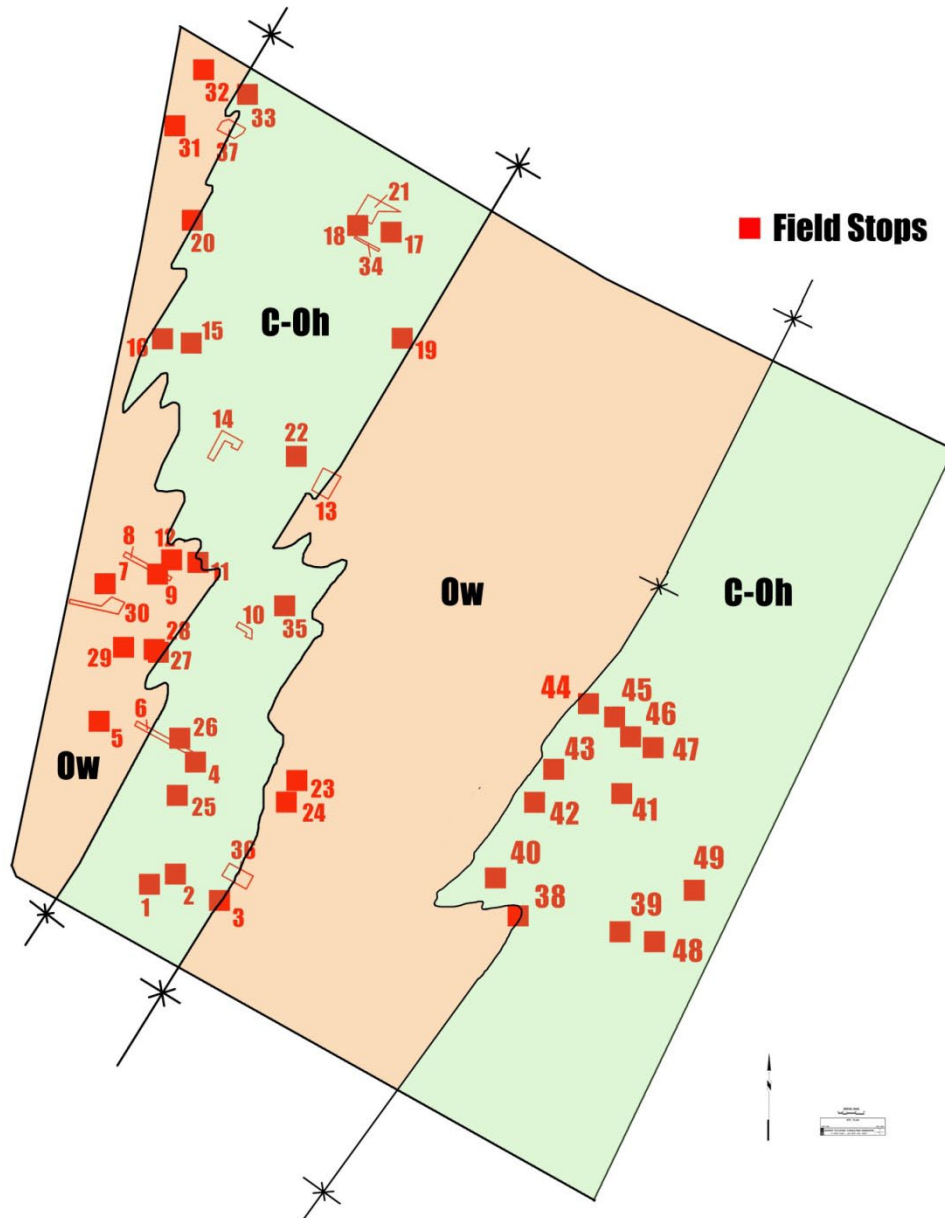
## WORLD TRADE CENTER GEOLOGY

Our joint core logging, field studies and petrographic analysis of the bedrock geology of the WTC indicate the presence of only Walloomsac and Hartland rocks (No Manhattan!) in a steeply inclined thrust-bound internally folded sequence ( $F_1 \times F_2 \times F_3$ ) that traverses from SW to NE through the site (Figure 7). Nearly 100 field stops and drill core sites were integrated to produce the preliminary geologic map of Figure 7. The map shows two dual belts of Hartland and Walloomsac rocks with NE-strike and subvertical dips. The duplication of rock types may be the result of folding, shearing or both but some degree of tectonic intermixing is indicated in the form of abrupt, sharp contacts between Walloomsac and Hartland lithologies (Figure 8). Both borings and actual field measurements indicate steep to vertical dips throughout the site. The rocks are highly flattened, sheared and imbricated and then cut by steeply plunging late folds of the foliation ( $F_3$ ) with NE-trending axial surfaces. Lithologic contacts are folded by  $F_3$  subvertical to steep SW-plunging  $F_3$  folds both in the map scale and the outcrop scale (Figure 9). No major through-going brittle faults were detected in our surveys though small, outcrop-scale brittle faults and joints are common.

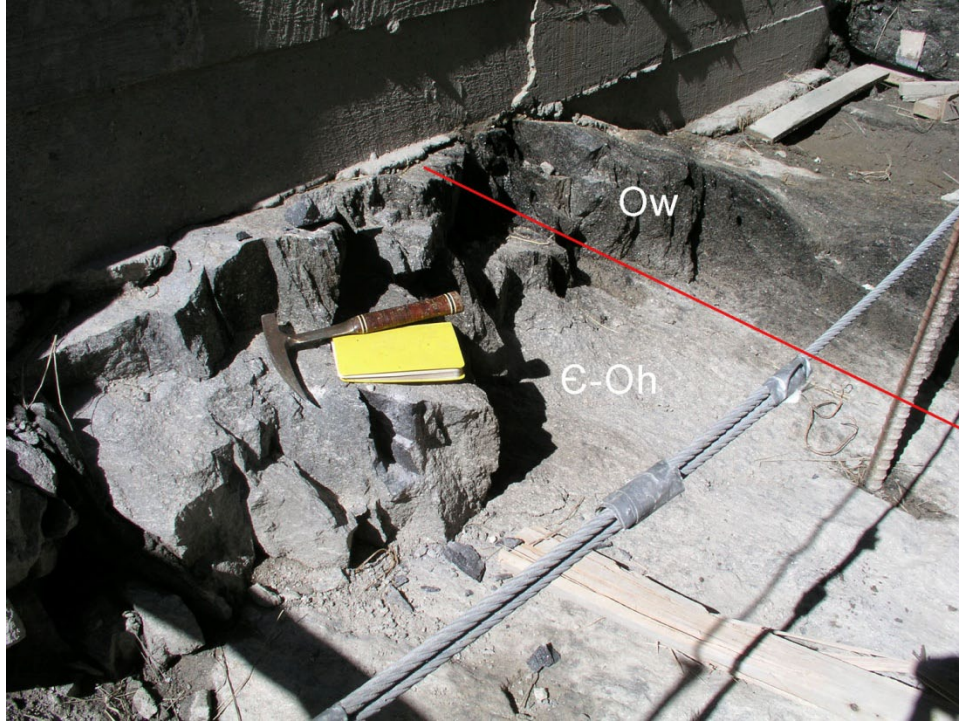
The **Hartland (Taconic Sequence)** at the WTC consists of well-layered dominantly gray-weathering, fine- to coarse-textured, muscovite-quartz-plagioclase-biotite-kyanite-staurolite-garnet schist, gneiss, and migmatite with cm- and m-scale layers of gray quartzose granofels and quartzite, coticule, and greenish amphibolite±biotite±garnet. The schistose facies is often lustrous and consists of fine- to coarse-textured muscovite that splits readily along the foliation. Coticules have been found scattered throughout the site in Hartland rocks and the peppered pink garnets show 12% MnO (microprobe analysis in 2013 by C.E. Nehru). Rocks also contain zones rich in red garnet, kyanite, and staurolite (Figure 10).

By contrast the **Walloomsac (Tippecanoe Sequence)** at the WTC consists of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase-kyanite-garnet-pyrite-graphite schist and migmatite containing interlayers centimeters to meters thick of plagioclase-quartz-mica granofels, layers of diopside±tremolite±phlogopite calcite ("Balmville") and dolomitic marble, and calc-silicate rock. Garnet occurs as porphyroblasts up to 1 cm in size but amphibolite is absent. Pleochroic reddish-brown biotite (titaniferous based on microprobe analysis in 2013 by C.E. Nehru), graphite, and pyrite are diagnostic mineralogical

features produced under the former reducing chemical environment indicated by the carbonaceous portions of the original strata (black shales).



**Figure 7** – Preliminary geological map showing stop locations for most of the stop locations used in this study. Note the duplication of two parallel belts of Walloomsac (Ow) and Hartland (C-Oh) rocks describing an overall steeply dipping sequence with NE-trend and late folding of contacts by asymmetric  $F_3$  folds. It is unknown at present whether the duplication is the result of isoclinal folding, strike-parallel shearing or both. Description in text. (Merguerian 2010).

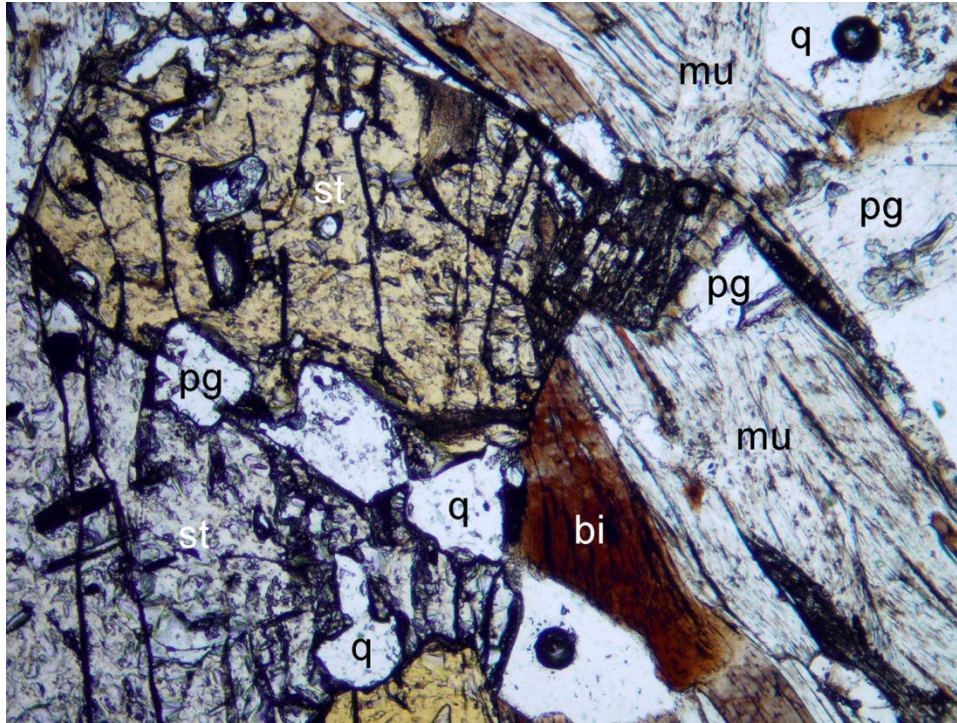


**Figure 8** – Field exposure showing sharp contact (red line) and color contrasts between gray Hartland schist (€-Oh) in foreground and darker Walloomsac schist (Ow) in the background. (CM digital image taken 20 April 2007; WTC Stop 06.)



**Figure 9** – Asymmetric  $F_3$  z-fold in Walloomsac schist and calc-silicate unit showing NE-trend, steep axial plane foliation and transposition foliation with subvertical plunge. (CJM Digital image, 2008; near WTC Stop 13.)



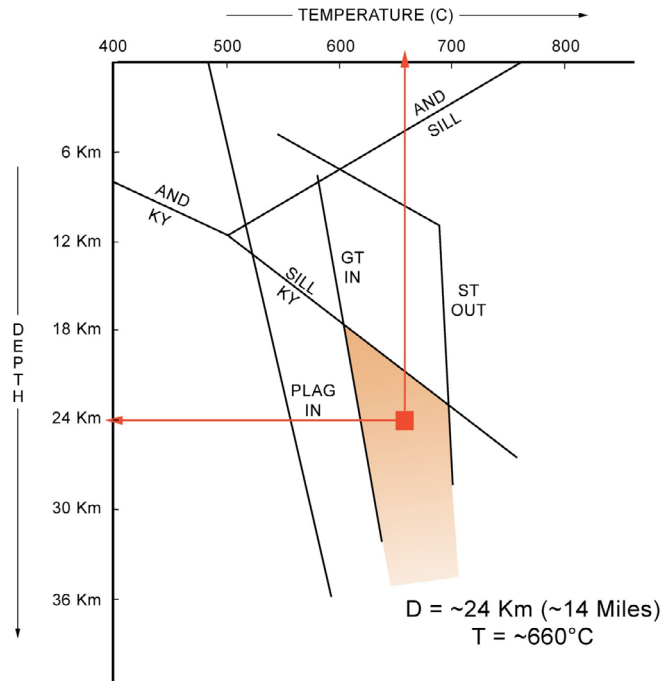


**Figure 10** – Photomicrograph of Walloomsac showing staurolite and characteristic pleochroic biotite with frayed muscovite, plagioclase and quartz. (Dukelabs Sample N-833; WTC Boring MR-4014, Run 1C; Field of view ~ 2 mm, plane polarized light.)

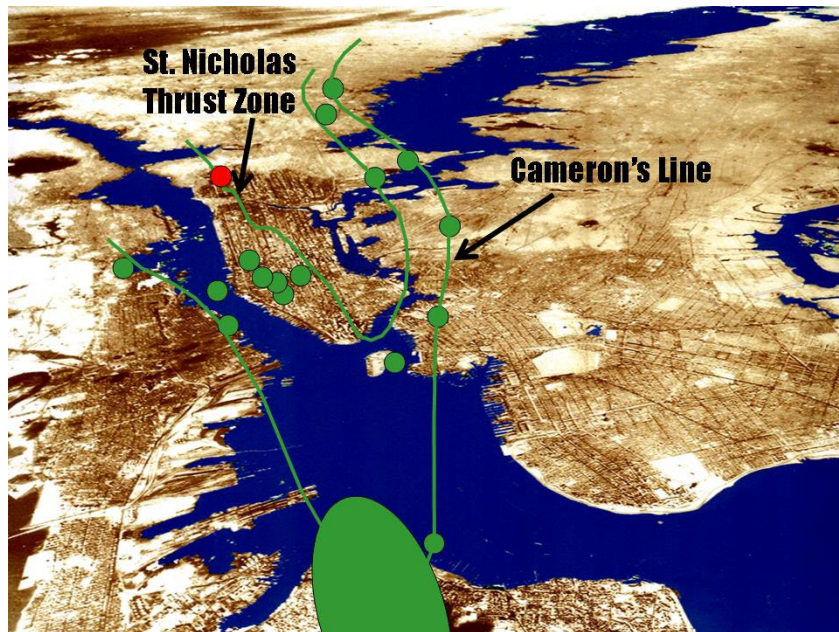
## METAMORPHISM

Both rock formations at the WTC contain garnet+staurolite+kyanite assemblages with relict sillimanite indicating amphibolite facies equilibrium conditions at former depths of ~24 km (Figure 11). The presence of comingled Walloomsac and Hartland lithotypes suggests shearing of a former carbonaceous and sulfidic clay-rich continental margin sequence (Tippicanoe Sequence) with allochthonous eugeoclinal strata of the Hartland Terrane (Taconic Sequence). Sheared rocks of the WTC lie within a belt of isolated serpentinite and sheared schistose rocks that are folded into a broad antiform that extends below the southern tip of Manhattan Island into Staten Island (Figure 12). This belt of sheared rocks + serpentinite masses may outline the location of a formerly deep-seated Taconian suture.

In NYC and vicinity, the association of serpentinite and the aluminous Hartland formation allows the interpretation that the serpentinites are slivers of dismembered ophiolite preserved in a sheared eugeosynclinal matrix. In deeply eroded terrains, such as the New England Appalachians, where significant deep-seated shearing, metamorphism, and imbrication of rock units have taken place, complete three-layer ophiolite sequences are seldom found presumably the result of significant internal shearing in a former convergent margin setting (Merguerian 1979, 2006).



**Figure 11** – Phase diagram showing the aluminosilicate triple point, plagioclase, garnet, staurolite reaction curves and possible P-T conditions for Hartland and Walloomsac rocks analyzed from the WTC (brown shading). Found in both formations, the assemblage kyanite+staurolite+garnet suggests approximate P-T conditions at former depths of ~ 24 km. (Adapted from Hyndman (1972; p. 517.)



**Figure 12** - 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 body associated with Walloomsac rocks in northern Manhattan described by Merguerian and Moss (2007).

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