# "Bedrock Geology of New York City: More than 600 m.y. of geologic history" Field Guide for Long Island Geologists Field Trip, October 27, 2001

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## INTRODUCTION.

Today we will see rocks that record critical events in New York City's long geologic history. The oldest rocks will be Fordham Gneiss, dating from c. 1.1 Ga (billion years); the youngest, muscovite-bearing granite and pegmatite with ages of ~380 Ma (million years). For your convenience, the five field trip stops are shown on the map (Figure 1), and Table 1 and Figure 4 tie the stops to specific geologic events.

For over twenty years we have studied the Manhattan Prong, principally in Westchester County. Field geology- the mapping of rocks and geologic structures, together with petrography- has been the springboard of our work, though we have been supplementing these with electron-microprobe studies of mineral assemblages, whole-rock geochemical analyses, and radiometric age determinations. In recent years we have proposed new interpretations of the metamorphic, stratigraphic, and tectonic histories of the Manhattan Prong (see, for instance, our abstracts for the Long Island Geologists conferences in 1998, 1999, and 2001). Here, we provide a brief outline of the geologic history of the region, which is also summarized on Table 1, "Simplified Geologic History of the New York City Area".

## BRIEF GEOLOGIC HISTORY

***Middle Proterozoic time.*** The Fordham Gneiss dominantly consists of metamorphosed igneous rocks, which range from felsic, through mesocratic, to mafic in composition. Our geochemical studies show that most of these rocks have compositions indicative of a volcanic-arc origin. Several recent U-Pb studies of zircons from metaigneous rocks of the Fordham indicate primary crystallization in the time period 900 Ma to 1.2 Ga years. From these data, we can envision that ~ one billion years ago an active continental margin existed here. Next, a major collision took place, triggering the late (Ottawan) phase of the Grenvillian orogeny; the rocks were deformed, deeply buried, and underwent high-grade (granulite-facies) metamorphism. In post-Grenville time (after ~ 900 Ma), the crust in the NYC area consisted of the compositionally varied, medium- to coarse-grained rocks now known collectively as the Fordham Gneiss ***(Stop 4)***.

***Late Neoproterozoic time.*** After a quiet period that lasted >400 million years, the ancient supercontinent (formed by Grenvillian collisions) began to split up (Figure 4A). From Quebec to Virginia, rift basins formed and basaltic rocks erupted at c. 550-570 Ma (Late Neoproterozoic). It was formerly believed that this rifting event "missed" NYC; Late Neoproterozoic strata were not recognized in the traditional stratigraphic column (Figure 2). However, over the past 12 years, we have been mapping a complex package of rock that lies, stratigraphically, over the top of the Fordham basement and below the Cambro-Ordovician Inwood Marble, and whose age is therefore constrained as Neoproterozoic. We have informally named this stratigraphic unit the Ned Mountain formation. The Ned Mountain formation is lithologically varied, and is divided into several members, illustrated on Figure 3.

Although the Ned Mountain formation was originally defined on the basis of its stratigraphic relationships and its particular lithologic characteristics, we have been testing our interpretation by whole-rock chemical analyses and zircon age determinations. We have found that all the components of the Ned Mountain formation are linked together by the special suite of mafic rocks (amphibolites) that they contain; these amphibolites have many chemical characteristics in common, which serve to distinguish them from the Fordham Gneiss and from most other rock units in the region. They share these characteristics, however, with rift-related Late Neoproterozoic-aged metabasites found elsewhere in the Appalachians. All of these Late Neoproterozoic mafic rocks are chemically similar to basalts found on oceanic islands, such as Iceland. Basalts on these islands are thought to arise from deep-seated mantle plumes, rather than from shallow-level depleted mantle of the kind that fuels volcanism at mid-oceanic ridges. We have proposed, therefore, that a mantle plume prompted rifting along eastern North America during Late Neoproterozoic time. This plume, we suggest, eventually opened the Iapetus Ocean, in the same way that the Iceland mantle plume triggered the opening of the northern Atlantic Ocean.

We interpret the felsic rocks long known as Yonkers gneiss as part of the Ned Mountain formation. Yonkers gneiss was previously interpreted as a component within the Fordham Gneiss (Figure 2). However, our recent work has shown that Yonkers is everywhere stratigraphically (or structurally) distinct from the Fordham Gneiss (Figure 3), that it is more regionally extensive than previously realized ***(Stop 1)***, and that it must have a blanket-like overall geometry, commonly being only a few hundred feet thick but cropping out for tens of miles along strike. Yonkers has a concordant, stratiform character, and therefore must be a metavolcanic (not plutonic) body. Zircons from the Yonkers gneiss in Westchester County have been dated at 563 Ma (Rankin and others, 1997), compatible with Late Neoproterozoic rifting elsewhere.

Bimodal (mafic+felsic) igneous rock suites like the Yonkers/amphibolite association are characteristic of continental rift zones. Our chemical data also show that the Yonkers is an A-type granitoid, a rock type strongly associated with continental rifting, and that it is compositionally distinct from the felsic components of the Fordham Gneiss and from Paleozoic granites of the Manhattan Prong.

In the northeastern Manhattan Prong, we find schists sitting on Fordham Gneiss that strongly resemble the Manhattan Schist. We assigned these rocks to the Ned Mountain formation (Metawacke member; Figure 3), and now have a zircon date confirming their Late Neoproterozoic age (at c.570 Ma). The Manhattan Schist is an allochthon, a detached sheet of rock (Figure 2), and its age and origin have been unclear. Our new data show that amphibolites in the Manhattan Schist are chemically identical to those found in the Ned Mountain formation, confirming that the two units are related to each other. We interpret the Ned Mountain formation and Manhattan Schist as age-equivalent, correlative units, and infer that the Manhattan Schist ***(Stop 3)*** represents a deeper-water facies than most of the Ned Mountain formation (Figure 3).

Amphibolite composition has also help untangle confusion regarding the “Hartland formation”. The Hartland is widely interpreted as exotic to ancestral North America, accreted during the Taconian orogeny in Ordovician time. We agree with this interpretation, but our geochemical investigation has revealed a problem with earlier mapping. We have found that the “true” exotic Hartland formation contains amphibolites having very distinct chemical characteristics, showing affinity with either volcanic arc basalt or with mid-ocean ridge basalt. “True” Hartland of this kind crops out from Pelham Bay Park in the Bronx, up north through eastern Westchester County and into Connecticut. However, west of this true, “Pelham Bay-type” Hartland, there are rocks which have been called Hartland, but that contain amphibolites of the Ned Mountain/Manhattan Schist variety. We call these rocks the "Bronx Zoo-type strata", and interpret them as North American strata of Late Neoproterozoic age (Figures 3, 4A).

***Cambrian to Early Ordovician time.*** Late Neoproterozoic rifting eventually led to the opening of the Iapetus Ocean. New, stable continental margins developed (Figure 4B). During Cambrian to Early Ordovician time, a marine incursion transformed much of eastern North America into shallow-water continental shelf environment. Climate was warm, and a carbonate bank flourished in the NYC area. Sediments deposited during this period are now preserved as the Inwood Marble ***(Stop 2)*****.**

***Middle to Late Ordovician time.*** By Middle Ordovician time, the ocean separating North America from an exotic volcanic-arc terrane had closed. Subduction occurred eastwards, beneath this arc. This exotic terrane began to ride up over North American crust, depressing it; in response, a deepening basin formed along the North American margin. Poorly oxygenated, sulfidic, carbonaceous (graphitic) sediments were deposited in this trough. These sediments, now metamorphosed, make up the Walloomsac Schist (Figures 2, 4C). The Walloomsac, therefore, is the product of the earliest phase of the Taconian orogeny. Only a little Walloomsac Schist crops out in NYC (Figure 1).

As convergence continued, the North American margin was fragmented into sets of westwards-directed thrust slices. Near the top of this structural pile, sheets of Late Neoproterozoic Manhattan Schist and "Bronx Zoo-type strata" were emplaced westwards, over the Middle Ordovician Walloomsac Schist (Figures 2, 3, 4C). Shortly later, our data show that rocks of the Manhattan Prong (including the young deposits of the Walloomsac) were buried to depths of at least 40 km, and possibly more.

The overlying Hartland terrane must account for a large proportion of the 12 kbar pressure experienced by the Manhattan Prong (Figure 4C). We see only a fragment of the Hartland that once existed (Figure 1), the remainder long removed by erosion. The ("Pelham Bay- type") Hartland formation in NYC consists of well-bedded quartz-feldspar gneisses and schists (originally turbidite deposits), amphibolite, and thin marbles ***(Stop 5)***. These rocks were deposited in a deep-marine setting in front of the volcanic arc, possibly in an accretionary prism. These rocks have not been radiometrically dated, but are interpreted as (?) Ordovician in age.

During the later stages of the Taconian orogeny, pressure decreased somewhat (overburden reduced to some 26 km), but temperature reached an extraordinary peak. In northern Westchester County, southern Putnam County, and adjacent Connecticut, we have found evidence of >850 °C, the highest-temperature regional metamorphism in the Taconian orogen. We have not done electron microprobe studies of rocks from NYC, but they show petrographic evidence of an early high-pressure/high temperature phase (K-feldspar + kyanite) followed by lower pressures and/or higher temperatures (K-feldspar + sillimanite). We infer that the two adjacent areas experienced comparable metamorphic histories.

The last stage of the Taconian orogeny included upright, accordion-style folding. In the NYC area, these late folds are generally shallow-plunging, so that lithologic units crop out in long, narrow belts (Figure 1). But the map pattern is complex, because we are seeing a *folded stack of thrust sheets* that have irregular, truncated boundaries against each other.

***Devonian time.*** After the Taconian orogeny, the next event to leave a distinct imprint on the NYC area occurred at ~ 380 Ma. Around then, thousands of small, two-mica granitic bodies intruded into NYC metropolitan region ***(Stop 5).*** Mya Mya Than has dated three of these granite bodies as part of her thesis work. The granites tend to cluster in groups, and are often associated with shearing. The granites brought vast amounts of water with them, largely rehydrating the gneisses and schists of the Manhattan Prong. The best-developed Devonian mineral assemblages crystallized at ~ 550°C and 20 km depth, a far cry from the much-higher-grade Taconian event. Devonian metamorphism is pervasive in much of NYC, and is responsible for the muscovite content of schists ***(Stops 3,5)*** and tremolite in the marbles ***(Stop 2)***. Taconian-aged assemblages survive in enclaves.

## STOP DESCRIPTIONS

**Please note: All stops will be in NYC parks. Do not hammer outcrops.**

**Stop 1. "Ravenswood Granodiorite"** Queensbridge Park, Queens. The "Ravenswood Granodiorite" is the only basement unit to crop out on Long Island, and here beneath the Queensboro Bridge we see one of the largest exposures. The name "Ravenswood" has been restricted to an entity only a few miles in length, occurring along the western margin of Queens. However, our recent studies firmly connect these rocks to a lithologic unit on the mainland: they are indistinguishable, in fact, from the Yonkers gneiss, a member of the Late Neoproterozoic Ned Mountain formation (Figure 3).

The "Ravenswood", like Yonkers gneiss, is a hornblende-biotite-garnet bearing plagioclase-K-feldspar-quartz gneiss. The unit is massive and homogeneous, rock texture is medium-grained, and color is pale pinkish to grayish, with darkness relating to the abundance of hornblende and biotite. The Geologic Map of New York State (1970) and various previous workers have considered the "Ravenswood" to be Lower Paleozoic in age. We tested the identity of the "Ravenswood" in two ways: by its chemical composition, and by its radiometric age. We found that the "Ravenswood" is an A-type granitoid, compositionally identical to the Yonkers gneiss and distinct from every other unit that occurs in the area. We had zircons from "Ravenswood" dated: they were found to be 555± 20 Ma, indistinguishable from the 563±3 Ma that Rankin and others (1997) obtained from the Yonkers gneiss in Westchester County. We conclude that "Ravenswood Granodiorite" is not a valid, separate unit; it consists, in fact, of the Long Island exposures of the Yonkers gneiss.

Geologists standing on exposed
Long Island Basement
(Yonkers Gneiss outcrop in Queens)

**Stop 2. Inwood Marble** at Isham Park, Manhattan Island. The Inwood Marble consists of white to grayish beds of dolomitic and dolomite-calcite marbles. It was deposited, over the Late Neoproterozoic Ned Mountain formation, on a stable continental shelf during Cambrian to Early Ordovician time (Figures 3, 4B). Grey layers are siliceous, and may represent beds of chert. The marbles are rich in magnesium, due to the dolomite content of their protolith, but poor in iron; hence, they contain very pale, Mg-rich phlogopite mica, diopsidic pyroxene, and (standing up on the surface of the outcrop)- white clumps of tremolite. The tremolite is a product of Devonian retrogressive metamorphism, which left a strong imprint in this area. Tight folding can be seen at this outcrop.

Inwood Marble with siliceous layer in center.
Coin on late vein is a quarter
(Click on image for larger image.)

**Stop 3. Manhattan Schist,** Inwood Hill Park, Manhattan Island. The Manhattan Schist here is predominantly a massive quartz-plagioclase-biotite-garnet gneiss, and with varying amounts of muscovite, sillimanite, staurolite, and kyanite. The late Taconian metamorphic grade was K-feldspar + sillimanite, but during Devonan retrogression, muscovite, staurolite, and kyanite grew at the expense of sillimanite + garnet + K-feldspar + biotite. The outcrop we see by the footpath displays coarse garnet porphyroblasts in a dark, biotite-rich matrix, and muscovite is fine-grained and subordinate. This rock was only partially recrystallized during Devonian time, and largely preserves its Taconian fabric. Elsewhere, however, retrogression was more complete, and muscovite has grown to dominate the appearance of the rock. We will not take the time to find Devonian-age muscovite schist in outcrop, but several rocks placed alongside the footpaths are representative of the retrograded rocks. These irregular degrees of retrogression are characteristic of the Devonian metamorphic event.

The Manhattan Schist is an allochthon, emplaced during the Taconian orogeny. We correlate Manhattan Schist with the Late Neoproterozoic Ned Mountain formation (Figure 3, 4A) primarily because of (a) its resemblance to the 570 Ma-year-old Ned Mountain Metawacke member, and (b) the presence of amphibolites chemically indistinguishable from those found in the Ned Mountain formation (and other rift-related Late Neoproterozoic units). Next to a footpath, we can see one of the amphibolite bodies of the Manhattan Schist.

Coarse garnet porphyroblasts in Manhattan Schist.
Coin is a quarter. (Click on image for larger image.)

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| Folded leucosomes in Manhattan Schist.<br>(Click on image for larger image.) |  |
| Blocks of Manhattan Schist<br>(Click on image for larger image.) |  |

**Stop 3. Fordham Gneiss**, Van Cortlandt Park, the Bronx. The Fordham Gneiss comprises the oldest rocks in the NYC area, making up the already-ancient basement that rifted during Late Neoproterozoic time (Figure 3, 4A). Here in Van Cortlandt Park, most of the Fordham consists of felsic plagioclase-quartz-biotite-garnet-hornblende-K-feldspar gneiss. The gneisses are fairly massive, though layering is locally visible. In addition to felsic rocks, we will see a small mafic layer, a subordinate component of the Fordham here. Chemical analyses tell us that Fordham leucocratic gneisses like these have volcanic-arc affinities; we can be reasonably confident that gneisses here originated in a continental-arc environment about a billion years ago. Most of these gneisses are medium-grained, but there are some fine-grained high-strain zones, probably dating to the Taconian orogeny. Growth of epidote and blue-green hornblende in these rocks reflects Devonian retrogressive metamorphism.

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| Discussion regarding Fordham Gneiss |  |

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| Fold in lichen covered Fordham Gneiss |  |
| Folded veins in Fordham Gneiss |  |

**Stop 4. "Pelham Bay-type" Hartland formation,** Pelham Bay Park, the Bronx. Now we have stepped off the old North American continent, onto the exotic terrane that arrived ~450 Ma ago (Figure 4C). The Hartland formation here contains a variety of rock types, including quartz-feldspar gneiss, biotite-sillimanite schist, amphibolite, and marble. Rhythmically bedded sequences of gneiss and schist occur; these are interpreted as turbidites, deposits from sediment-laden flows spewed into deep water. On the northwestern side of North Twin Island, graded bedding is preserved, allowing us to deduce the direction of stratigraphic tops. Thanks to the excellent bedding, we can observe Taconian-age isoclinal folding of the turbiditic sequences on both the Twin Islands, as well as local truncations along shear zones.

Amphibolites in the "Pelham Bay-type" Hartland show either volcanic-arc or ocean-floor chemical affinities. During deformation, the amphibolites were less ductile than the surrounding schists and gneisses, and many were broken into boudins. On North Twin Island, we can see that thin white-and-pink banded marbles are associated with many amphibolite beds. Scapolite is present alongside.

The metamorphic history of the Hartland formation here parallels that of the Manhattan Prong. Ordovician and Devonian metamorphism both affected the Pelham Bay area. The earliest-known assemblage in the pelitic rocks is K-feldspar + kyanite, which is indicative of both high pressure and high temperature. This early assemblage was replaced by K-feldspar + sillimanite, indicating a drop in pressure, rise in temperature- or both. Partial melting of the schists and gneisses produced the abundant quartz-feldspar leucosomes. Much later, during Devonian time, retrogressive metamorphism occurred –and muscovite grew to replace sillimanite, in the same irregular manner as in Inwood Hill Park. Epidote now present in many Pelham Bay amphibolites probably was crystallized at the same time.

Here at Pelham Bay Park there are several intrusions belonging to the ~380 Ma-old Devonian granitic suite. They occur as crosscutting dikes, many with straight, planar boundaries, and all unaffected by the tight folding that deformed Taconian-age granitic leucosomes. These Devonian bodies tend to be pegmatitic, and may contain books of muscovite and sprays of tourmaline. A narrow contact metamorphic (or metasomatic) margin is visible around some of these granites. Thousands of similar granites are present in the NYC/ Westchester region. These granites derived from very wet magmas; as these granites crystallized, water-rich fluids percolated through the surrounding rocks, inducing the retrograde metamorphism we observe all around.

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| Folded leucosomes in Hartland Formation.<br>Coin is a quarter.<br>Click on images for larger images. |  |
| Quartz-feldspar gneiss and biotite-sillimanite schist of Hartland Formation cut by strongly folded veins and undeformed late pegmatite |  |
| Close up of late pegmatite. |  |

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| Folded epidotized amphibolite |  |
| Cavities left by dissolution of calcite in amphibolite. |  |
| Glacial grooves in Hartland Formation |  |

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