Lithologic and Structural Constraints on TBM Tunneling in New York City

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Charles Merguerian, Ph.D.
Geology Department
114 Hofstra University
Hempstead, NY 11549
geocmm@hofstra.edu

and,

Duke Geological Laboratory
36 Fawn Lane
Westbury, NY 11590
charlesm@dukelabs.com

ABSTRACT

In medium- to high-grade metamorphic terrains such as found in New York City (NYC), rock mass texture and mineralogy are important factors in predicting TBM penetration destiny. Integration of data from over two decades of traditional field and tunnel mapping suggest that hard-rock TBM penetration in the NYC area depends upon textural, mineralogic, and structural control. The bedrock of NYC consists of many different lithologic units of varying age, composition, texture, and metamorphic grade including many varieties of intrusive rock. In addition, brittle faults of numerous orientations cut the polydeformed crystalline bedrock, producing zones of highly fractured and disturbed ground and high water inflows.

Pre-bid compilation of published bedrock data, drill core analysis by geologists to establish lithologic and mineralogic trends, integrated surface geologic mapping along a proposed alignment, and targeted petrographic and geotechnical investigations to characterize the rock mass conditions together constitute an important prelude to successful subsurface bidding and tunneling. A carefully planned program of as-built geological mapping, structural analysis, fracture class mapping, and monitoring of machine performance data provide important information for adjusting to changed conditions. In complex terrains, a clear understanding of the structural geology of any proposed tunnel line is the simplest and most cost-effective method to mitigate losses encountered during TBM tunneling.

INTRODUCTION

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, W. W. Mather, and F. J. H. Merrill. Research over the past 100 years and the rich legacy of geological work performed by Merrill and his predecessors are largely ignored by the tunneling industry in favor of compilation and analysis of hundreds of archival boring logs from previous construction efforts gathered at great expense along any proposed alignment and new borings specific to an alignment. Indeed, the pendulum has swung to overkill and over-compilation of existing geotechnical work. In the face of this approach, basic geologic research (mapping, stratigraphy, structure, mineralogy, and petrography) have been under emphasized. As it turns out, such fundamental research by geologists can inexpensively predict the destiny of most TBM tunnel endeavors in hard crystalline rocks, such as found in NYC.

MINERALOGICAL CONTROLS ON TUNNELING

Mineralogic Fundamentals

The earth's crust consists of rocks and rocks consist of minerals. Construction efforts that rely on penetration through and excavation of such materials must take into account the physical properties of minerals. The mineralogy of any rock mass is simply established using standard petrographic techniques on existing drill core. In this method a thin slice of the core is mounted on a glass slide and ground to a specific optical thickness of 30 microns by any number of firms specializing in such work. Petrographic analysis by a trained specialist can establish the percentage of component minerals and specifically identify the existence and volume % of hard, abrasive minerals.

For the benefit of the non-geologist, below are simple definitions of the terms **Color Index**, **Hardness**, **Cleavage**, and **Specific Gravity** from Bennington and Merguerian (2004).

Color index. The color index of any rock is simply the percentage of mafic minerals (those enriched in elements Fe, Mg, and Ca) vs. total rock volume. A value can be readily assigned during routine petrographic examination using % comparison charts published by the AGI (American Geological Institute 1982). The color index is directly related to specific gravity because mafic minerals increase the density of any rock mass.

Hardness. The hardness of a mineral is a measure of its **resistance to scratching or abrasion**. Hardness is determined by testing if one substance can scratch another -- no more. Hardness in a numerical form is based on a relative scale devised by the German-born mineralogist, **Friedrich Mohs** (1773-1839), who spent most of his career scratching away in Vienna, Austria. His scheme, now known as the **Mohs Scale of Hardness**, starts with a soft mineral (talc) as No. 1 and extends to the hardest mineral (diamond) as No. 10. In terms of absolute hardness, the differences between successive numbered scale-of-hardness minerals is not linear, but increases rapidly above hardness 7 because of the compactness and internal bonding of the lattice.

Cleavage. The way a mineral breaks is a first-order lattice-controlled property and thus is extremely useful in mineral identification. The broken surface may be irregular (defined as "**fracture**") or along one or more planes that are parallel to a zone of weakness in the mineral lattice (defined as "**cleavage**"). Cleavage is not just a particular plane surface but rather is "**a direction**." In other words, the concept of cleavage includes not only a single plane surface, but all planar surfaces that are parallel to it. A cleavage direction is the physical manifestation of a plane of weakness within the mineral lattice. This weakness results from a planar alignment of weak bonds in the lattice. The strength or weakness of these aligned bonds affects the various degrees of perfection or imperfection of the cleavage (degree of smoothness/flatness of the surfaces).

Specific gravity (Density). Density is the ratio of mass (or weight) to volume and answers the question of how much matter is packed into a given space.

$$density = \frac{mass}{volume}$$

Unfortunately, precise measurements of density can be tricky because it is often very difficult to measure volume accurately. To get around this problem another concept, similar to density, called **specific gravity** is employed in mineral and rock analysis. Specific gravity is a unitless ratio that compares the mass of an object to the mass of an equal volume of water. In fact, if measured in grams per cubic centimeter, density and specific gravity are exactly the same. Calculating specific gravity is simply measured using a suspension balance and the following equation:

$$spGravity = \frac{wt_{air}}{wt_{air} - wt_{water}}$$

Discussion of Mineral Physical Properties

Minerals common to NYC bedrock are listed alphabetically in Table 1 along with their Mohs hardness, cleavage, and specific gravity. Minerals that exhibit cleavage tend to split or break more readily under point-load strain than those that exhibit fracture. Table 1 shows that, in general, softer minerals show cleavage whereas harder minerals exhibit little or no cleavage. Thus, for both reasons, rocks rich in minerals such as quartz, garnet, kyanite, and sillimanite tend to inhibit penetration and foster the production of excessive fines. Accurate identification, tabulation and graphing of the percentage of hard minerals with little or no cleavage (such as quartz, garnet, kyanite, and sillimanite) in any rock type will provide data for predicting TBM penetration, cutter wear, and the production of excessive fines.

The density or specific gravity of rocks is also a simple litmus test for predicting TBM penetration. (See Merguerian and Ozdemir 2003; Figure 5, p. 1026.) Rocks consisting of higher density minerals such as garnet, pyroxene, and aluminosilicate minerals such as sillimanite and kyanite are less penetrable by TBM mining. A density profile along any tunnel alignment can help identify variations over the planned TBM course and can help plan machine design parameters.

Table 1 – Selected physical properties of minerals common to NYC bedrock.

Mineral	Hardness	Cleavage(s)	Sp. Gr.
Amphibole	5-6	Two @ 60° and 120°	2.8-3.45
Biotite	2.5-3	One	2.8-3.2
Calcite	3	Three @ 75°	2.72
Dolomite	3	Three @ 74°	2.85
Feldspars	6	Two @ 90°	2.54-2.75
Garnet	6.5-7.5	Fracture	3.5-4.3
Graphite	1-2	One	2.3
Kyanite	5-7	One	3.56-3.66
Muscovite	2-2.5	One	2.76-3.10
Pyroxene	5-6	Two @ 87° and 93°	3.15-3.5
Quartz	7	Fracture	2.65
Sillimanite	6-7	One	3.23

LITHOLOGIC CONTROLS ON TUNNELING

Drill Core Analysis

Typical core logs include information on fracture density, recovery, lithology, and sometimes the nature of fracture surfaces. Statistical analysis should include detailed study of lithologic, mineralogic, and petrographic characteristics of the borings by a trained professional geologist and one with local geotechnical research experience would be a preferred choice for such investigations. Such integrated drill core research should be targeted at the depth of the tunnel horizon but comparative analysis outside the tunnel horizon can better identify variations that could result in surprises during actual tunneling. All of the drill core should be examined by the same geologist or team to establish consistency and any core logging by drillers without professional degrees in geology or geological engineering should not be relied upon without careful rechecking. Anomalous lithologies are the common cause of changed condition losses in underground work. Professional geologists are more likely to accurately identify unique lithologies – many examples of misidentified rock types have resulted in tunneling inefficiencies related to changed conditions.

The overall composition of the rock mass holds a first order control on TBM penetration. Stated simply, the more mafic (iron- and magnesium-rich) the rock mass the lower the penetration. Careful core analysis and tabulation should discriminate between felsic, intermediate, and mafic lithotypes at the tunnel horizon by compiling the color index of the rocks as described above. Weighted bar- or pie-graphs display such information in an easy to understand graphical method. In this way, a clear quantification of the anticipated rock types can be established during the planning stages of TBM engineering.

Special rock types (such as fine grained or glassy dike rocks, amphibolite, pegmatite, intrusives, garnetiferous zones, quartz veins) have important bearings on TBM penetration and these should be identified and categorized accurately. Unique igneous and metamorphic textures can make or break a tunneling contract.

Metamorphism

Most of the bedrock of NYC was metamorphosed under amphibolite facies conditions. In formally clay-rich strata this resulted in the growth of oriented mica along with kyanite and sillimanite in a matrix of flattened and recrystallized quartz, plagioclase, and garnet to produce a foliated schistose rock. Interlayered former sandy units recrystallize into mica-poor layers known as granofels, consisting of intergrown quartz and plagioclase. Mafic volcanic rocks recrystallize into foliated amphibole and plagioclase rich rocks known as amphibolite.

Metamorphism is a dehydration reaction that tends to drive water out of minerals. At higher metamorphic grades (upper amphibolite or granulite facies) this can result in the destruction of hydrous phases (mica and amphibole) and the replacement of these foliation-producing minerals by dense, anhydrous phases that include garnet, ortho- and clinopyroxene, kyanite, and sillimanite, often with the liberation of quartz. The growth of these phases in a rock mass can turn a foliated rock mass into compact mica-poor rock mass consisting of equigranular minerals showing 120° crystal intersections and no preferred orientation. As such, original foliated rock masses can be transformed by intense metamorphism into non-foliated (granoblastic) rock masses. At the highest metamorphic grades (granulite or high pressure granulite facies), thorough recrystallization results in an anisotropic rock mass. Such textures, easily identified by the petrographic microscope, produce tough rock masses that are legendary for their poor penetration rates, blocky ground, and production of excessive fines.

Crystalline Rock Texture

Textural varieties in crystalline rocks vary greatly depending upon whether they are igneous, metamorphic, or hybrid and also upon their orientation with respect to TBM drive direction.

Metamorphic Texture. The nature and orientation of foliation (or the lack thereof) holds a first order control on effective TBM mining. Most foliated rocks are rich in mica, a soft mineral (See Table 1) that tends to provide internal weakness in the form of a basal cleavage. The mineralogy of the foliation is of importance. Although mica is the most common foliation-producing mineral, not all foliated rocks are micaceous. Amphibole (hornblende is the common variety) can produce a foliation in rocks in much the same way that spilled box of pencils can flatten out into a planar orientation on the floor.

Lineated metamorphic terrains are isotropic in that penetration parallel to the lineation is less than across the lineation although this will depend on the actual mineral and its individual lattice properties. Deformation can produce planar and linear anisotropies in rocks in the form of grain-shape flattening (lenticular quartz), strain hardened mylonitic textures, and crystallographic lineations (aligned c-axes of quartz, aluminosilicates, and amphiboles).

Highly foliated rocks (slate, phyllite, and schist) tend to split readily along the foliation. Compositional layering, related to original sedimentary deposition can also provide planes of weakness that help facilitate rapid excavation. Favorable orientations of foliation or compositional layering occur when these fabric elements dip steeply away from or toward the TBM cutterhead with the strike more or less perpendicular to the tunnel springline. When the foliation dips toward the heading, crown fallout in the heading may be a problem but when the foliation dips toward the TBM head, stable faces and high penetration rates can be anticipated. Gentle dips create more difficult tunneling conditions because excessive fines can result when the TBM cuts across the edge of the foliation or compositional layering (subhorizontal or vertical orientation). Regional mapping and oriented core study will alert contractors to the prevailing orientation and adjustments in TBM drive direction may enhance penetration. Stereonet analysis is the most effective method of understanding the variation and prevailing orientation of foliation along a given terrain.

As-built geotechnical testing of the Queens Tunnel gneisses revealed the impact of layering orientation of granulite facies gneisses on rock tensile strength (Merguerian and Ozdemir 2003). The tensile strength across the layering, which corresponds to machine operation when the strike of the layering is more or less parallel to tunnel axis, was found to be about 38 % higher than when the TBM was operating perpendicular to the gneissic layering. Because the strike of gneissic layering encountered in the tunnel was mostly sub-parallel to machine advance, rock chipping efficiency and the TBM performance was adversely impacted.

Igneous Texture. Fine-textured aphanitic igneous rocks (1 mm – 0.05 mm) and glassy textured rocks (no crystals) have proven to be an impediment to efficient mining because such rocks do not produce TBM chips as readily as coarse-textured or foliated rocks. Instead they tend to produce sharp, angular blocks that clog grizzlies and damage cutters and belted conveyance systems. Glassy textures, as found in shallow-level dike rocks, are highly injurious to cutters.

On the positive side, very coarse-textured rocks (pegmatitic textures have individual crystals > 10 mm in size) tend to break more readily as the large crystals tend to fail along their cleavage surfaces or along adjacent crystal boundaries. Moderate textured rocks with phaneritic textures (1 mm – 10 mm) break with moderate ease depending upon the texture and whether the rocks have been annealed by high-grade metamorphic reheating. High-grade metamorphic recrystallization can produce granoblastic textures in igneous or metamorphic rocks of appropriate composition that inhibit the production of proper TBM chips because of the lack of internal surfaces of weakness.

GEOLOGY OF NEW YORK CITY

NYC is situated at the extreme southern end of the Manhattan Prong (Figure 1), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terrains of New England. Southward from NYC, the rocks of the Manhattan Prong plunge unconformably beneath predominately buried Mesozoic rocks, Cretaceous strata, and overlying Pleistocene (glacial) sediment that cap Long Island and much of Staten Island.

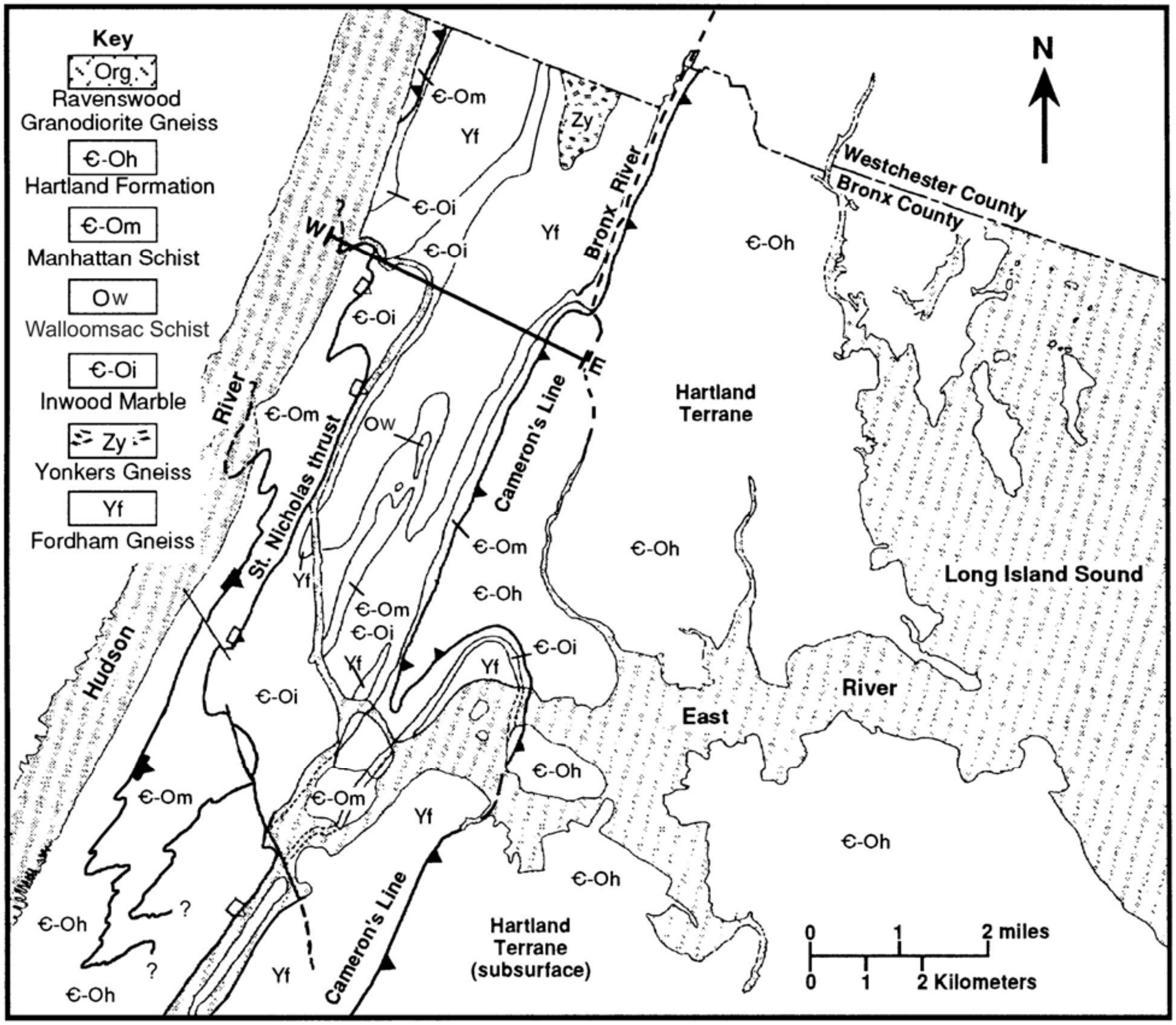

Figure 1 – Geological map of New York City showing the generalized structural geology of the region. Adapted from Merguerian and Baskerville (1987) and Merguerian and Merguerian (2004). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most faults and intrusive rocks have been omitted.

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. This pioneering work by Merrill and coworkers set the stage for a series of detailed investigations by many geologists in the 1900's that helped define the lithology and structure of NYC bedrock units.

My field- and laboratory investigations of the bedrock geology in NYC since 1972, based on study of over 500 natural exposures, a multitude of drill core, and construction excavations define a complex structural history and 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) as indicated in the cross section across the northern tip of Manhattan into the Bronx (Figure 2).

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 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 Manhattan and the effects of the late NW-trending upright folds. Details of the structural geology of NYC are described in a later section.

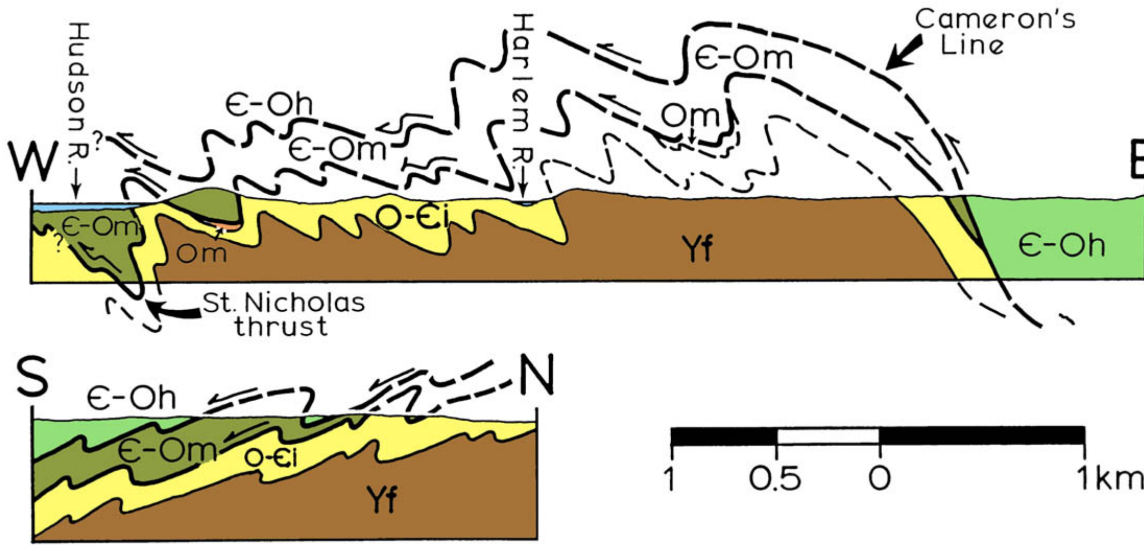

Figure 2 – Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). See Figure 1 for the line of the W-E section. The N-S section runs through the east edge of Central Park. Arabic numerals indicate field-trip stops of Merguerian (1996).

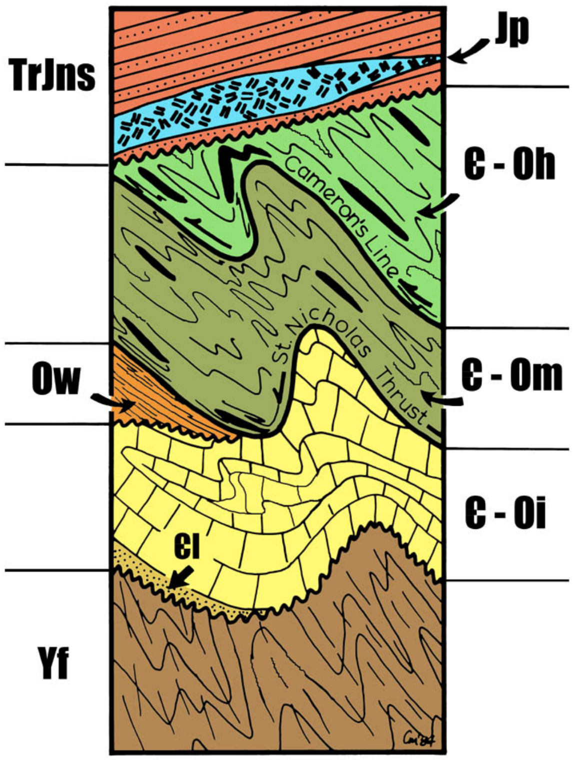

Figure 3 – Bedrock stratigraphy of New York City as described in text. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive sheet (Jp).

Hartland Schist. The structurally high Hartland formation (Ꞓ-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, and gneiss (Figure 4) with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite±garnet. *(Note: Minerals in 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. Because it is lithologically identical to the Late Proterozoic to Ordovician Hartland Formation of western Connecticut and Massachusetts, I have correlated them with the Hartland and extended the name Hartland into NYC (Merguerian 1983). 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.

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 testament to its durability to weathering owing to the lack of layering and presence of wear-resistant garnet, kyanite, and sillimanite.

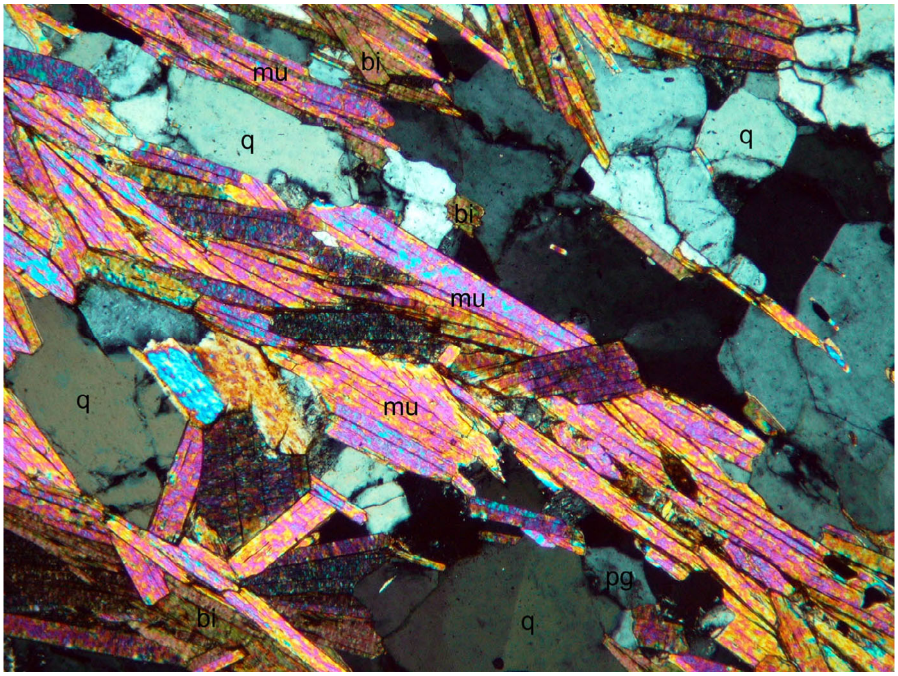

Figure 4 – Photomicrograph in cross-polarized light of the Hartland Schist (Ꞓ-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the high mica content and prevalence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

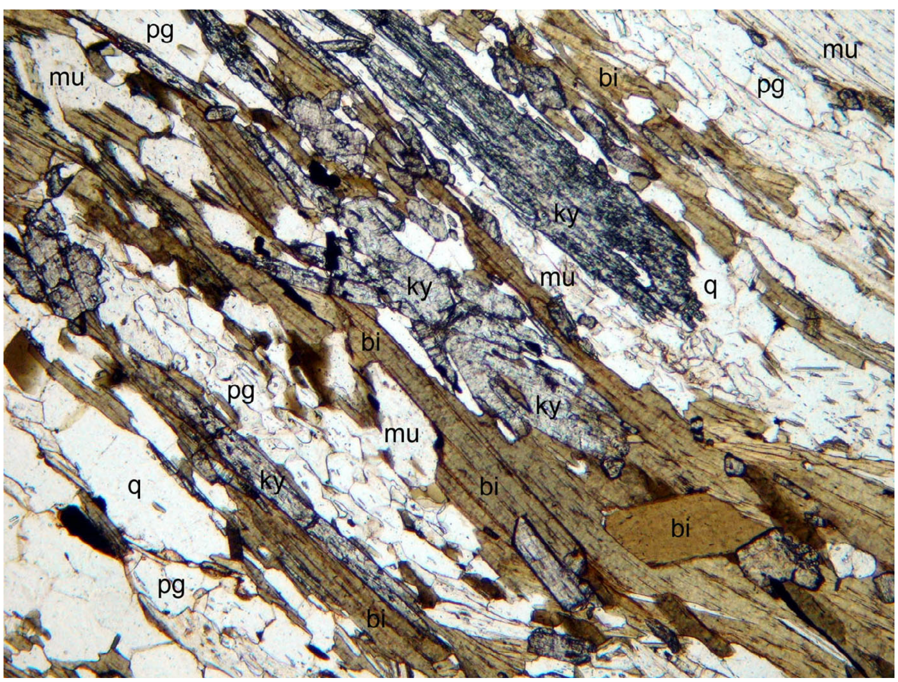

Figure 5 – Photomicrograph in plane-polarized light of the Manhattan Schist (Ꞓ-Om) showing an aligned intergrowth of biotite (bi), kyanite (ky), and muscovite (mu) in a fine-textured matrix of intergrown plagioclase (pg) and quartz (q). The foliation in this view is diagonal across the image. (Sample N217; South of George Washington Bridge approach, Manhattan; 2 mm field of view.)

The Walloomsac Schist and the Inwood Marble are structurally overlain by the Manhattan Schist (Ꞓ-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 (Hall 1976; Merguerian 1983, 1985). These rocks, which contain calc-silicate interlayers in western Connecticut (Merguerian 1977) are inferred to represent metamorphosed sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America.

Walloomsac Schist. This discontinuous unit is composed of fissile brown- to rusty-weathering, fine- to medium-textured, 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 diopside±tremolite±phlogopite ("Balmville") calcite and dolomitic marble 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 biotite, garnet, graphite, and pyrite are diagnostic petrographic features of the formation.

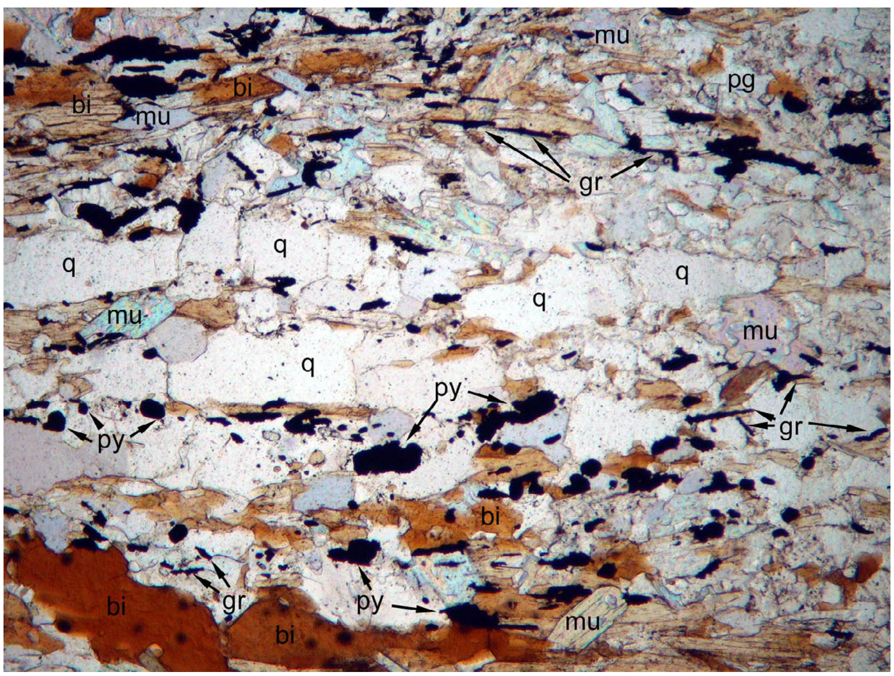

Figure 6 – Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal in this view) defined by aligned biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals locally overgrow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

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). Because it is interpreted as being autochthonous (depositionally above the Inwood Marble and underlying Fordham gneiss), it is assigned a middle Ordovician age. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels enables 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 and Mechanical Properties of the Schistose Rocks of New York City

The schistose rocks of NYC (Hartland, Manhattan, and Walloomsac schists) 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, 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 interlayers. This has resulted in mineralogically distinct schist enriched in biotite, graphite, and pyrite.

In terms of TBM excavation, of the three schistose rock units that underlie NYC, the Hartland Schist is relatively easy to excavate because of its high muscovite mica content, pervasive foliation, and presence of internal compositional layering. Two recent TBM contracts in Manhattan (Con Edison steam tunnel between 36th and 20th Streets along First Avenue and the Manhattan tunnel of NYC Water Tunnel #3 bored southward from 30th Street and 10th Avenue) experienced average penetration rates in excess of 3.5 m/hour in this well-layered formation. The Walloomsac, owing to the presence of graphite and fissile foliation is another unit that will yield high penetration rates in my opinion but this unit is thin and sparsely distributed in NYC. Thus, of the three schist units in NYC, the Manhattan Schist would be the least penetrable owing to the abundance of hard minerals (quartz, garnet, sillimanite, and kyanite) often occurring in layers and lenses, the general lack of internal layering and resulting massive character.

NYC Bedrock Formations Beneath the Schistose Formations

Inwood Marble. The Inwood (Ꞓ-Oi in Figures 1, 2, and 3) consists of typically white to bluish-gray coarse- to medium textured calcitic and dolomitic marble locally with siliceous interlayers containing tremolite, phlogopite, actinolite, quartz, and diopside (Figure 7). Layers of fine grained gray quartz with a cherty appearance are also locally present. White and bluish-gray fine-textured dolomitic- and calcite marble form subordinate members. The Inwood Marble underlies the Inwood section 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 rocks found along the entire Appalachian chain along the east coast of North America.

The Inwood Marble offers excellent TBM penetration potential owing to the abundance of calcite and dolomite, two relatively soft and highly cleaved minerals. (See Table 1.) Recent NYC DEP Water Tunnel #3 contract alignments in Westchester County purposely avoid this formation based on poor experience in drill and blast tunneling operations. TBM mining would clearly benefit from the relatively soft mineralogy of this formation.

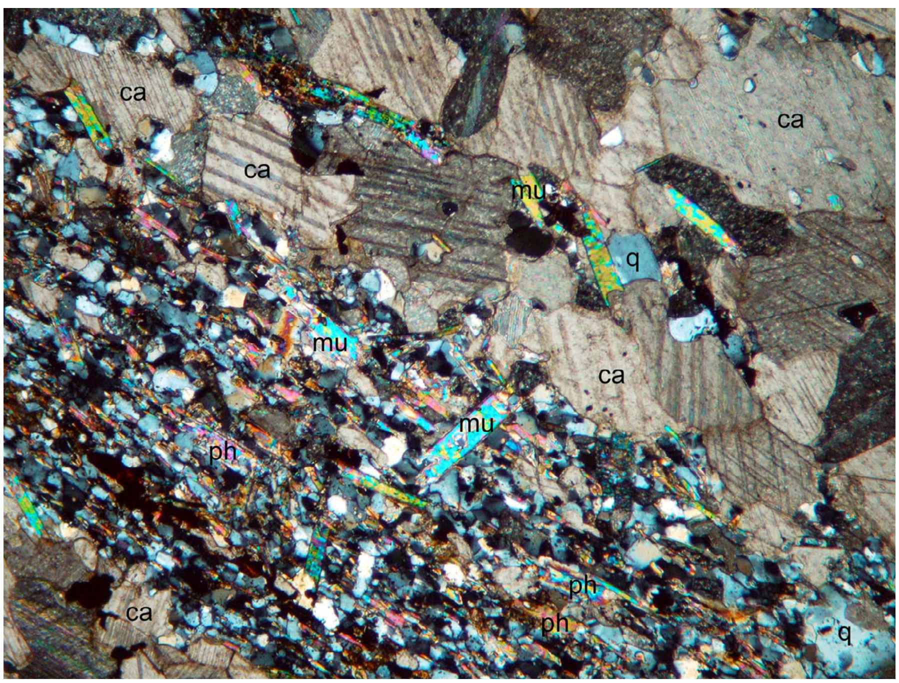

Figure 7 – Photomicrograph in cross-polarized light of the Inwood Marble near the contact with the Walloomsac showing the granoblastic texture produced by recrystallized twinned calcite (ca). A mica-rich zone cutting diagonally across the slide defines the foliation which here consists of aligned muscovite (mu) and phlogopite (ph) in a matrix of recrystallized quartz (q), calcite, and biotite (bi). (Sample N113-4; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

Fordham Gneiss. The Fordham Gneiss (Yf in Figures 1, 2 and 3) constitutes the oldest underpinning of rock formations in the NYC area and consists of a complex assemblage of Proterozoic Z ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks. In NYC, only a few attempts have been made to decipher the internal stratigraphic relationships, hence, the three-dimensional structural relationships remain obscure. Based on detailed studies in the Queens and Brooklyn NYC water tunnels (Merguerian 2000; Merguerian, Brock, and Brock 2001; Brock, Brock, and Merguerian 2001) the Fordham consists of predominately massive mesocratic, leucocratic, and melanocratic orthogneiss with subordinate schistose rocks. They have been metamorphosed to the high pressure granulite facies which has produced a tough, anhydrous interlocking mineral texture consisting of primary pyroxene, plagioclase, and garnet that has resisted hornblende and biotite grade retrograde regional metamorphism (Figure 8).

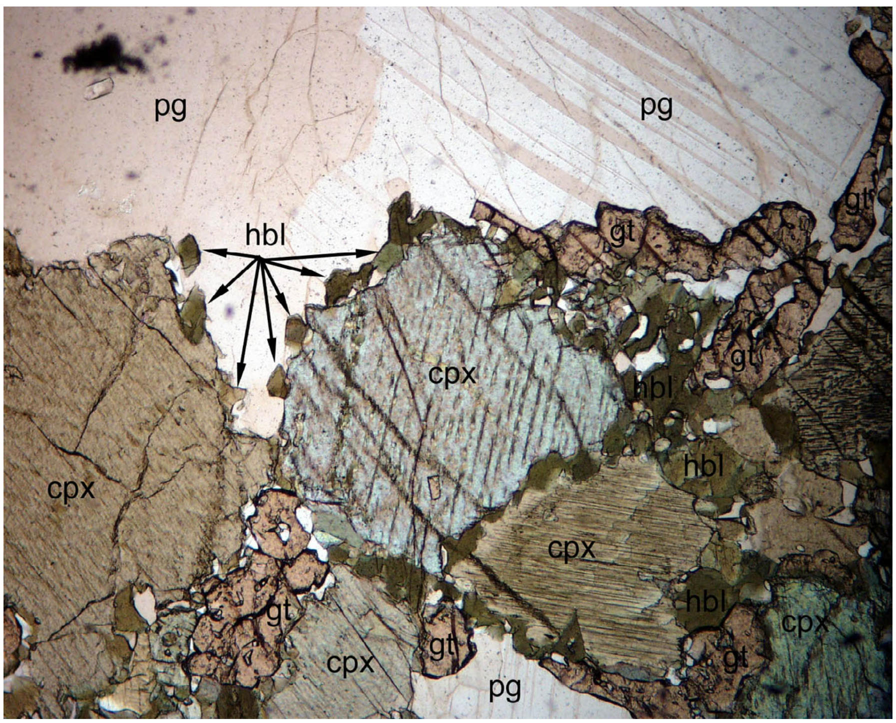

Figure 8 – Photomicrograph in plane-polarized light of Proterozoic mafic orthogneiss showing a coarse-textured granular intergrowth of clinopyroxene (cpx), plagioclase (pg), and garnet (gt) produced during an early stage of metamorphic recrystallization of a former mafic igneous rock. Granular hornblende (hbl) was produced during a secondary metamorphism but the older interlocking metamorphic texture has prevailed. (Sample Q114; Queens Tunnel Station 015+90; 2 mm field of view.)

Average TBM penetration rates of <2 m/hour were encountered in this formation during excavation of the Queens Tunnel. Despite the fact that pre-bid documents provided by the NYC DEP indicated that the Hartland Formation was anticipated along the tunnel alignment, as-built structural, lithologic, and petrographic studies showed that the rocks of the Queens Tunnel consisted of orthogneiss of mesocratic, leucocratic, and mafic composition. These metaigneous rocks developed coarse-textured fabrics during Grenvillian granulite facies metamorphism, and retained their nearly anhydrous, poorly foliated character during subsequent high-grade

Ordovician and younger deformation and retrograde metamorphism. Lacking a penetrative foliation, the coarse granoblastic rock texture and extraordinary garnet content (up to 50% in some zones) together proved an impediment to efficient chip production and resulted in bimodal production of blocks and excessive fines (Merguerian and Ozdemir 2003). Depending upon the scope of the tunneling endeavor, traditional drill and blast methods might be more efficient in this older formation.

Rocks Associated with to the Bedrock Series

Serpentinite. In addition to the famous Staten Island serpentinite, many scattered bodies of serpentine rock have been encountered in the subsurface of NYC. In addition to a few bodies known in Manhattan near 59th Street and 10th Avenue, the Bruckner Boulevard/Cross Bronx Expressway/Hutchinson River Parkway interchange at the north end of the Bronx-Whitestone Bridge approach in The Bronx, and a few bodies that were penetrated during construction of the Brooklyn Tunnel (Schnock 1999), a new body has been found in a building construction site at 43rd Street and Sixth Avenue in midtown Manhattan (Merguerian and Moss 2005). These sheared masses are interpreted as ophiolitic scraps and are commonly found in ductile fault contact with the surrounding Hartland Formation or at the Manhattan-Hartland contact (Merguerian 1979). The serpentinites are black to greenish fine grained rocks containing serpentine group minerals including chrysotile, chromite, magnetite, orthoamphibole, magnesite, talc, calcite, chlorite, and relict olivine and pyroxene. They are known to cause sidewall instability and diameter changes in bored tunnels and to create zones of slippage for TBM grippers. In addition, they are a source of airborne asbestiform minerals during mining and cause environmental problems in removal and transport.

Granitoids. All units of the NYC bedrock described above are intruded by granitoids that range from sheared pre- and syn-tectonic intrusives to post-tectonic bodies. They range from fine-textured to pegmatitic and occur as dikes, sills, stocks, and small plutons consisting of essential microcline, orthoclase, quartz, plagioclase, biotite, hornblende, muscovite, and subordinate garnet. The mining of granitoids presents no special problems except when they are metamorphosed to the granulite facies and harbor tough, granoblastic textures. Pegmatites are particularly easy to mine given their very coarse texture and abundance of rectangular cleaved feldspar.

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

The rhyodacites dikes are highly porphyritic (Figure 9). Suspended in the red, siliceous groundmass are non-aligned 1 mm to 6 mm euhedral phenocrysts of hornblende, clinopyroxene, biotite, plagioclase, and subordinate K-feldspar. The groundmass is enriched in quartz and K-feldspar and dusted with fibrous aggregates of iron oxide - the probable result of quenching and devitrification of initial felsitic volcanic glass. Numerous rounded and irregularly shaped vesicles roughly 1 mm in diameter indicate former high vapor content. Many of the voids are rounded in outline indicating that they were the products of outgassing during cooling of a melt. Some of the voids are sub-angular with remnant phenocrysts and corroded replacement crusts of calcite and zeolite minerals, indicative of in-situ alteration of primary mineral phases by late-stage igneous processes.

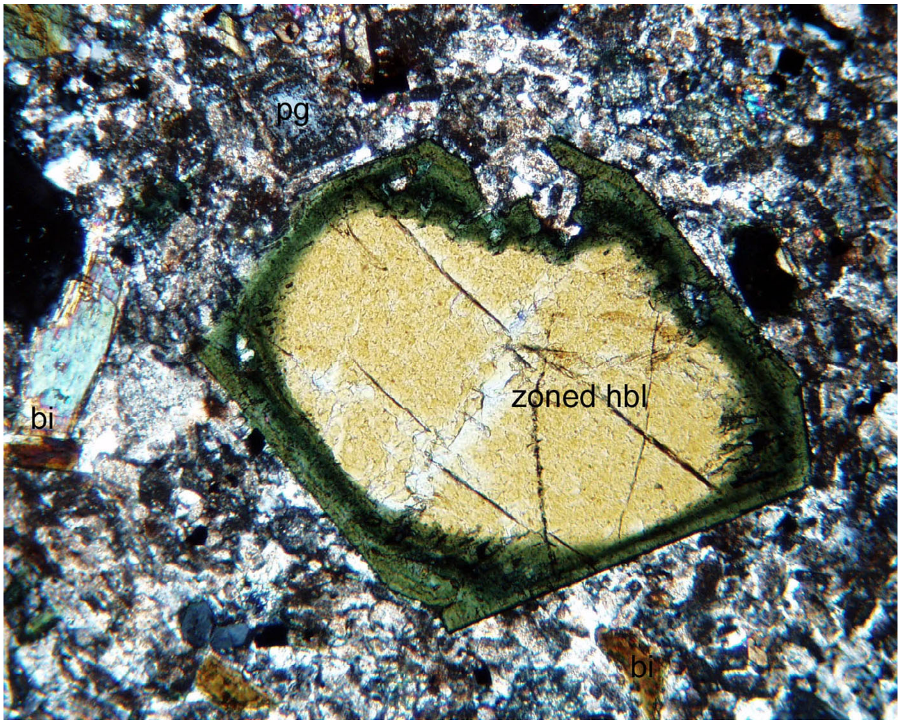

Figure 9 – Photomicrograph in cross-polarized light of a rhyodacite dike showing a 1mm phenocryst of zoned hornblende (hbl) surrounded by a siliceous and partly glassy groundmass consisting of quartz and K-feldspar dusted with fibrous aggregates of iron oxide – the probable result of quenching and devitrification of felsitic volcanic glass. Note the microphenocrysts of plagioclase (pg) and biotite (bi) to the top left, left, and bottom right of the hornblende. Such porphyritic textures are unique to the rhyodacite dikes of the Queens Tunnel. (Sample Q006C; Queens Tunnel Station 151+80; 2 mm field of view.)

The unique devitrified texture of the groundmass and the presence of vesicles unequivocally identify the rhyodacite as a hypabyssal rock. The pervasive reddish color of the dikes is not an indication of near-surface weathering and chemical alteration because the color is evenly found throughout the rock mass. Rather, the unique coloration is produced by iron oxide minerals found within the groundmass, the result of devitrification of quenched glass during late-stage igneous processes. The iron may have been introduced by assimilation of the host rocks based on the abundance of gneissic inclusions in the dike rocks. The dikes are Permian in age (295 Ma) and crosscut folded Proterozoic Y granulite facies rocks of the Queens Tunnel Complex with which they are genetically and temporally unrelated. The injection of a suite of rhyodacite dikes that are chemically, texturally, and temporally unrelated to their bedrock hosts, mark an anomalous geological formation that adds a new chapter to the evolution of the NYC area. The rocks are hard and flinty with a multitude of smooth cooling joints whose intersections produce loose cobble- to boulder-sized multifaceted blocks and slabs that exhibit short stand up times. The rhyodacites were associated with loose, blocky ground and created unstable crowns, sidewalls, and headings during TBM mining of the Queens Tunnel. They were misidentified as "weathered gneiss" in the boring logs supplied by the NYC DEP and caused severe tunneling problems.

STRUCTURAL GEOLOGY OF NEW YORK CITY

Deformational Episodes

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

The obvious map scale folds in NYC (Figures 1 and 2) are those with steep N- to NE-trending axial surfaces (S_3) and variable but typically shallow plunges toward the S and SW. The folds are typically overturned to the NW with a steep SE-dipping schistosity (Figure 10). Shearing along S_3 axial surfaces typically creates a transposition foliation of S_1, S_2, and S_3 that is commonly invaded by granitoids to produce migmatite during both the D_2 and subsequent D_3 events. The third-generation structures deform two earlier structural fabrics (S_1 and S_2). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of overturned F_3 folds). I suspect that all of these structures (D_1, D_2, and D_3) are products of the protracted Taconic orogeny (Merguerian 1996).

During D_2, the rocks acquired a penetrative S_2 foliation consisting of oriented mica and intergrown sillimanite and kyanite with flattened quartz together with staurolite and garnet porphyroblasts. Distinctive layers and lenses of kyanite+quartz+magnetite developed in the Manhattan formation and very locally in the Hartland during D_2. Near ductile fault contacts the S_2 fabric is highly laminated with frayed and rotated mica and feldspar porphyroclasts, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins all developed parallel to the axial surfaces of F_2 folds. The D_3 folding event, a period of L-tectonism, smeared the previously flattened kyanite+quartz layers and lenses into elongate shapes parallel to F_3 axes.

Although the regional S_2 metamorphic grain of the NYC bedrock trends N50˚W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25˚. (See Figure 10.) S_3 is oriented N30˚E and dips 75˚SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges.

The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz and kyanite lenses and layers into elongate shapes. Metamorphism was of identical grade with D_2 which resulted in kyanite overgrowths and annealed mylonitic textures (Merguerian 1988).

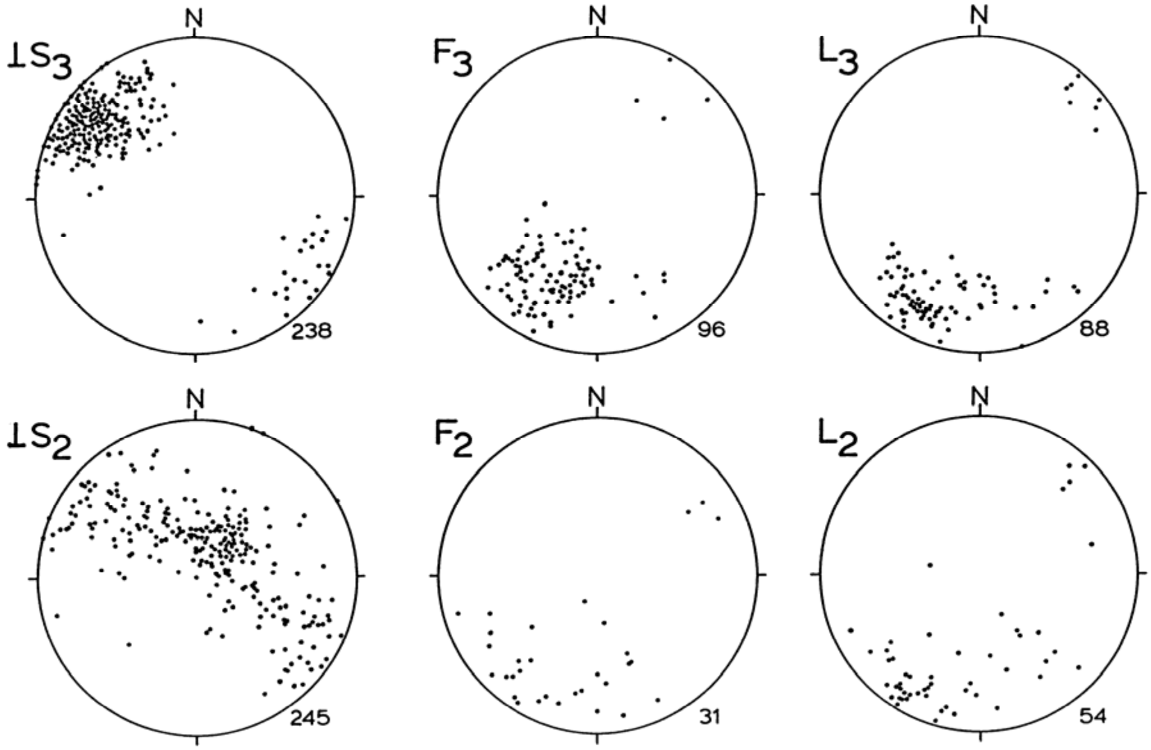

Figure 10 – Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, Figure 26, p. 113.)

The D_1 to D_3 folds and crosscutting fabrics formed during the Taconic orogeny are overprinted by two- and possibly three fold phases that, based on their style and general lack of attendant foliation, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics. The younger fold phases record the effects of the Acadian- and terminal-stage Appalachian orogeny. A geological map of Central Park (Merguerian and Merguerian 2004) shows the F_4 folds as a series of warps and open folds with axial traces that strike roughly N30°W and exhibit dominantly steep dips to the SW. The effects on map contacts of these late features is negligible but the scatter of poles to S_3 and localized northward plunges of F_3 fold axes and L_3 lineations are deemed the result of post-D_3 deformation. (See Figure 10.) Brittle S_4 cleavages in the bedrock may have helped localize the late stage brittle NW-trending faults that cut the region. Idioblastic muscovite pseudomorphs after D_3 kyanite are common throughout Central Park. Their abundance suggests a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of wet Devonian granitoids throughout the Manhattan Prong as discussed by Brock and Brock (1999).

Brittle Faults, Joints, and Seismicity

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

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

Slip along NW-trending faults has produced recent seismicity in the Manhattan Prong. The epicenter of a small earthquake (~2.4 Richter) localized in NYC on 17 January 2001 was adjacent to the trace of the Manhattanville fault near 102nd Street and Park Avenue in Manhattan. Later that year (27 October) another small earthquake (~2.6) struck NYC with an epicenter near 55th Street and Eighth Avenue. Seismicity along the NW-trending Dobbs Ferry fault in late October 1985 produced two small (~4.0) tremors and many aftershocks. More robust earthquakes in and around the vicinity of NYC were recorded in 1884 (~5.0-5.5), 1783 (~4.9), and 1737 (~5.2). In the Bronx, field evidence suggests that right-lateral offset of surface drainage (Bronx River) along the NW-trending Mosholu fault is post-glacial in age (Merguerian and Sanders 1997). A pattern of neotectonic seismicity along NNW- and NW-trending faults has clearly established itself in NYC. The need to evaluate the seismic potential of these neotectonic features is evident.

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

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

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

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

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

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

Although fracturing generally aids in the TBM excavation of rock, zones of intersecting fractures are related to crown and sidewall instability, slippage of TBM grippers, downtime for installation of additional support and ring steel, and high water inflows.

CONCLUSIONS

NYC will be the focus for a significant amount of TBM tunneling in the foreseeable future. Detailed study of the mineralogy and texture of component minerals in rocks by competent geologists should be an essential prelude to bidding subsurface work since these studies hold the key to predicting TBM penetration destiny. During the as-built stage, geological mapping, structural analysis, fracture class mapping, and machine performance data together provide the ability to adjust to changed conditions.

TBM borability in crystalline terrains can best be evaluated on the basis of soft mineral content (volume % muscovite, biotite, calcite, graphite). The volume % of dense, abrasive, hard minerals needs to be determined as their presence above background levels (a few %) can negatively impact TBM penetration rates and enhance the production of excessive fines. Petrographic study can best identify textural properties that will negatively impact TBM mining. The degree of granite intrusion and migmatization is an issue of geotechnical concern but can be readily established by standard methods.

Crystalline terrains provide an unforgiving medium for effective TBM utilization and penetration. A clear understanding of the geology of any tunnel line is the simplest and most cost-effective method to mitigate potential losses encountered during TBM tunneling in such terrains. The borability of NYC rocks is strongly dependant upon the mineralogy, texture, metamorphism, and structure of the rock mass. Such integrated analysis allows for adjustments in the metallurgy of cutters, cutter spacing, and head configuration well in advance of TBM mining.

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