

GEOLOGICAL CONTROLS ON MEANS AND METHODS OF HARD ROCK EXCAVATION, NEW YORK CITY, NY

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ABSTRACT

A number of geological properties of coalescing importance dictate the destiny of hard rock excavation in the city of New York. Critical to both surface and subsurface geotechnical design engineering, a thorough investigation of such properties can provide important clues concerning performance and productivity during the bid and as-built stages of major construction efforts and help to avoid the expense and inefficiency of changed condition claims. Investigations over the past century have shown that the geology of NYC is complex with over a billion years of geological history emblazoned in the rock mass. NYC's former position at the core zone of convergent mountain building during Proterozoic and Paleozoic times has created a unique set of geological formations and variable rock mass properties that, when ignored (i.e. – "Rock" is "Rock" mentality), have proven to be an impediment to efficient mining and excavation and has resulted in claim hardships for owners and contractors.

In addition to normal core data analysis and standard geotechnical testing for establishing rock mass properties, prudent contractors and design engineers must factor in intrinsic geological properties. Often overlooked, targeted petrographic microscopic analysis of mineralogy, texture, lithology, structure, and metamorphic fabrics are critical rock mass properties to establish. Megascopic study of stratigraphy, rock mass density, fabric orientation, ductile and brittle fault analysis and joint analysis are also paramount. Such allied studies hold the clues toward fully understanding the excavation behavior of the rock mass and will establish the proper means and methods for safe and efficient rock removal (roadheader, hydraulic ram, drill and blast, mini-mole, TBM, or a medley of methods).

INTRODUCTION

Rock does not equal rock when it comes to cost-efficient excavation of rock in NYC. Proactive geological investigations in the pre-bid and as-built periods can mitigate losses encountered during hard-rock excavation (Merguerian 2005a). Type I and II changed rock condition scenarios can be totally avoided early with professional geological study and risk sharing between owners and contractors. Drawing from three decades of standard geological mapping and rock analysis experience in NYC and from geological data gathered from the NYC Water Tunnels (Brooklyn, Queens, Manhattan), the Con Edison Utility Tunnel, East Side Access, South Ferry, World Trade Center and a multitude of shallow excavations throughout the city, this paper will offer suggestions to better mate various mechanical excavation means for variable geological domains of New York City (NYC). To better understand the geological controls on excavation, a thorough understanding of the geology of New York City is an important first step.

THE 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 nonconformably beneath predominately buried Mesozoic rocks, younger Cretaceous strata, and the overlying Pleistocene (glacial) sediment found capping much of the region including all of Long Island and much of Staten Island.

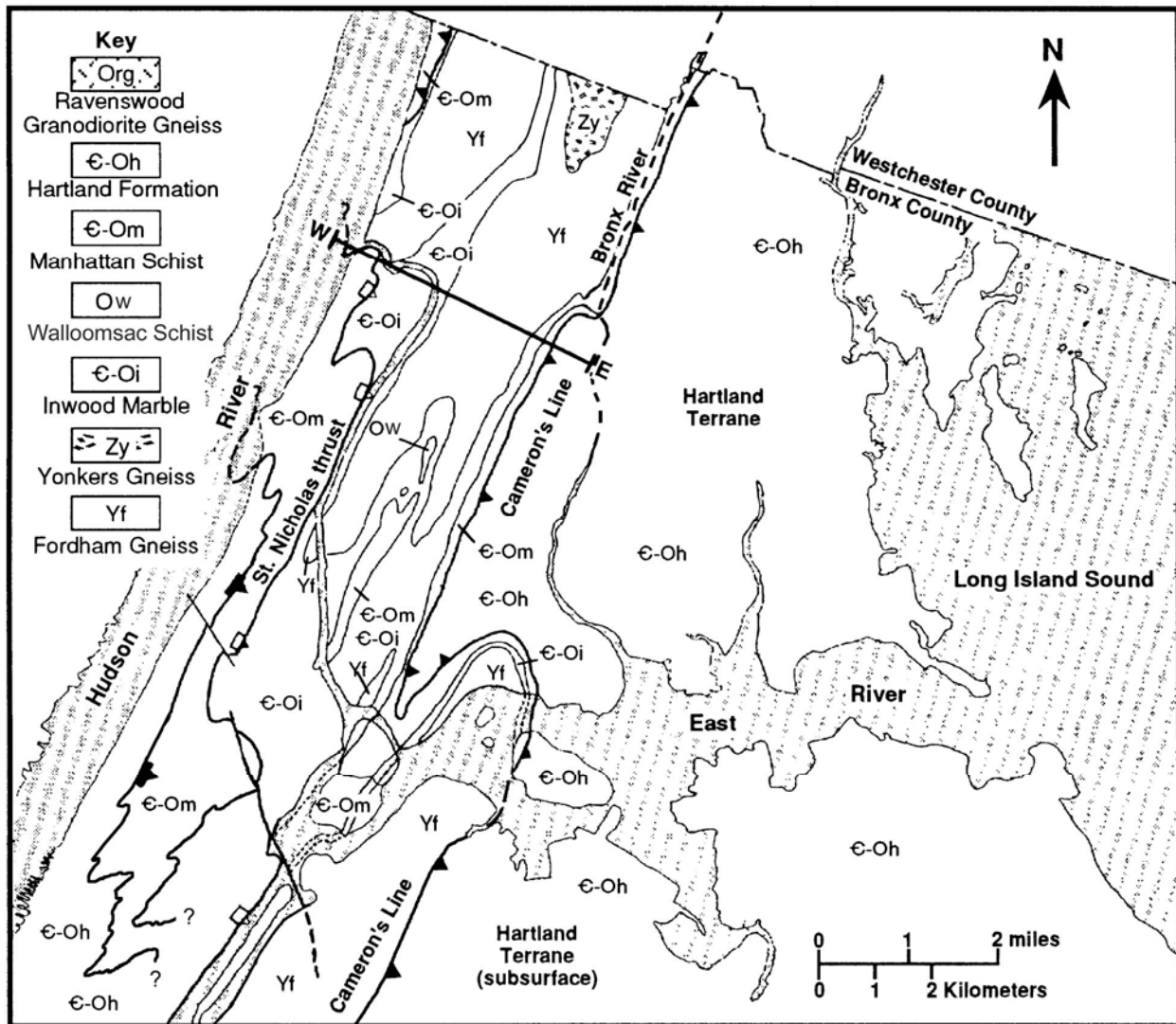


Figure 1 – Geological map of New York City showing the generalized structural geology of the region. Adapted from Merguerian and Baskerville (1987) and Merguerian and Merguerian (2004). Triangles show the dip of Cameron’s Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate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

Will the Real Manhattan Schist Please Stand Up - Bedrock Stratigraphy of New York City

The history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991) so the following is a brief overview. In 1890, Merrill named the Manhattan Schist for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of L. D. Gale (1839, 1843), and 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 details of lithology and structure of NYC bedrock units.

Based on study of over 700 natural exposures, a multitude of drill core and construction excavation analyses, my investigations of the bedrock geology of NYC since 1972 have portrayed a complex structural history and suggests that the Manhattan Schist formation exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three separable map units known as the **Hartland, Manhattan, and Walloomsac** formations (Figure 1). These subdivisions agree with designations proposed by Hall (1976, 1980) but suggest the presence of a hitherto-unrecognized, structurally higher unit that is a direct correlative of the Hartland Formation of western Connecticut (Merguerian 1981, 1983, 1985, 1987). The three schistose units are imbricated along regional ductile faults known as the St. Nicholas thrust and Cameron's Line (Merguerian 1994, 1996) as indicated in the cross section across the northern tip of Manhattan into the Bronx (Figure 2).

Keyed to Figure 1, the W-E section of Figure 2 shows the general structure of NYC and how the St. Nicholas thrust and Cameron's Line overthrusts position the Manhattan and Hartland formations above the Walloomsac formation and the Fordham-Inwood basement-cover sequence. Late-stage 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 tectonostratigraphic units exposed in central Manhattan and the effects of the yet younger NW-trending asymmetric folds. The structural geology of NYC is detailed in a later section and the stratigraphy is diagrammed in Figure 3.

Hartland Formation. The structurally high Hartland formation (€-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and migmatite (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.*) The formation consists of interlayered schist, gneiss, granofels, and amphibolite. The schistose facies is lustrous and consists of dense, aligned fine- to coarse-textured muscovite that splits readily along the foliation. The gneiss and granofels varieties are massive, commonly migmatitic, and may or may not show pronounced foliation. Although typically not exposed at the surface, the Hartland underlies most of the central 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 extended the name Hartland into NYC (Merguerian 1983).

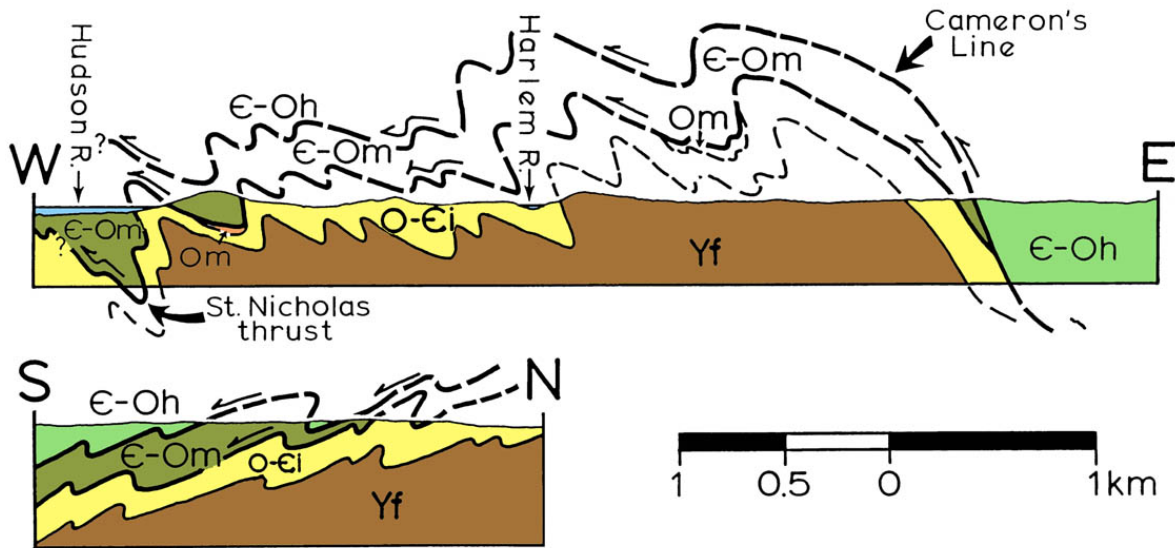


Figure 2 – Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). See Figure 1 for the line of the W-E section. The N-S section runs through the east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

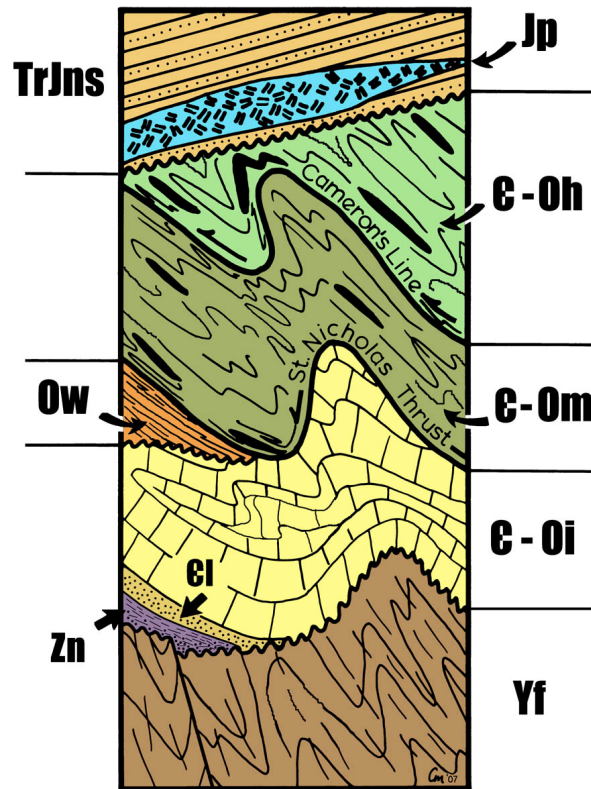


Figure 3 – Bedrock stratigraphy of New York City as described in text. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).

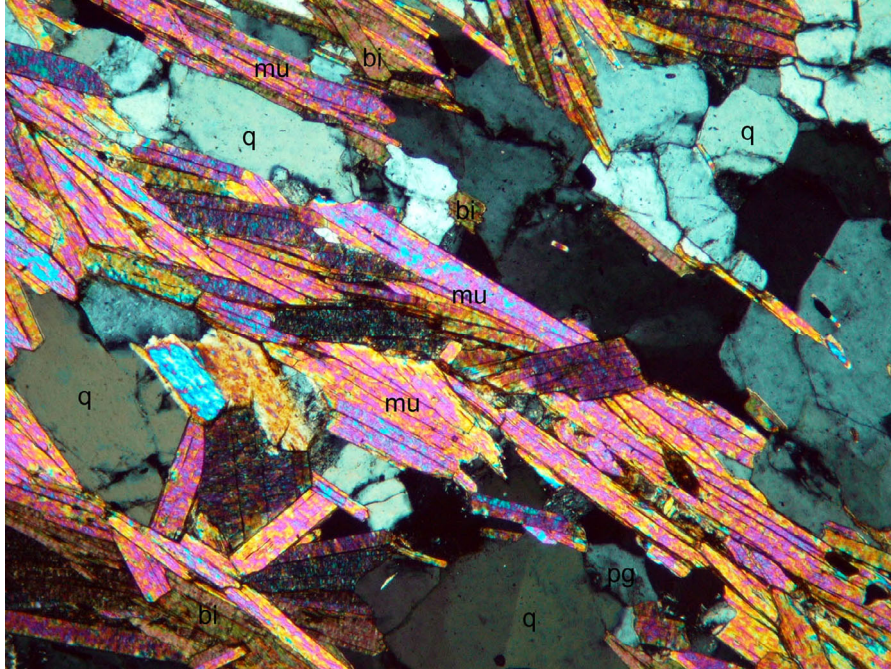


Figure 4 – Photomicrograph in cross-polarized light of Hartland schist (€-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the high mica content and prevalence of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

Manhattan Formation. The Manhattan formation (€-Om) consists of very massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss, migmatite, and to a lesser degree, schist (Figure 5). The unit is characterized by the lack of internal layering except for 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 minerals quartz, feldspar, garnet, kyanite, and sillimanite.

The Manhattan Formation forms the bulk of the “exposed” Paleozoic metamorphic rocks of northern Manhattan including most northern Central Park exposures. The Manhattan 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 Formation. This discontinuous unit (Ow) is composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-pyrite-graphite schist and migmatite containing interlayers centimeters to meters thick of

plagioclase-quartz-muscovite granofels, layers of diopside±tremolite±phlogopite (“Balmville”) calcite and dolomitic marble, and hard 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, pinkish garnet, graphite, and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation.

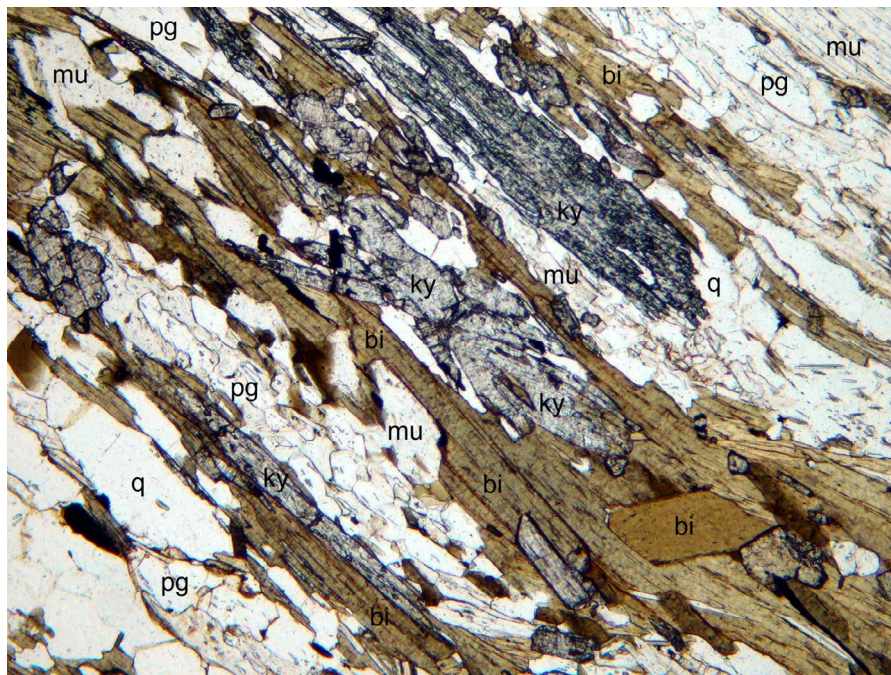


Figure 5 – Photomicrograph in plane-polarized light of the Manhattan Schist (C-Om) showing an aligned intergrowth of biotite (bi), kyanite (ky), and muscovite (mu) in a fine-textured matrix of intergrown plagioclase (pg) and quartz (q). The penetrative foliation in this view, which consists of aligned micas and kyanite as well as flattened quartz and feldspar, is diagonal across the image and marks a structural discontinuity that may split readily. (Sample N217; South of George Washington Bridge approach, Manhattan; 2 mm field of view.)

Exposed Walloomsac Formation can be found interlayered with the underlying Inwood at five 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). The Walloomsac has also been detected sheared against Hartland rocks in numerous borings and excavations from (4) northern and (5) southern Manhattan (Merguerian and Moss 2006, 2007) including the new World Trade Center site (Merguerian and Moss [in press]).

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).

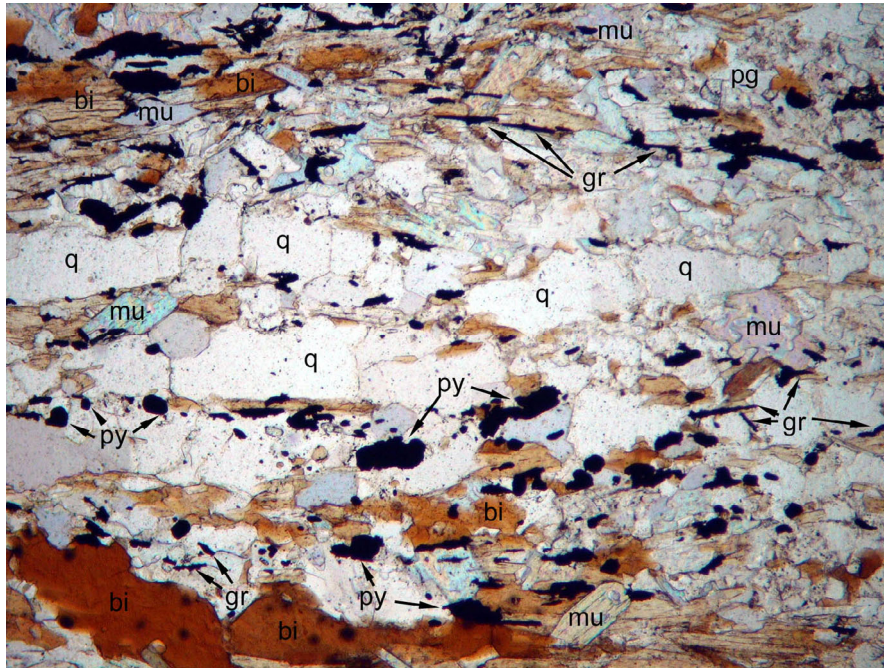


Figure 6 – Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal in this view) defined by aligned biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals locally overgrow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

Origins of the Hartland, Manhattan, and Walloomsac Formations

Now metamorphosed to amphibolite facies grade, the exposed metamorphic cover rocks of NYC (Hartland, Manhattan, and Walloomsac formations) were originally deposited as sediment and intercalated volcanic and volcanoclastic materials, though in vastly different environments (Figure 7). The Hartland Formation was originally deposited in a deep ocean basin fringed by offshore volcanic islands. The marginal ocean basin was the receptor of a huge influx of terrigenous and volcanogenic material. This produced a thick sequence of interlayered clay, silt, sand, and interlayered volcanogenic strata which resulted in a variable rock sequence after Paleozoic dynamothermal metamorphism. Compositional layering was preserved in the Hartland, forming a dominantly well-layered metamorphic rock mass consisting of interlayered and locally migmatitic schist, gneiss, granofels, and amphibolite.

The Manhattan Formation originated along the edge of the former North American continental margin as thick clay-rich sediment with occasional sand interlayers. (See Figure 7.) As a result, the Manhattan is often more massive in character than the Hartland. The Walloomsac Formation 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 schistose rock enriched in biotite, graphite, and pyrite together with layers of calcite marble and calc-silicate rock. The contrast in internal compositional layering and mineralogy allows for separation of the three units in the field and also during routine core analysis though petrographic work is the most diagnostic.

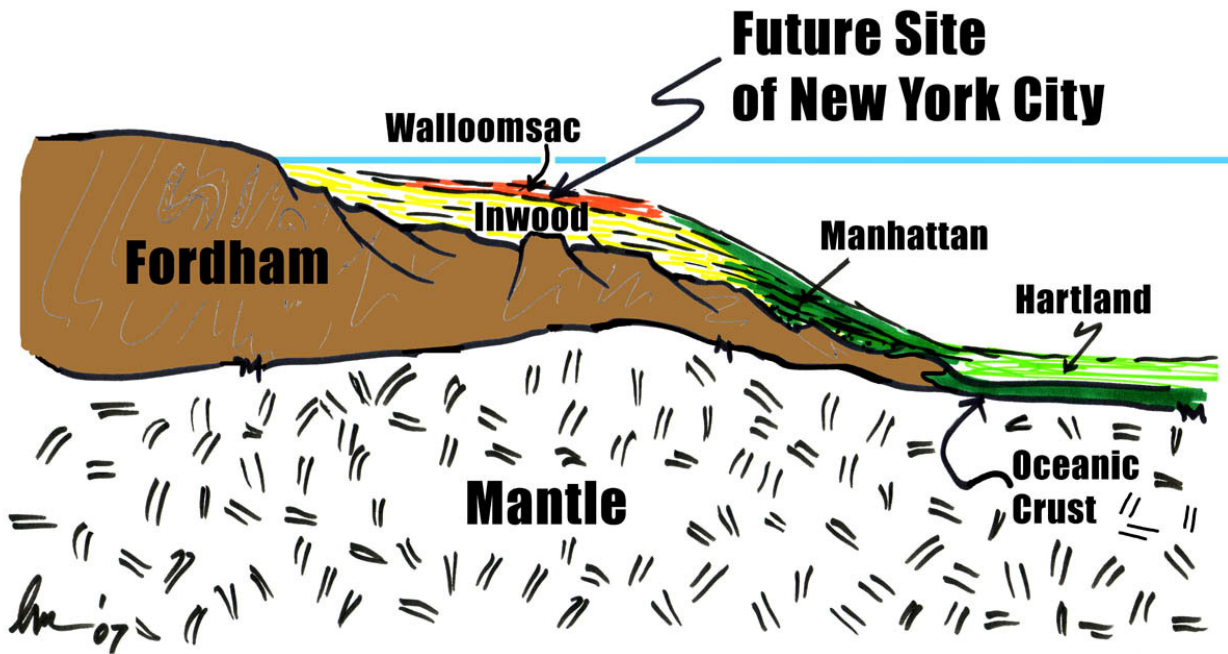


Figure 7 – Diagrammatic cartoon of eastern North America after rifting from Rodinia and during deposition of the Paleozoic strata that are to become the Hartland, Manhattan, and Walloomsac formations. Note the correlation of units and their relationships to the underlying units of the partly coeval Inwood and older Fordham.

NYC Bedrock Formations Beneath the Hartland, Manhattan, and Walloomsac Formations

The metamorphic rocks described above are in structural or unconformable contact with the predominately older units described below.

Inwood Marble. The Inwood (Є-Oi in Figures 1, 2, and 3) consists of typically white to bluish-gray fine- to coarse-textured calcitic and dolomitic marble locally with siliceous interlayers containing tremolite, phlogopite, actinolite, quartz, and diopside (Figure 8). Layers of fine grained gray quartzite with a cherty appearance are also locally present. White and bluish-gray fine- to coarse textured dolomitic- and calcite marble form subordinate members. The unit is found in the Inwood section of northern Manhattan, the Harlem lowland NE of Central Park, in thin belts in the East River channel, in the subsurface of southeastern Manhattan, and also crops

out in The Bronx and Westchester County. The Inwood is correlative with an outcrop belt of Cambro-Ordovician rocks found along the entire Appalachian chain of North America.

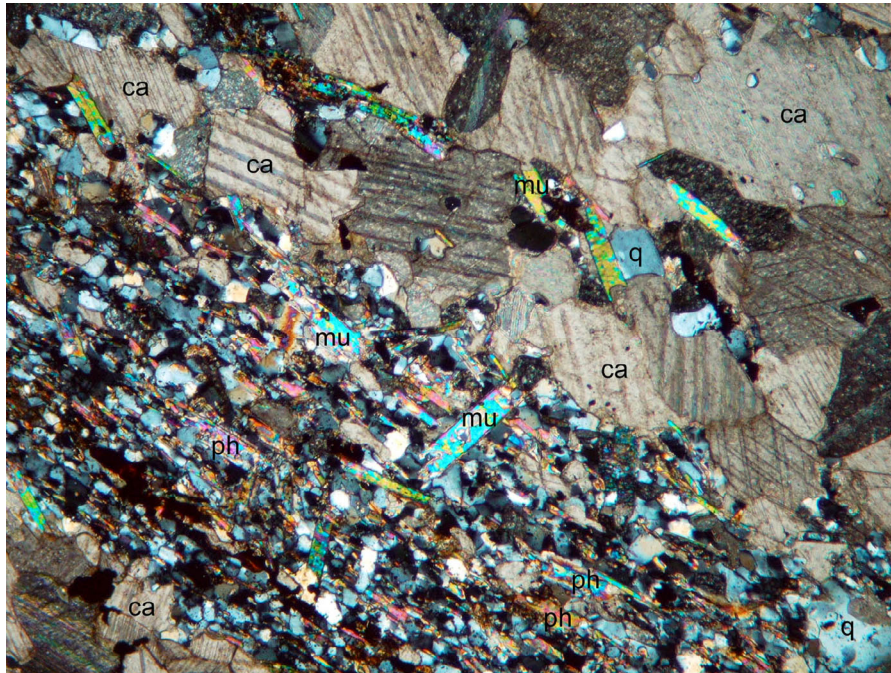


Figure 8 – Photomicrograph in cross-polarized light of the Inwood Marble near the contact with the Walloomsac showing the granoblastic texture produced by recrystallized twinned calcite (ca). A fine-textured mica-rich zone cutting diagonally across the slide defines a foliation which here consists of aligned muscovite (mu) and phlogopite (ph) in a matrix of recrystallized quartz (q), calcite, and biotite (bi). Normally the Inwood is quite pure and consists of coarse textured granoblastic calcite or dolomite. (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 Y 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 partially resisted hornblende and biotite grade retrograde regional metamorphism (Figure 9).

The Fordham is found in the Bronx, in the subsurface of SE Manhattan, the East River channel, and western Queens and Brooklyn, and underlies most the entire region at greater depth. (See Figure 7.) Occurring locally between the Inwood and Fordham are two minor units. One is the very local Lowerre Quartzite (Norton 1959) and the other an areally restricted late

Proterozoic unit known as the Ned Mountain Formation (unit Zn in Figure 3) of Brock (1989, 1993). The Ned Mountain is correlative with Proterozoic Z rocks mapped as the Yonkers Gneiss (Scotford 1956) and the Ravenswood Granodiorite Gneiss (Ziegler 1911) found in Westchester County and in western Queens, respectively. They have little bearing on the primary focus of this paper and are referenced for sake of academic completion but will not be discussed further here.

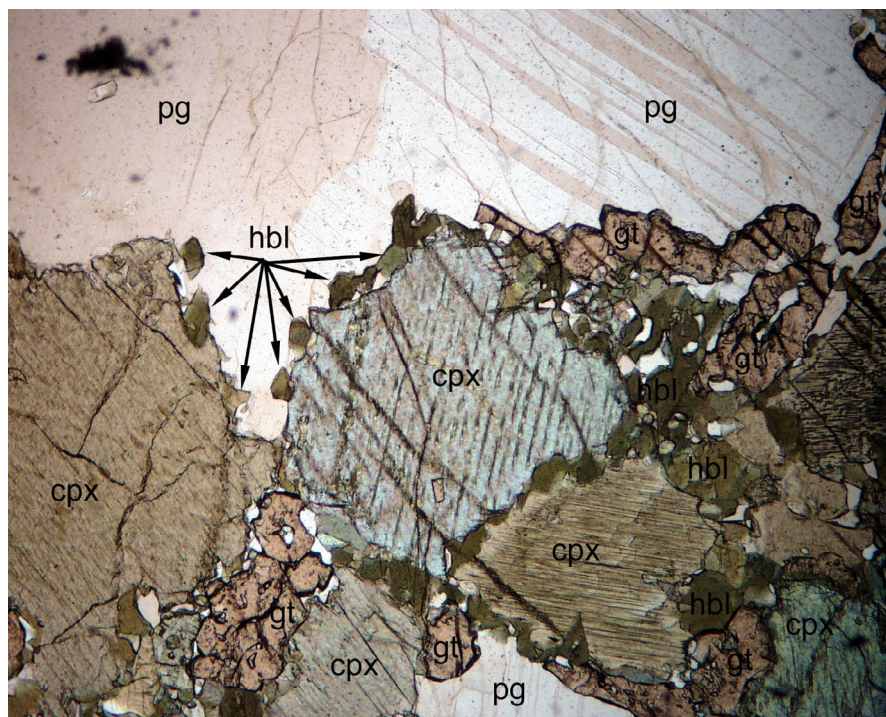


Figure 9 – Photomicrograph in plane-polarized light of Proterozoic mafic orthogneiss showing a coarse-textured granular intergrowth of clinopyroxene (cpx), plagioclase (pg), and garnet (gt) produced during an early stage of metamorphic recrystallization of a former mafic igneous rock. Granular hornblende (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.)

Other Rocks Associated with 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 over the years (Figure 10). 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). Serpentinite has also been found in a building construction site at 43rd Street and Sixth Avenue in midtown Manhattan (Merguerian and Moss 2005) and in northern Manhattan (Merguerian and Moss 2007). These sheared masses are interpreted as ophiolitic scraps and are commonly found in ductile fault contact with the surrounding Hartland Formation or near 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.

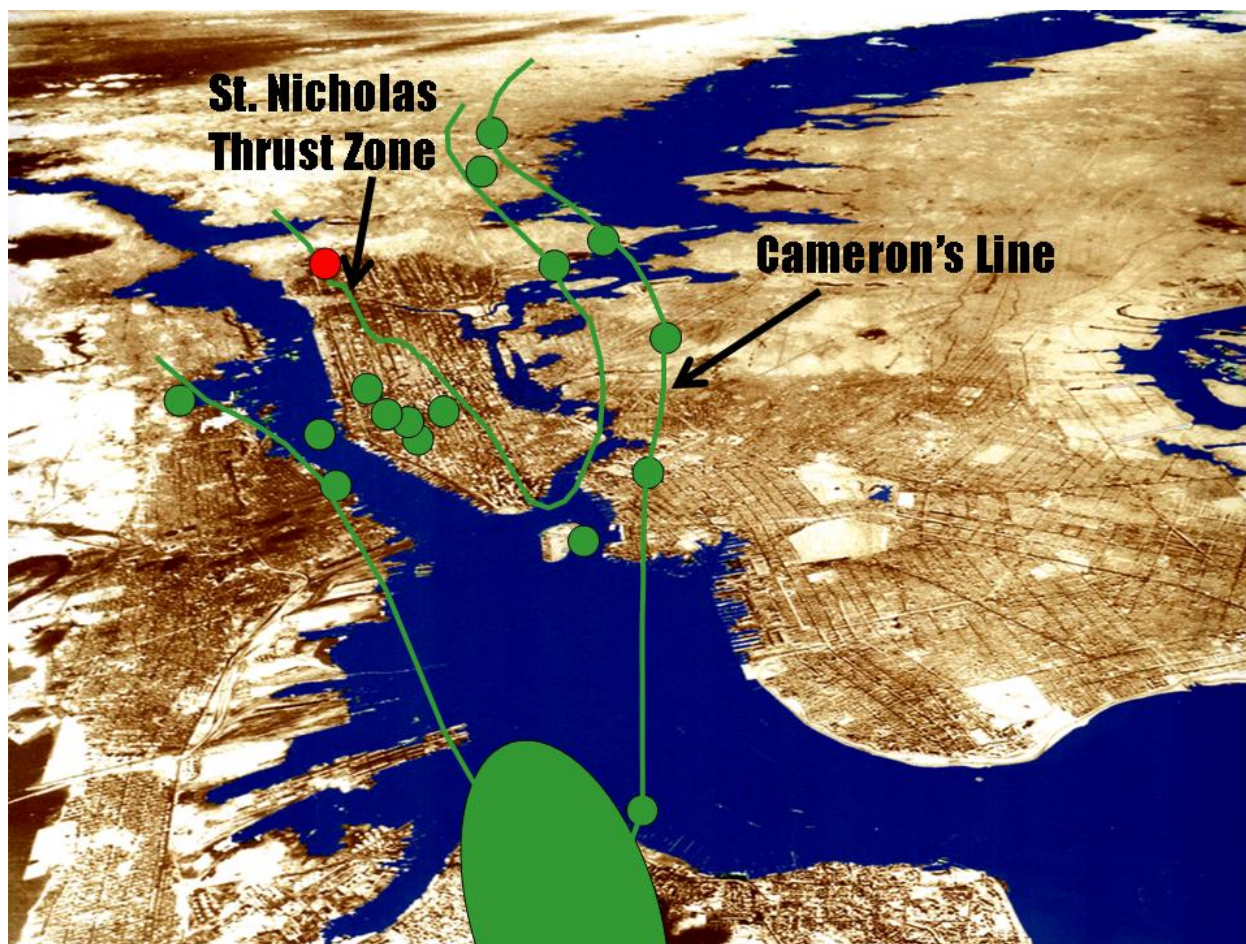


Figure 10 – Cartoon showing distribution of 18 known areas of serpentinite in the New York City area with the site of this report shown in red. The green lines surround areas of serpentinite defining a zone of sheared rock broadly coincident with the St. Nicholas thrust and Cameron’s Line, two important elements of the Taconian suture zone in New York City. The red dot shows the location of a newly discovered serpentinite in northern Manhattan described by Merguerian and Moss (2007).

Granitoids. All units of the NYC bedrock described above have been intruded by granitoids that range from foliated and internally 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. Minor tourmaline and beryl are also reported.

Rhyodacite. Found exclusively beneath the area of Woodside, Queens, a swarm of five thin sub-parallel rhyodacite dikes, all displaying pristine igneous textures, were penetrated during construction of the Queens Tunnel (Merguerian 2000, 2001). They occurred as tabular, discordant injections 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/cm³).

The unique devitrified texture of the groundmass and the presence of vesicles unequivocally identify the Queens Tunnel rhyodacite as a hypabyssal rock. 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 Permian 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.

Mapping in conjunction with construction of NYC Water Tunnels # 1 and 2 also defined mafic and alkalic dike rocks (Berkey 1911, 1933, 1948) and I have seen mafic dikes in the Queens Tunnel and elsewhere in NYC and throughout New England. Some of them are foliated and of Ordovician age and others contain pristine igneous textures and are most likely associated with the early Jurassic Palisades intrusive epoch.

STRUCTURAL GEOLOGY OF NEW YORK CITY

Deformational Episodes. All bedrock units in NYC have shared a complex Paleozoic structural history which involved three superposed phases of deep-seated deformation (D₁-D₃) followed by three or more episodes of open- to crenulate folds (D₄-D₆). The synmetamorphic juxtaposition of the various units occurred very early in their structural history (D₂) 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 Alleghenian) 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 highly metamorphosed.

The obvious map scale folds in NYC are those with steep N- to NE-trending axial surfaces (S₃) and variable but typically shallow plunges toward the S and SW. (See Figures 1 and 2.) The folds are typically overturned to the NW with a steep SE-dipping schistosity (Figure 11). Shearing along S₃ axial surfaces typically creates a transposition foliation of S₁, S₂, and S₃ that is commonly invaded by granitoids to produce migmatite during both the D₂ and subsequent D₃ events. The third-generation structures deform two earlier structural fabrics (S₁ and S₂). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of overturned F₃ folds). I suspect that all of these structures (D₁, D₂, and D₃) are products of the protracted middle Ordovician Taconic orogeny (Merguerian 1996).

During D₂, the rocks acquired a penetrative S₂ 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 D₂. Near ductile fault contacts the S₂ 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.

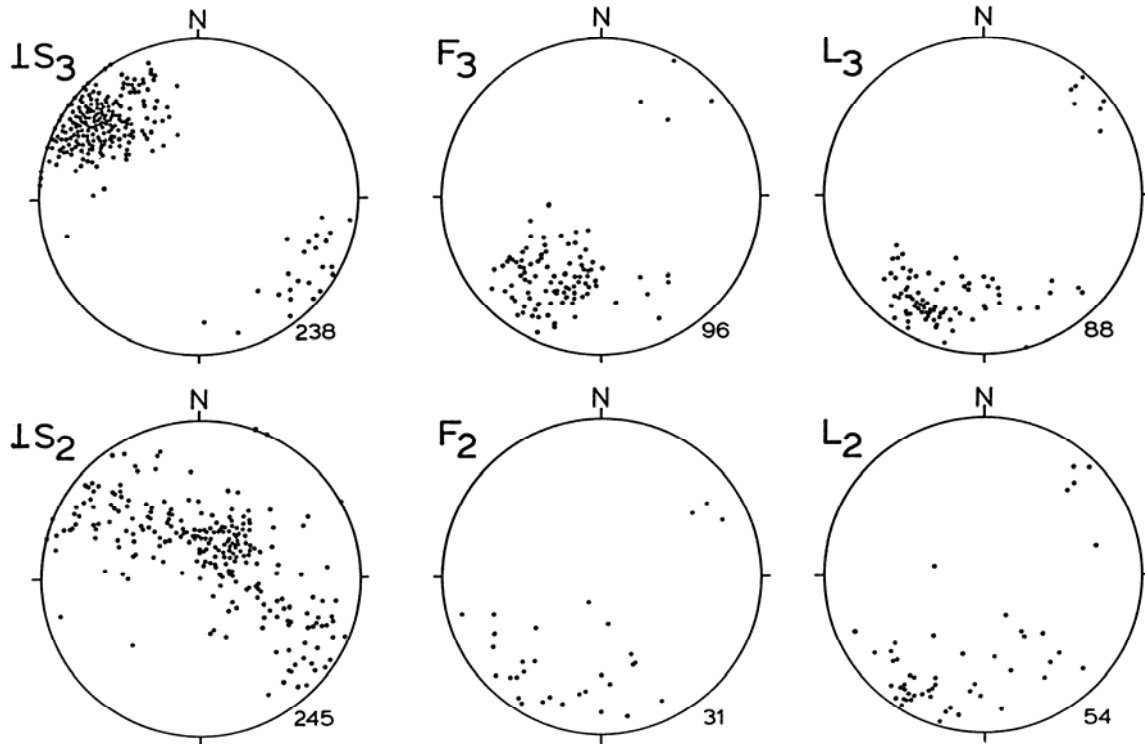


Figure 11 – Equal area stereograms showing the distribution of poles to S_2 and S_3 , the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, Figure 26, p. 113.)

Although the regional S_2 metamorphic grain of the NYC bedrock trends $N50^\circ W$, 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 11.) S_3 is oriented $N30^\circ E$ and dips $75^\circ SE$ 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 annealing of former mylonitic textures (Merguerian 1988).

Originating within the convergent walls of a major subduction zone formerly situated off shore from proto-North America, 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 $N30^\circ W$ 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 the result of post- D_3 deformation. (See Figure 11.) 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 and Joints

Five generations of brittle faults and joints 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.

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 F₃ 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 excavation of rock, in TBM endeavors zones of intersecting fractures are related to working face, crown, and sidewall instability, slippage of TBM grippers, downtime for installation of additional support and ring steel, and high water inflows. Intersecting joint sets can cause similar problems in traditional excavations and therefore careful study and analysis of core and regional trends are important preludes to job bidding and initiation or approach.

GEOLOGICAL CONTROLS AND EXCAVATION CHARACTERISTICS OF NYC BEDROCK

The combined effects of metamorphism and structural deformation has transformed the bedrock units of NYC into a complicated rock mass of varying physical and mechanical properties. Indeed, mineralogy, lithology, texture, metamorphic grade, and structure have a controlling influence on the way rocks break and therefore provide a fundamental link to the methods and means of efficient excavation. A discussion of the influence of these controls follows.

Mineralogical Controls

Construction efforts that rely on penetration through and excavation of rock must take into account the physical properties of minerals. During the pre-bid stage, the mineralogy and hardness index of a 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 volume percentage of component minerals and a weighted hardness value based on Mohs Hardness Scale can easily be calculated for comparison to previous excavation experience.

Minerals common to NYC bedrock are listed alphabetically in Table 1 along with their Mohs hardness, cleavage, and specific gravity. Softer minerals that exhibit cleavage tend to split or break more readily under stress than those that are harder and exhibit fracture. Rocks enriched in hard minerals such as quartz, garnet, kyanite, and sillimanite tend to inhibit penetration by any means and methods and can foster the production of excessive fines.

The density or specific gravity of rocks is a simple litmus test for predicting rock excavation especially by means of mini-mole or TBM. (See Merguerian and Ozdemir 2003; Figure 5, p. 1026.) Rocks consisting of higher density minerals such as garnet, pyroxene, sillimanite, and kyanite are less penetrable by TBM mining or any other excavation method. A density profile along any tunnel alignment can help identify variations over the planned TBM

course and can help plan machine design parameters. All other things being equal, denser rocks tend to be more difficult to excavate in terms of breakage and off-site transport. The volume % of dense, abrasive, hard minerals needs to be determined as their presence above background levels (a few %) can negatively impact excavation rates and enhance the production of excessive fines.

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
Chlorite	2.0-2.5	One	2.6-2.9
Diopside	5-6	Two @ 87° and 93°	3.2-3.3
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
Phlogopite	2.5-3.0	One	2.86
Pyroxene	5-6	Two @ 87° and 93°	3.15-3.5
Quartz	7	Fracture	2.65
Sillimanite	6-7	One	3.23

Table 1 – Physical properties of minerals common to NYC bedrock units.

Lithologic Controls

Rock type has a major influence on any decision concerning removal. During the process of dynamothermal metamorphism, increasing metamorphic grade transforms parent materials into hard rock with the transition from slate to phyllite to schist to gneiss to migmatitic gneiss a prelude to total internal melting and production of magmatic fluids. In NYC, owing to the metamorphic grade of the rocks, slate and phyllite are not found but schist, gneiss, and migmatite are common along with the associated rocks (amphibolite, serpentinite, granitoids, and dike rocks) mentioned earlier. The mechanical properties of schist and gneiss are well understood by contractors and the recent use of terms schistose gneiss, gneissic schist and the like in boring logs are confusing without definition. According to the venerable **American Geological Institute Glossary of Geology** (1982), the term **schist** is defined as “*A strongly foliated crystalline rock, formed by dynamic metamorphism, that can be readily split into thin flakes or slabs due to the well developed parallelism of more than 50% of the minerals present, particularly those of lamellar or elongate prismatic habit, e.g. mica and hornblende*”.

The AGI Glossary of Geology defines the term **gneiss** as “*a foliated rock formed by regional metamorphism, in which bands or lenticles of granular minerals alternate with bands or lenticles in which minerals having flaky or elongate prismatic habits predominate. Generally less than 50% of the minerals show preferred parallel orientation. Although gneiss is commonly*

feldspar- and quartz-rich, the mineral composition is not an essential factor in its definition. Varieties are distinguished by texture (e.g. augen gneiss), characteristic minerals (e.g. hornblende gneiss), or general composition and/or origins (e.g. granite gneiss)."

The AGI Glossary of Geology defines the term **migmatite** as “*a composite rock composed of igneous or igneous-appearing and/or metamorphic materials, which are generally distinguishable megascopically.*” Migmatites are metamorphic rocks that are stewed in their own juices with injection of melted granitic fractions, an important part of the processes that tend to stitch together, strengthen and solidify any original rock type. Migmatitic rocks are difficult to excavate because of their recrystallized texture and pervasive interlocking of minerals.

Very clear definitions of the common rock types found in NYC exist in the literature and by experience all contractors know that schists are more readily removed by any method compared to gneiss or migmatite. Luckily, the determination of schist vs. gneiss is an easy process with careful core study and petrographic analysis and both should accompany any Geotechnical Baseline Report. Careful stereoscopic analysis of split core is also helpful in this regard but no substitute for careful petrographic analysis by skilled technicians.

Foliation Controls

The nature and orientation of foliation (or the lack thereof) holds a first order control on efficient mining by mechanical means. Most foliated rocks are rich in mica (a soft mineral with hardness ~2.5 on Mohs' scale) that tends to provide structural weakness in the form of a perfect basal cleavage. 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. In addition to mica and amphibole, highly sheared rocks that are not subsequently recrystallized contain highly flattened or lenticular quartz, feldspar, and other phases that impart a preferred parallel orientation to the rock texture. Such rocks impart a foliated texture despite the fact that the common phases mica and amphibole are not in excess of 50% of the rock volume. (See Figure 6.) In NYC, owing to the degree of late-stage metamorphic recrystallization, such textures are usually annealed (Merguerian 1988). Highly foliated rocks, such as schist and phyllite, tend to split readily along the foliation thus providing a discontinuity (planes of weakness) that help facilitate rapid excavation (Figure 12). Poorly- to non-foliated rocks (granofels, gneiss, migmatite) resist breakage as a result of stable, interlocked crystal boundaries, typically the result of high grade metamorphism and a lack of alumina (= low clay content in original parent material) to produce mica or amphibole (Figure 13).

Metamorphic Controls

Most of the bedrock of NYC was metamorphosed under amphibolite facies conditions. In formerly 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. (See Figure 12.) Interlayered former sandy units recrystallize into mica-

poor layers known as granofels, consisting of intergrown quartz and plagioclase. Mafic volcanic and pre-tectonic dike rocks recrystallize into foliated amphibole- and plagioclase rich rocks known as amphibolite.

Deep-seated metamorphism is a dehydration reaction that tends to drive water out of minerals. At higher metamorphic grades (upper amphibolite or granulite facies) this results in the total 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 transform 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 high-grade 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. (See Figure 13.) Such textures, easily identified by the petrographic microscope, produce tough rock masses that are legendary for poor penetration rates, production of blocky ground and excessive fines.

Control of Folds and Metamorphic Fabrics

Folding in response to mountain building results in reorientation and recrystallization of new minerals (typically micas in rocks of appropriate composition) in a direction perpendicular to maximum compressive stress (Figure 14). Such deformation can produce a foliation in a rock mass because of rotation, growth, and parallelism of new mica in the axial regions of folds (the plane of maximum compression). A penetrative axial planar foliation can result if the rocks are aluminous enough to produce micas (abundant original clay in the parent rock is a necessary element). In alumina-poor parent starting materials no degree of strain can produce a mica foliation because the chemistry will not support mica growth. Even within a schistose formation, mica-poor rocks can occur as a result of original compositional variations including clay poor silty or sandy facies, turbidites, or clean quartzose sand interlayers.

Superposed deformation can produce numerous generations of crosscutting metamorphic fabrics that can be traced in the field and also verified by petrographic examination. The history of a rock mass can be deduced in this fashion since different deformations typically produce their own unique set of distinctive minerals based on extant pressure-temperature conditions. Thus, cross-cutting relationships establish the relative age of metamorphic fabric elements and allow for the interpretation of complex terrains such as found in NYC.

In rocks that experience high shear strains, excessive ductile flow can disrupt folds with attendant shearing and dislocation along the limbs and axial surfaces of folded structure. Figure 15 shows a typical example of this phenomenon wherein folded layers in the upper part of the diagram have been dislocated with respect to the lower part of the diagram. Such structures are well-known in highly sheared metamorphic rocks. Examples of sheared out folds and intense localized folding have been recorded at many places in NYC. They disrupt stratigraphy and can introduce different rock facies within a thin interval. As a result, widely spaced vertical borings

may not adequately define the rock mass for a particular contract, especially when the major geological features are steep to vertical in orientation.

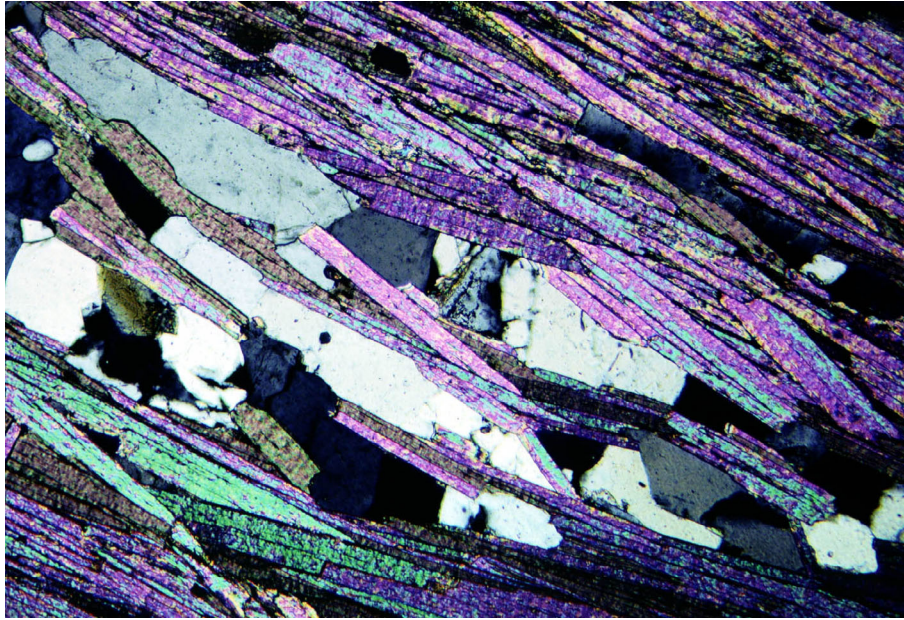


Figure 12 – Photomicrograph in crossed nicols of aluminous Hartland schist (N403-1; World Financial Center site, lower Manhattan). The section shows fine-grained lenticular quartz and minor plagioclase separated by aligned muscovite and minor biotite (highly colored crystals). Such directional mineral growth results in a penetrative micaceous foliation.

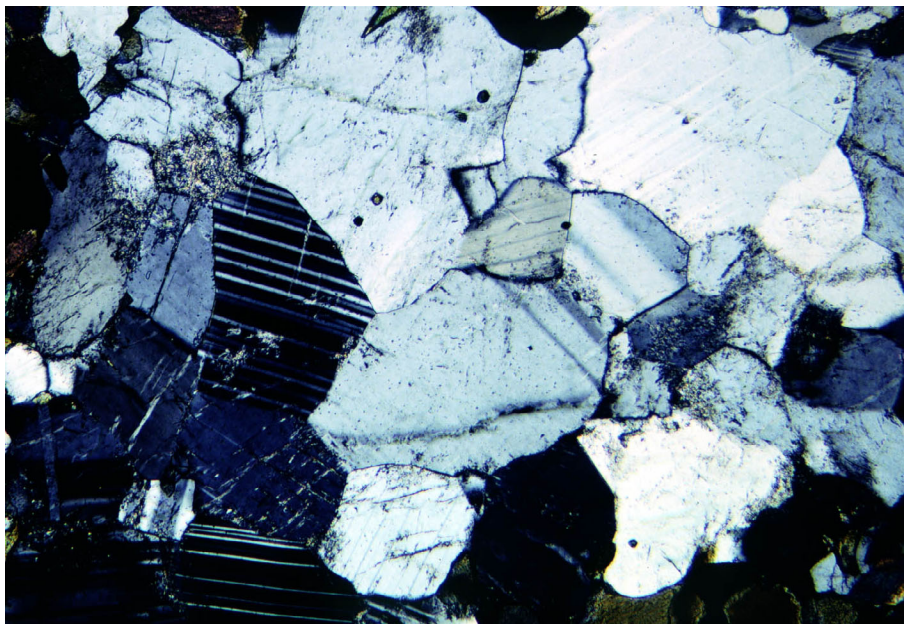


Figure 13 – Photomicrograph in crossed nicols of Queens Tunnel gneiss (Q085; Station 159+80) showing granoblastic intergrowth of plagioclase and minor quartz. Note the medium-grained granular texture, the stable 120° grain boundaries of the interlocking plagioclase, and the lack of any penetrative foliation. Both photomicrographs are 2 mm across.

Such ductile superposed fabrics are found in localized areas of NYC (near ductile shear zones such as Cameron’s Line and the St. Nicholas thrust). In the areas where intense shearing has taken place induced deformational fabrics and injection of migmatizing fluids tends to stitch together the rock texture and toughen the rock mass because of the destruction of foliation and replacement by granitic material to produce migmatite. Careful regional and site-specific geological mapping and examination of core by petrographic methods can readily identify such areas and avoid the hardship of poor excavation rates.

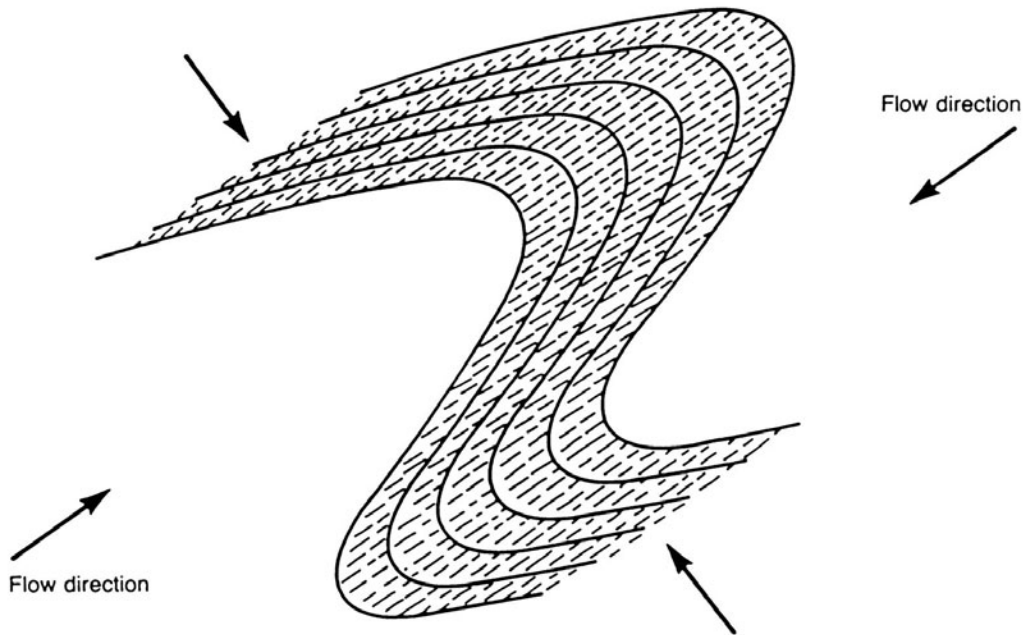


Figure 14 – Sketch showing how strain related to maximum compressive stress (black arrows) deforms bedrock into folds with flow and recrystallization perpendicular to the maximum compressive stress orientation. In metamorphic rocks, the rotation of existing fabric elements and the growth of new minerals bisects the fold in half along a new orientation parallel to the flow direction producing an axial planar foliation (in rocks of appropriate composition!).

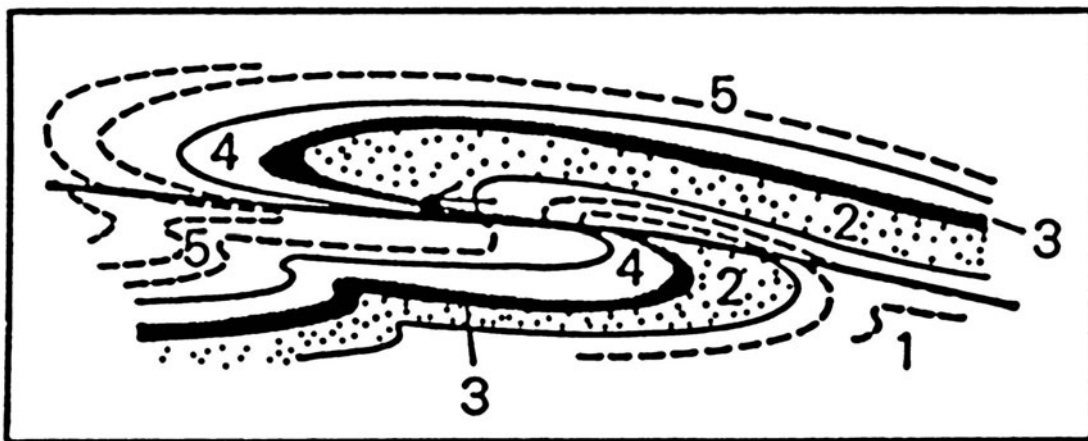


Figure 15 – Sheared overturned fold broken by a low-angle thrust fault, schematic profile section. Units are numbered in order to illustrate dislocation across shear surface.

Control of Superposed Fold Structures

The rocks of NYC display intense localized isoclinal- and shear folding in association with the development of the primary (S_2) regional foliation. In some places ductile shear zones developed initially during D_2 and subsequent D_3 deformation and produced a shredded, ductile fault fabric that was hardened by annealing during subsequent recrystallization. Thus, the combined effects of intense isoclinal folding and recrystallization are to produce composite parallel fabrics in the rock mass and to create a tough rock that resists breakage. Note in Figure 16, the massive nature of the rock mass, the result of intense localized folding, shearing, and migmatization. The rock, Hartland migmatitic gneiss from the South Ferry subway excavation in southern Manhattan, exhibits the effects of protracted deformation and shearing in the form of shear folds and the production of parallel S_2 and S_3 fabric elements. Note the older S_2 foliation (yellow lines in Figure 16) is discontinuous and associated with quartzofeldspathic granitoid. The quartz+feldspar laminae were formerly separated by thin mica folia but they were subsequently subjected to intense F_3 shear folding. Metamorphism coincident with the F_3 folding annealed the S_2 ductile fabrics and produced F_3 shear folds with characteristic sheared out limbs yet preserved the S_2 granitoid layers in the fold hinge area. Owing to the similarity in metamorphic grade between the D_2 and D_3 events, some garnet is flattened and deformed by the F_3 fold while some of the garnet is equant and overgrows the S_2 fabric as porphyroblasts.

Another type of structural control involves less intense F_3 folding (crenulate folds). Here, because of the effects of superposed F_3 folds, the older S_2 fabric is highly dislocated and warped into irregular complex patterns. Figure 17 is a composite diagram showing a large slab of mica gneiss from the South Ferry subway excavation in a number of petrographic views. Pane A shows the rock structure in plane polarized light with obvious deformation of a sparse mica foliation outlined by biotite and muscovite. Note the abundance of mica is much less than 50%, hence qualifying the use of the term gneiss because of the predominance of quartz and feldspar (gray, yellowish, and clear minerals in crossed polarized light (Pane B)). The S_2 foliation is strongly folded by F_3 folds (Pane C) and the S_2 mica foliation is overprinted by S_3 mineral growth parallel to the axial surfaces of the F_3 folds. At this location, the complex intertwining of S_2 and S_3 metamorphic fabrics resulted in a complex rock texture dominated by multi-directional growth of discontinuous zones of mica. The effect of this was to “stitch” or “knit” the rock mass together and increase the resistance to breakage by mechanical means.

Detailed petrographic examination of the same South Ferry sample shows the knitted nature of the rock texture (Figure 18). Here, the growth of older biotite in numerous orientations is quite obvious as is the growth of younger muscovite mica at contrasting directions. The lower pane (B) shows that quartz and feldspar are also locked together as sutured crystals and as interlocking crystals with stable 120° boundaries. The short, discontinuous micas grown at various directions serve to “knit” the rock mass together (in much the same way that soft fiberglass fibers strengthen concrete) and the stable 120° crystal boundaries in the hard minerals resist fracture. This variety of knitted texture results in poor excavation rates regardless of method. The contractor at this job had tremendous difficulty removing the rock by hydraulic ram and mechanical means as specified in the contract and had to resort to limited blasting. The loss in time and increased construction costs resulted in an acrimonious dispute between the contractor and the NYC MTA.

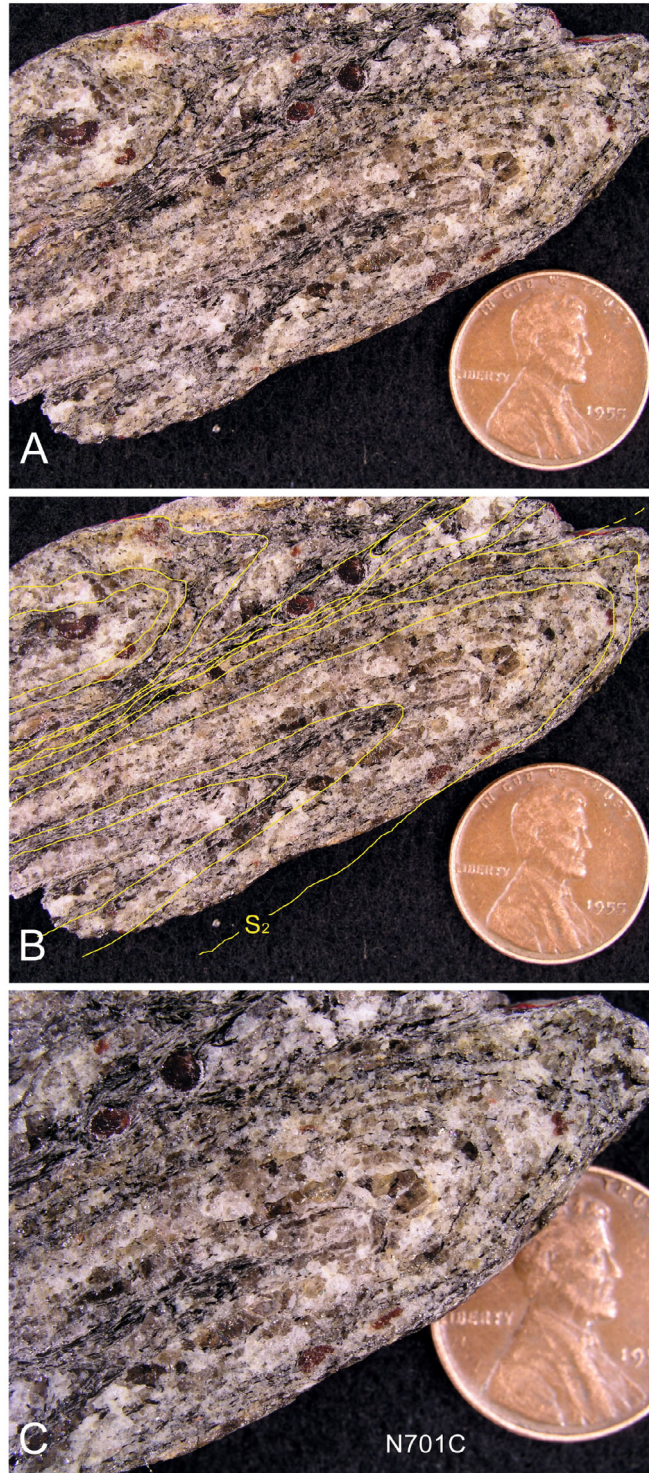


Figure 16 – Series of images showing F_3 shear folds from the South Ferry subway excavation where Hartland migmatitic gneiss predominates. Pane A shows a sawn and polished slab from southern Manhattan. Pane B shows the deformation of older S_2 fabric (in yellow) that is stitched together by quartz-feldspar segregations produced during D_2 . The S_2 ductile fabric is deformed by D_3 shear folds that exhibit marked dislocation along the limbs of the fold and growth of parallel S_3 fabrics including garnet. Pane C is a close detail of the fold hinge area showing preservation of the older S_2 fabric. Elsewhere S_2 is bent into parallelism with S_3 along the F_3 fold limbs.

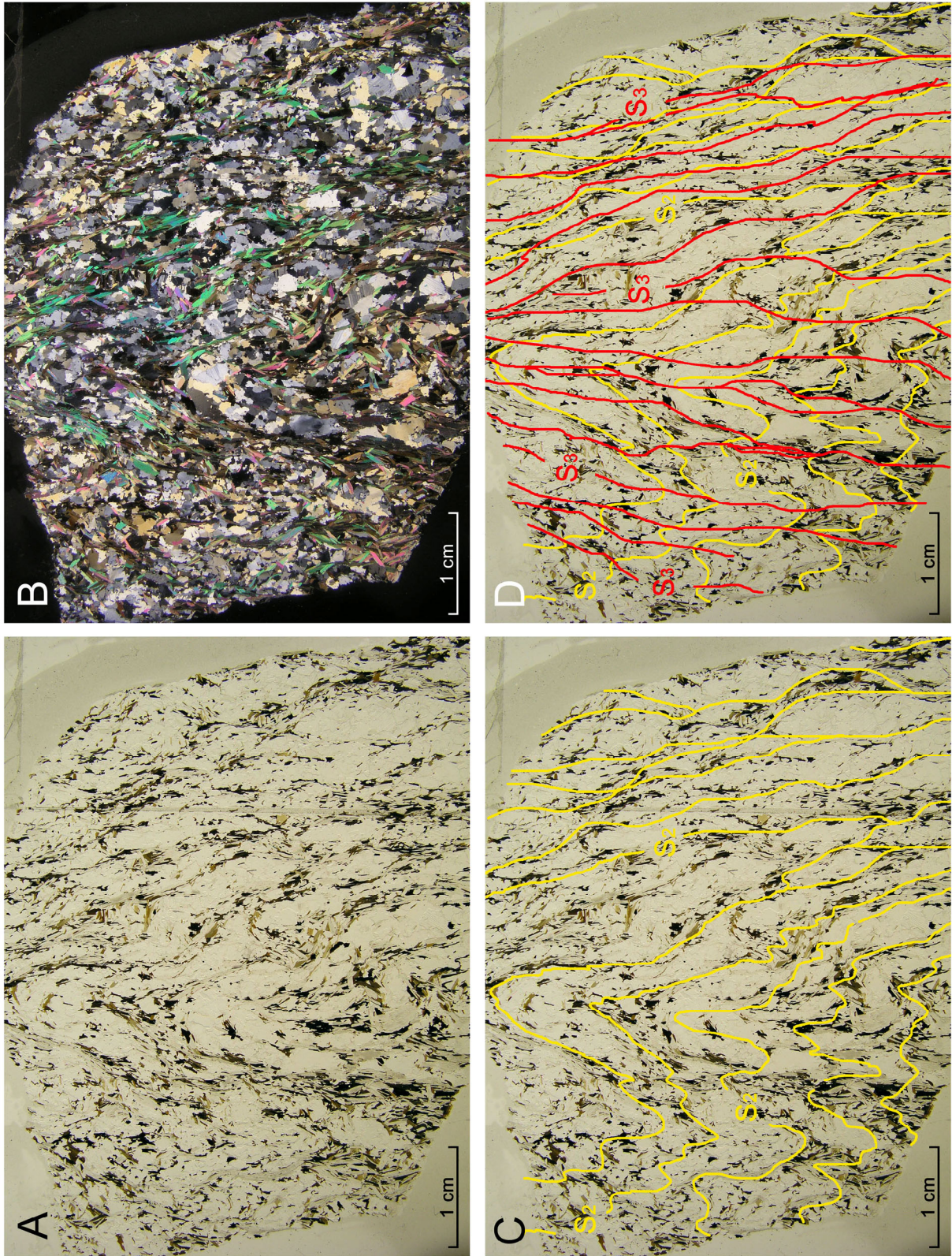


Figure 17 – Macroscopic images of large sawn sample of Hartland migmatitic gneiss from the South Ferry excavation in Manhattan showing a complex texture produced by superposed S₂ (yellow) and S₃ (red) fabrics.

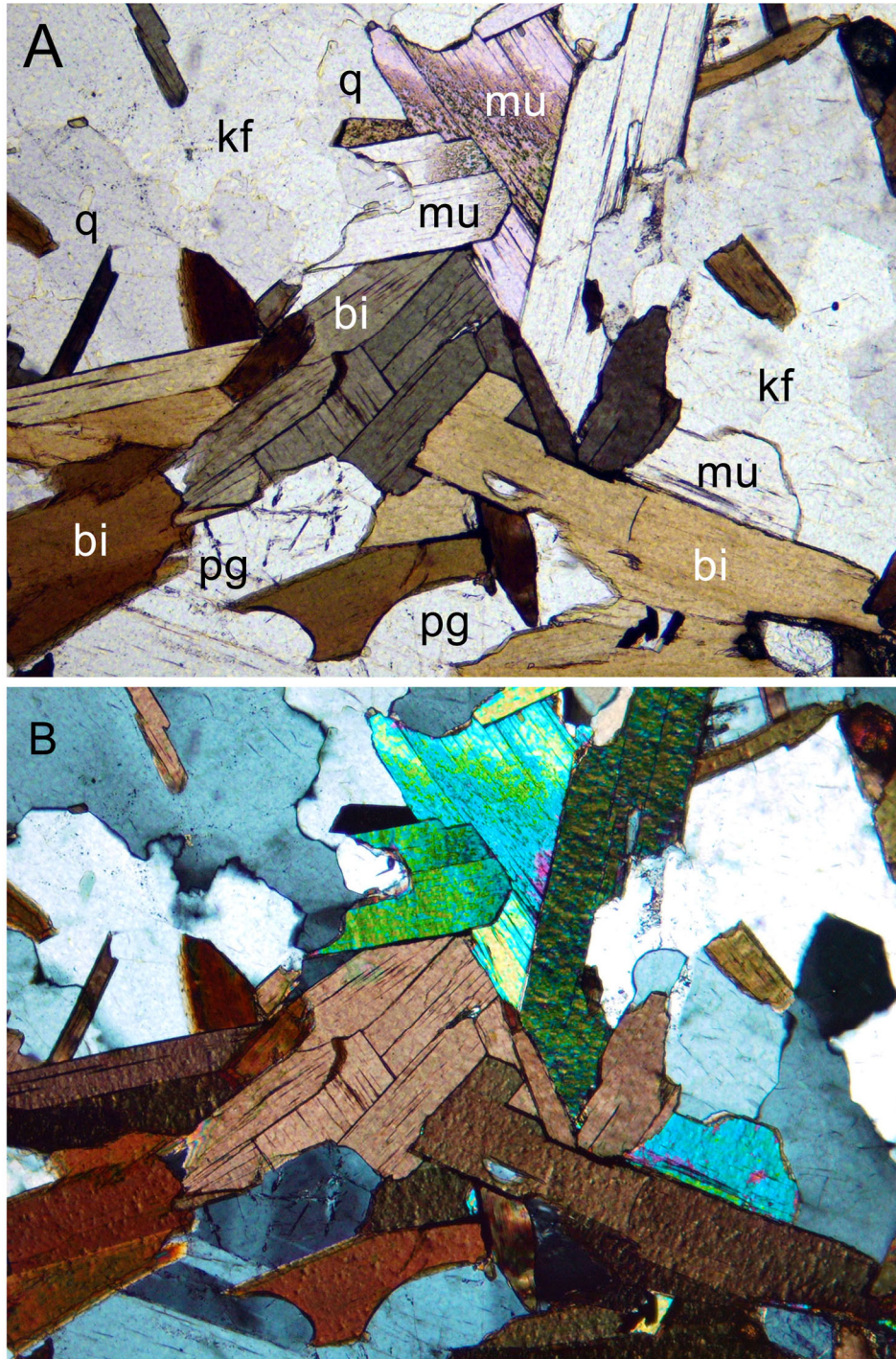


Figure 18 – Photomicrographs in plane-polarized (A) and cross-polarized light (B) showing the fabric of a sample from the South Ferry excavation in southern Manhattan. (Same sample as Figure 17.) Note the multi-directional nature of the individual mica crystals and how biotite micas are overprinted by late muscovite – also at odd growth angles. The lack of parallelism of constituent micas and interlocked texture of the hard minerals (quartz and feldspars) controlled poor penetration in highly folded rocks at this site. The short, discontinuous micas knit the rock mass together and the stable 120° crystal boundaries in the hard minerals resist fracture. Notation in plane-polarized view (A) is as follows: q = quartz, pg = plagioclase feldspar, kf = K-feldspar, mu = muscovite mica, bi = biotite mica. (Field of view 1.6 mm across.)

EXCAVATING CRYSTALLINE ROCKS

Regardless of means and method (roadheader, hydraulic ram, drill and blast, mini-mole, or TBM) the excavation of crystalline rock relies upon the failure of discontinuities in the rock mass under stress. Naturally, a thorough understanding of the joint density, orientation, and spacing (RQD and recovery values from core examination) are of great importance in this matter except for the recognition that RQD values of 100 do not specify actual spacing of fractures greater than 4 inches. The overall composition of the rock mass holds a first order control on excavation. Stated simply, the more mafic (iron- and magnesium-rich) the rock mass the lower the penetration. Careful petrographic core analysis and density measurements and tabulation should discriminate between felsic, intermediate, and mafic lithotypes at the excavation horizon.

The nature and orientation of foliation (or the lack thereof) also holds a prominent control on effective rock removal regardless of method. 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 paramount importance including recognition of unique textures or structures. Although mica is the most common foliation-producing mineral, not all foliated rocks are micaceous and foliation can be produced by flattened mineral species such as lenticular quartz and feldspar. 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. 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). 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 properties.

Highly foliated rocks (slate, phyllite, and schist) tend to split readily along the slaty cleavage or 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 advance direction with the strike more or less perpendicular to the advance (Merguerian and Ozdemir 2003). Regional mapping and oriented core study will alert contractors to the prevailing orientation and adjustments in advance direction may enhance excavation. Unless exposed bedrock is available for field study, stereonet analysis of oriented core is the most effective method of understanding the variation and prevailing orientation of foliation and fractures along a given terrain.

Excavation Destiny of NYC Rocks

In terms of mechanical excavation of bedrock units that underlie NYC, the schistose portion of the **Hartland Formation** is relatively easy to excavate because of its high mica content, pervasive foliation, and presence of interlayered lithologic components. 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. This unit was readily excavated at many sites by hydraulic ram from midtown Manhattan southward to the World Trade Center and vicinity. The **Walloomsac** schist, owing to the presence of graphite and fissile foliation is another unit that will yield high penetration rates but this unit is thin and sparsely distributed throughout NYC. The formation also contains layers and lenses of hard calc-silicate rock that is difficult to excavate. Of the three Paleozoic metamorphic cover units in NYC, the schists of the **Manhattan Formation** would be less penetrable than the Hartland or Walloomsac owing to the abundance of hard minerals (quartz, garnet, sillimanite, and kyanite) which often occur in layers and lenses, the general lack of internal layering, and resulting massive character.

Not all subunits in the Hartland, Manhattan, and Walloomsac formations are true schists as defined by the American Geological Institute. Gneissic and granoblastic rock interlayers or migmatitic zones within these formations offer a challenge to excavation for the textural and structural reasons described in a previous section and a thorough understanding of the lithologic variation and spatial distribution of such rocks can help in selecting the proper means and methods for efficient excavation.

The **Inwood Marble** offers excellent TBM penetration potential owing to the abundance of calcite and dolomite, two relatively soft and internally 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 but mechanical means (roadheader and hydraulic ram) would be less effective given the massive nature and overall granoblastic texture of the rock mass.

Average TBM penetration rates of <2 m/hour were encountered in the **Fordham Gneiss** during excavation of the Queens Tunnel with significant periods of down time the result of cutter, machine, or conveyor damage. 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 excavation endeavor, traditional drill and blast methods might be more efficient in this older formation.

Serpentinite masses are typically small isolated bodies generally less than 40m in extent. Because of their internal weakness and soft component mineralogy (rich in talc and serpentine group minerals) they are known to cause sidewall instability, diameter changes in bored tunnels and deep excavations, and to create zones of slippage for TBM grippers. In addition, they are a

source of airborne asbestiform minerals during drilling and mining and can pose severe environmental problems during various phases of removal and transport.

The mining of **granitoids** presents no special problems except when they are metamorphosed to the granulite facies and harbor tough, granoblastic textures. 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.

Dike rocks (rhyodacite dikes, mafic dikes, etc.) 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. 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 or fail 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. The rhyodacites were associated with loose, blocky ground and created unstable crowns, sidewalls, and headings during TBM mining of the Queens Tunnel.

CONCLUSIONS

NYC will continue to be the focus for significant hard rock excavation in the foreseeable future. Crystalline terrains provide an unforgiving medium for effective utilization of equipment and excavation rates regardless of means and method. A clear understanding of the geology of any construction project is the simplest and most cost-effective method to mitigate potential losses encountered during excavation in such terrains. The excavation of NYC rocks is strongly dependant upon the mineralogy, texture, metamorphism, and structure of the rock mass. In addition to standard core study, geotechnical testing, and analysis, detailed study of the mineralogy and texture of component minerals in rocks by competent geologists should be considered an essential prelude to bidding work since these allied studies hold the clues toward predicting excavation destiny. Excavation in crystalline terrains can best be evaluated on the basis of soft mineral content (volume % muscovite, biotite, calcite, graphite), rock mass density, lithology, structure, and metamorphic history. Field analysis and petrographic study can best identify textural properties that will negatively impact mining.

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