Chapter 2. Review of New York City bedrock with a focus on brittle structures

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Abstract

Over four decades of mapping of natural exposures and subsurface engineering projects has allowed for a thorough investigation of NYC bedrock features. This paper focuses on young brittle geological features that are superimposed on granulite to amphibolite grade polydeformed bedrock consisting of Proterozoic basement and Paleozoic cover rocks. Two groups of brittle faults prevail in NYC. The older of these are post Permian (295 Ma) and trend NNE with steep dips. These are reactivated by NW-trending discontinuities with steep to moderate dip that locally show post-glacial offset.

Introduction

Geological mapping and geotechnical data from many engineering construction projects in NYC have provided an opportunity for evaluation of brittle discontinuities in NYC bedrock. This paper presents mapping and geotechnical data selected from the Queens Tunnel section of NYC Water Tunnel #3, the East Side Access project across Manhattan into Grand Central Station, the Croton Water Treatment Plant and various NYC parks together with framework data from over 1,000 other locations in and around NYC.

Two pervasive and geomorphologically evident post-Paleozoic fracture sets cut the region. The older of these (Group D - NNE trend) with steep dips exhibits dip-slip offset and local reactivation since these are cut by a younger set (Group E - NNW to NW trend) with moderate to steep dips and strike-slip and oblique-slip mechanisms. Brittle discontinuities affect both the Paleozoic cover and Proterozoic basement sequences but not all groups are found in the cover rocks. The age of Group D fractures is unclear but are possibly associated with Mesozoic rifting as they truncate Permian (295 Ma) rhyodacite dikes in the subsurface of Woodside, Queens (Merguerian 2001, 2002a). Evidence from the Bronx River in the NY Botanical Garden suggests post-glacial offset by the NW-trending Group E Mosholu fault (Merguerian and Sanders 1996a, 1997). The Group E fractures may be the result of contemporary stress or transcurrent fracture propagation away from the Atlantic Ocean ridge into the continental crust. This notion may explain the neotectonic reactivation of brittle crustal features although other mechanisms or combinations of mechanisms are clearly possible.

Physiography of New York City and vicinity

NYC is situated at the extreme southern end of the Manhattan Prong (fig. 1), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic Y basement to Lower Paleozoic cover rocks that widen northeastward into the crystalline terrains of New England. Southward from NYC, the rocks of the Manhattan Prong plunge nonconformably

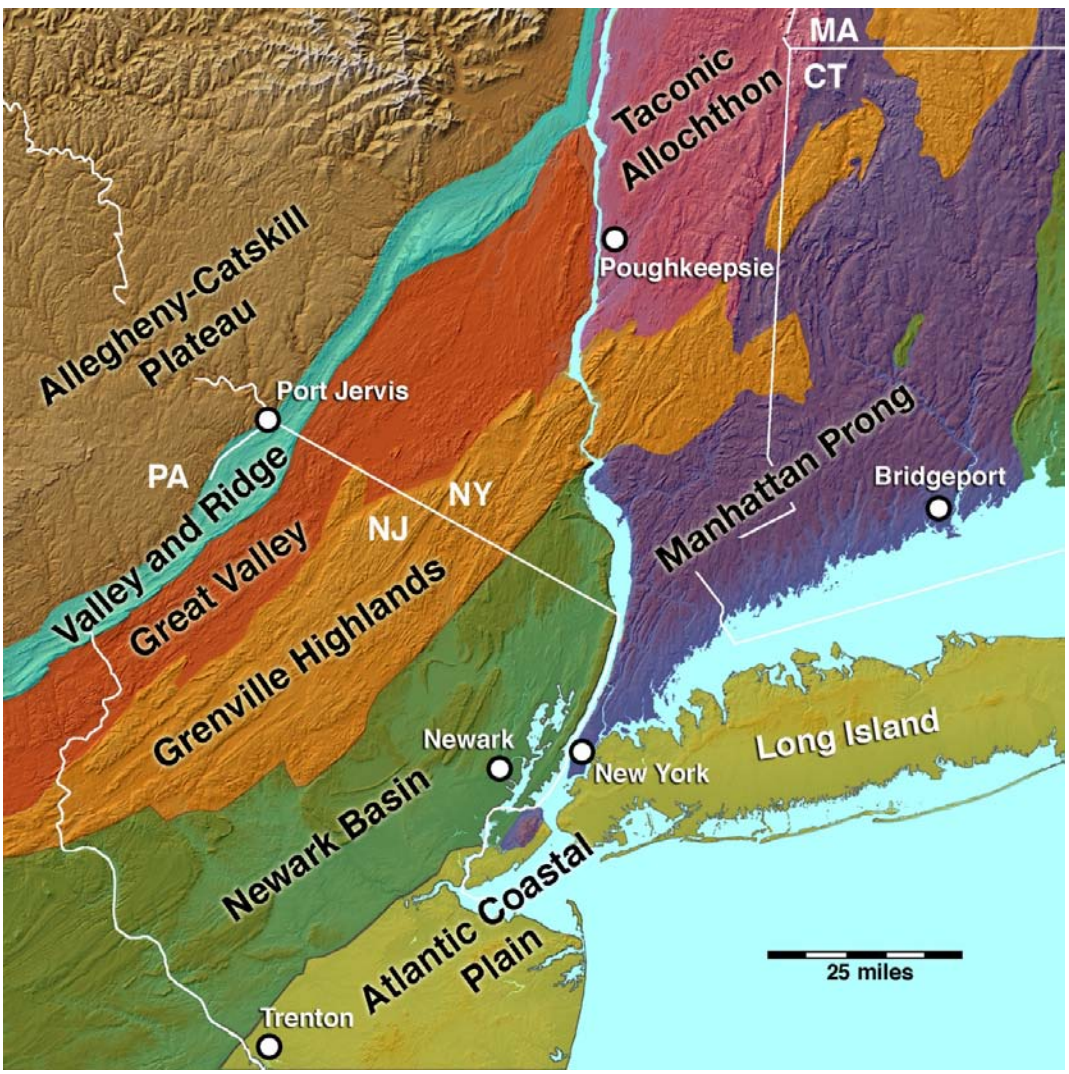

Figure 1. Physiographic diagram showing the major geological provinces in southern New York, northern New Jersey, and adjoining states (From Bennington and Merguerian, 2007).

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.

The history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991b). My involvement in NYC bedrock studies began in the late 1960s as a City College student in NYC and I have continued my investigations both academically and as a geotechnical consultant, logging over four decades of geological study. The major findings of this period have been presented elsewhere (Merguerian 1983a, 1984, 1994, 1996c, 2002b; Merguerian and Baskerville 1987; Merguerian and Merguerian 2004, 2012, 2014a; and Merguerian and Moss 2005, 2006a, 2007, 2015). Much of the data presented in this paper and posted in the associated online GANJ 2015 web repository is from proprietary reports associated with now long-settled industry claims.

New York City bedrock

Two basic subdivisions of NYC crystalline bedrock (fig. 2) include a substrate of:

1) *Paleozoic cover rocks* including schist, marble, and associated lithotypes that overly

2) *Proterozoic Y basement rocks* including granulite facies gneiss and crosscutting igneous rocks.

Both rock sequences were internally folded and sheared during Paleozoic orogenesis and cut by younger brittle fracturing (faults and joint discontinuities). The following are descriptions of the respective units.

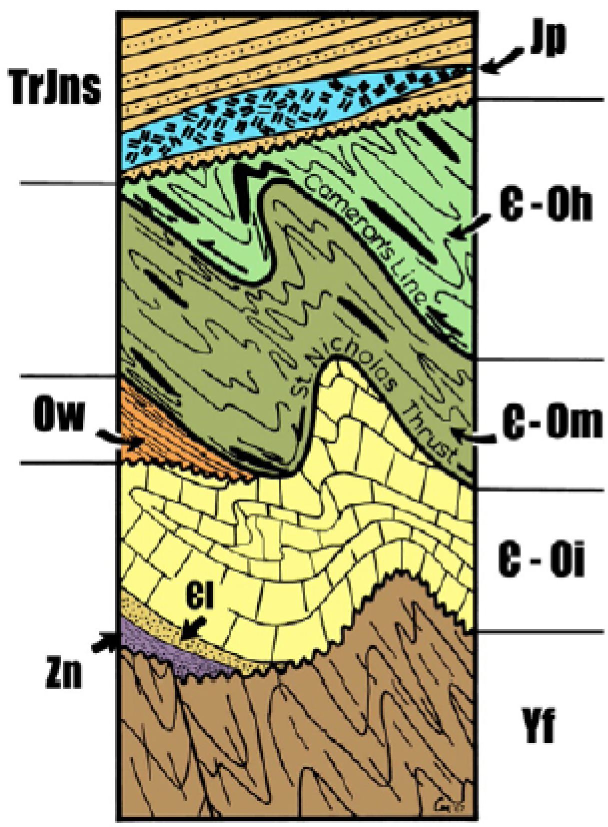

Figure 2. Bedrock stratigraphy of New York City as described in text. The polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).

Paleozoic cover rocks

***Hartland Formation* (Ꞓ-Oh)** - Gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase±kyanite±garnet schist, gneiss, and migmatite with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite±biotite±garnet. Known for relatively easy excavation because of pervasive jointing parallel to layering, the unit has been encountered in

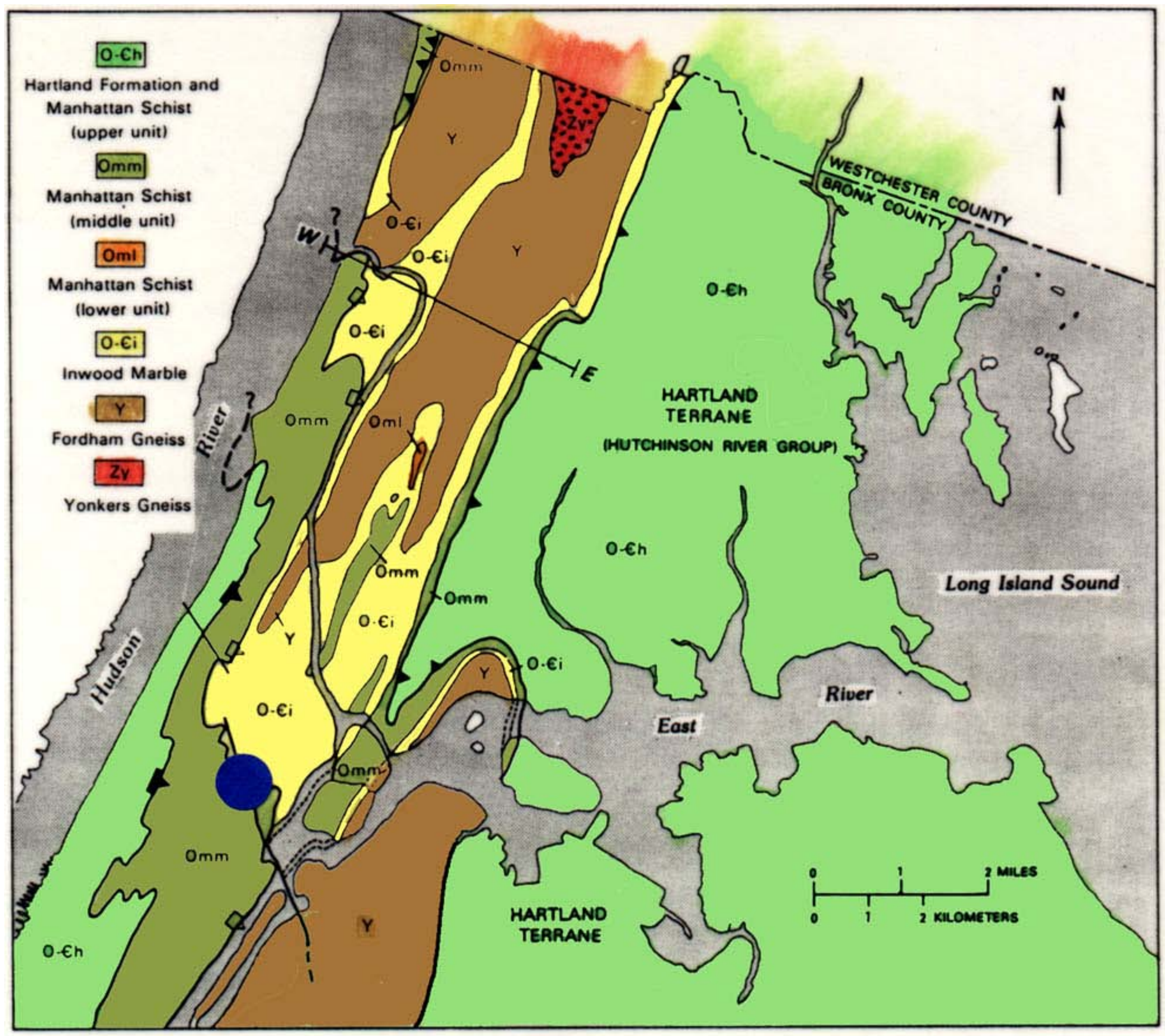

Figure 3. New York City generalized geological map and cross sections adapted from Merguerian and Baskerville (1987). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most brittle faults and intrusive rocks have been omitted. Blue dot shows earthquake epicenter of magnitude 2.4 (21 January 2001) that projects above the trace of the Manhattanville fault (Group E). Cross sections in the Bronx (left and top of map) and Manhattan (right) depict the general, ductile style of folding and faulting involving Cameron's Line and the St. Nicholas thrust. The S-N section is about located were the epicenter symbol near Central Park. Note that the unit Omm is equivalent to Ow in this report.

the East Side Access, Second Avenue Subway, Manhattan Water Tunnel, #7 Line IRT Extension and Con Edison Steam Tunnel projects. It is has been extended into NYC from western Connecticut and Massachusetts based on stratigraphic correlation (Merguerian 1983a) and it is considered a part of the Taconic allochthon (Merguerian and Sanders 1996b).

Manhattan Formation **(Ꞓ-Om) –** Massive, rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz±garnet±kyanite±sillimanite-magnetite gneiss, migmatite, and schist. Characterized by the lack of internal layering except for kyanite± sillimanite+quartz+magnetite interlayers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite, and scarce quartzose granofels. It forms the bulk of exposed Paleozoic metamorphic rocks of northern Manhattan including the northern Central Park exposures. These allochthonous rocks are grouped with the Hartland formation as part of a Taconic Sequence.

Walloomsac Formation **(Ow)** – A discontinuous unit 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 calcite- and dolomitic marble, and greenish calc-silicate rock. *Amphibolite is absent.* Strongly pleochroic reddish biotite, pinkish garnet (porphyroblasts up to 1 cm), graphite and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels invite the interpretation that this unit is metamorphosed middle Ordovician carbonaceous shale and greywacke of the autochthonous Annsville and Normanskill formations of SE New York and the Appalachian Martinsburg Formation.

Inwood Marble **(Ꞓ-Oi) -** White to bluish-gray fine- to coarse-textured dolomitic and lesser calcitic marble locally with siliceous interlayers containing diopside, tremolite, phlogopite, muscovite (white mica), and quartz together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite. Layers of fine-textured gray quartzite with a cherty appearance are also locally present. The Inwood is correlative with the Cambro-Ordovician carbonate platform sequence of Appalachians.

Proterozoic basement rocks

Fordham - Queens Tunnel Gneiss **(Yf)** - The oldest rocks in NYC are a complex assemblage of Proterozoic Y ortho- and paragneiss, metasedimentary, metavolcanic and granitoid rocks. Based on detailed studies in the Queens and Brooklyn portions of NYC Water Tunnel #3 (Merguerian, 1999, 2000; Brock, Brock, and Merguerian 2001), the Fordham correlative is known as the Queens Tunnel Complex (QTC) which consists of predominately massive mesocratic, melanocratic and leucocratic orthogneiss with subordinate schist, granofels, and calc-silicate rocks. Grenvillian high pressure granulite facies metamorphism produced a tough, anhydrous interlocking texture consisting of clino- and orthopyroxene, plagioclase, and garnet that has resisted amphibolite grade Paleozoic retrograde regional metamorphism. Geological details of the QTC are presented in a later section.

Paleozoic orogenesis

The venerable Manhattan Schist of NYC, exposed in Manhattan and the Bronx, consists of three separable map units: the Hartland, Manhattan, and Walloomsac formations (figs. 2 and 3). These subdivisions agree, in part, with designations proposed by Hall (1968, 1976, and 1980) but recognize a structurally higher unit that is a direct correlative of the Hartland Formation of western Connecticut (Merguerian 1981, 1983b, 1985c, and 1987). The three schistose tectonostratigraphic units are imbricated along regional ductile faults known as the St. Nicholas thrust and Cameron’s Line, as indicated in a simplified cross section across the northern tip of Manhattan into the Bronx (Merguerian 1994, 1996a). The NW-SE section shows the general folded structure of NYC and how the St. Nicholas thrust and Cameron's Line overthrusts place the Manhattan and Hartland formations above the autochthonous Walloomsac and Inwood and the Fordham basement sequence. Major F_3 folds produce digitations of the regional S_2 foliation, which dips gently southward (downward) and out of the page toward the viewer. The NE-SW section illustrates the southward topping of tectonostratigraphic units exposed in central Manhattan and the effects of the yet younger NW-trending asymmetric F_4 folds.

Now metamorphosed to amphibolite facies grade, the exposed Paleozoic metamorphic cover rocks of NYC were originally deposited as sediment and intercalated volcanic and volcaniclastic materials, though in vastly different environments (fig. 4). The Hartland was originally deposited in a deep ocean basin fringed by offshore volcanic islands. The Manhattan originated along the edge of the Laurentian continental margin as thick clay-rich sediment with occasional sand interlayers and mafic dikes or flows. The Walloomsac is mineralogically unique since it originated under restricted oceanic conditions (reducing environment) which consisted of thick accumulations of carbonaceous and sulphidic clay-rich sediment with occasional sandy and calcareous interlayers.

Underthrusting of the accretionary prism associated with the Taconian arc-continent collision produced the deformation, internal shearing, imbrication and amphibolite facies regional metamorphism of the Paleozoic cover rocks with basement involvement. The underlying Fordham-Queens Tunnel Complex basement rocks experienced localized retrograde metamorphism of Grenville granulite facies fabrics during Taconian and younger events.

In NYC and in most crystalline terranes inherent ductile geological structure holds a first-order control on development and geometry of subsequent brittle discontinuities. As such, a brief synopsis of NYC structural geology is here appropriate.

Paleozoic deformational episodes

All Paleozoic cover sequences in NYC have shared a complex structural history which involved three superposed phases of deep-seated Taconian deformation (D_1, D_2, D_3) followed by three or more episodes of open- to crenulate folds (D_4-D_6) in mid- to late Paleozoic or younger time. Synmetamorphic juxtaposition of the bedrock units occurred very early in their structural history (D_2) based upon field relationships. The Fordham-Queens Tunnel basement sequences harbor a more complex history having endured deformation and metamorphism during the Grenville orogeny (~1.1 Ga) in addition to the three Paleozoic orogenies (Taconian, Acadian, and Alleghenian - see chapter 4) whose effects are concentrated in the overlying Inwood, Walloomsac, Manhattan, and Hartland rocks.

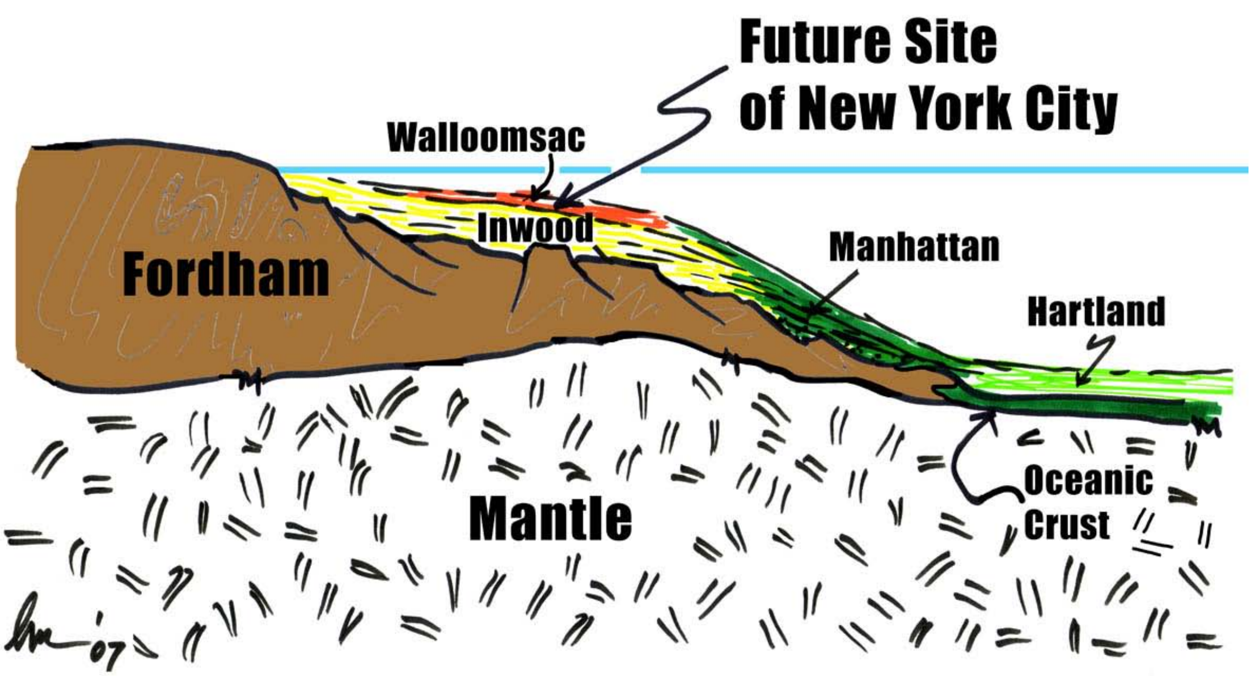

Figure 4. Stylized profile of eastern North America after Late Proterozoic rifting from Rodinia and during deposition of the Paleozoic shelf sequence of the Hartland, Manhattan, and Walloomsac formations. Note the correlation of units and their relationships to the underlying units of the partly coeval Inwood and older Fordham.

The obvious map scale F_3 folds in NYC are those with steep N- to NE-trending axial surfaces (S_3) and variable but typically shallow plunges toward the S and SW (figs. 2 and 3.) The folds are typically overturned to the NW with a steep SE-dipping foliation (fig. 5).

Shearing in fold limbs and 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. These third-generation structures deform two earlier penetrative structural fabrics (S_1 and S_2). The older penetrative fabrics trend roughly N50°W and dip gently toward the SW except along the limbs of F_3 folds. I suspect that all of these structures (D_1, D_2, and D_3) are all products of protracted Taconian orogenesis (Merguerian 1995).

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

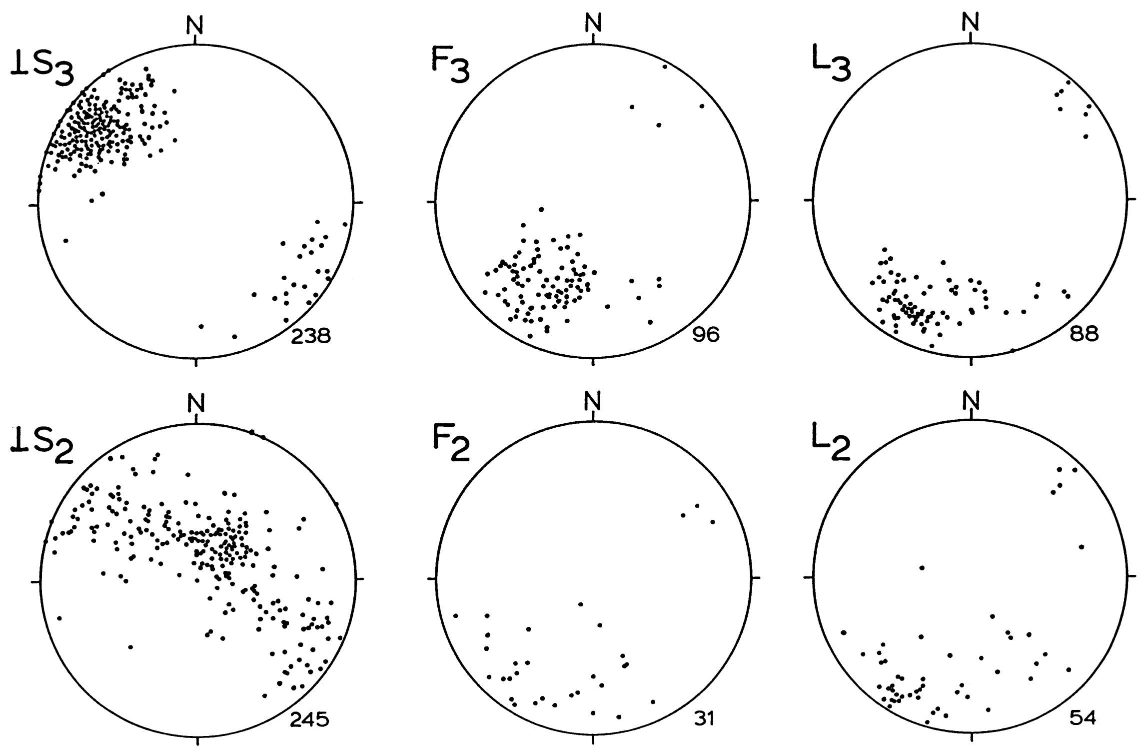

Figure 5. Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hinge lines, and the orientation of L_2 and L_3 lineation. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders 1991, figure 26, p. 113.)

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 in schistose rocks. Porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to F_3 hinge lines in the Inwood Marble of northern Manhattan.

Although the regional S_2 metamorphic grain of the NYC bedrock trends N50°W and dips gently SW 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° (fig. 5). 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 limbs. The F_3 folds and related L_3 lineation 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 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. Presumably, the younger fold phases record the effects of the Acadian- and terminal-stage Appalachian orogenies. Stay tuned for news on brittle structures!

Queens Tunnel Complex, city water tunnel #3, stage 2

Between 1996 and 1999, a high-performance tunnel-boring machine (TBM) excavated a 7 m wide, 7.7 km long, and 214 m deep tunnel through the subsurface of southwestern Queens (fig. 6). Taking almost twice as long as expected, low TBM penetration rates resulted from an unusual high-grade metamorphic rock mass and disturbed ground conditions resulting from superposed brittle faults (Merguerian, 2000). Field mapping at 1"=10', petrographic, geochemical, and geochronologic studies conclusively proved that the TBM excavated predominately mesocratic granulite-facies orthogneiss containing broad zones of garnet enrichment. The coarse granoblastic textures of interlocking plagioclase, clino- and orthpyroxenes, and garnet produced an impediment to mining. Proterozoic Fordham Gneiss is now known to underlie western Queens and Brooklyn, a covered region where layered Paleozoic metamorphic rocks of the Hartland formation were formerly anticipated.

In this report, use of the place name *Queens Tunnel Complex* (QTC) for the gneissic rocks exposed in the Queens Tunnel indicate a lithostratigraphic correlation with the billion year old Fordham Gneiss. Results from geochronologic tests have indeed confirmed that the QTC contains ~1 billion year old rocks (Brock, Brock, and Merguerian 2001). A complex ductile and brittle history has emerged from study of the QTC. This paper focuses on the brittle fault history, a protracted episode of fracturing that is superimposed on older ductile structures, summarized in table 1.

Please note that the table reflects current understanding of the geological sequence of events in the QTC (Fordham Gneiss) during analyzed construction. The different deformation metamorphic, intrusive, and folding (F) sequences noted are based on relative timing of crosscutting structures. The events are numbered from oldest (1) to youngest (9) in time. Ongoing petrographic and allied microprobe work may refine this interpretation.

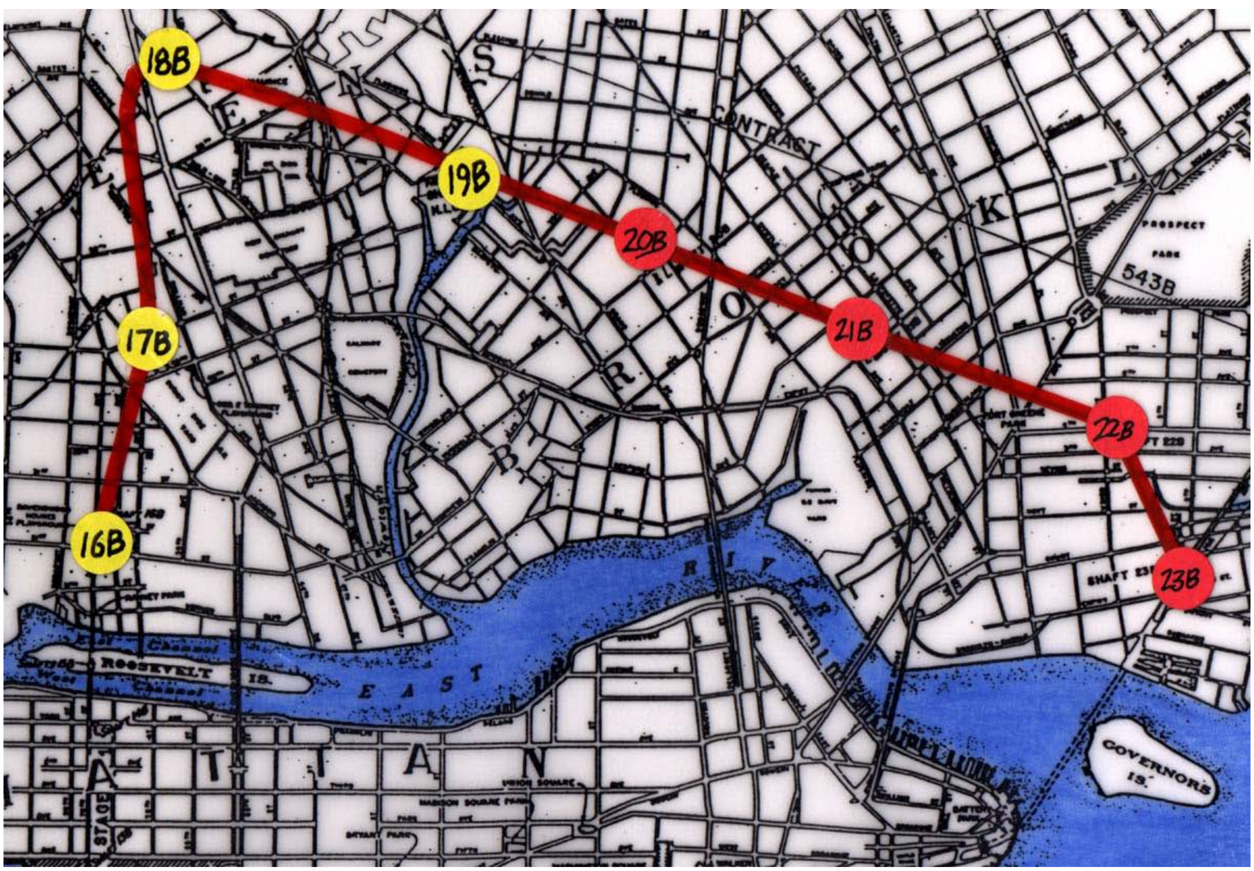

Figure 6. Index map showing the plan view of a part of New York City Water Tunnel #3, Stage 2. The positions of Brooklyn Tunnel (Red colored shafts 23B to 19B) and the Queens Tunnel (Yellow colored shafts 19B through 16B) are shown. North is toward the lower left corner.

Table 1. Geological events recorded in the Queens tunnel

D_9 – Steep NNW-trending strike-slip faults of Group E and sub-parallel joints which continue to affect the region to the present day.

D_8 – NNE-trending, steep oblique slip faults of Group D with thick clay-rich gouge- and crush zones.

I_6 and **M_5** – Permian (295 Ma) hypabyssal injections of Woodside rhyodacite dike swarm and retrograde contact metamorphism at former depths of ~ 0.5 to 1 mile.

D_7 – Lengthy sub-horizontal ramp-like faults and fractures of Group C, commonly exhibiting little offset.

D_6 - Steep brittle faults of Group B oriented ~N60°E cut region.

D_5 – Steep NW-trending normal- and reverse faults and joints of Group A. Event is considered to merge with I_5 and D_4.

I_5 - Intrusion of megacrystic K-feldspar pegmatite dikes.

D_4, I_4, and **M_4** – F_4 recumbent to asymmetric folding and ramp-like low-angle ductile faulting with foliated granitoids and pegmatite intruded into brecciated faults (Group A) oriented ~N50°W and low SW dips (<30°). Zones of granitization, biotitization, and retrograde metamorphism found adjacent to fault zones and intrusives. Based on metamorphic grade, these events followed a period of regional uplift and erosion.

I_3 – Intrusion of non-garnetiferous mafic dikes.

D_3 and **M_3** – Gentle SW-plunging tight to isoclinal ~N35□E-trending F_3 folds of S_1+S_2 metamorphic layering with localized development of a penetrative foliation and localized D_3 shear zones under conditions of M_3 amphibolite facies metamorphism. Responsible for initial deformation of I_2 Ravenswood-type rocks and slight- to moderate retrograde metamorphism of older granulites.

I_2 – Intrusion of Ravenswood-type (Taconian?) granitoid, dioritic, and gabbroic magmas which later (D_3) form weakly foliated orthogneiss.

D_2 and **M_2** – Isoclinal F_2 folding and shearing of both Fordham S_1 and I_1 intrusive suite producing foliated orthogneiss bodies from I_1 intrusives. Development of medium- to coarse-grained S_2 gneissic layering under granulite facies metamorphic conditions. Garnetiferous mafic dikes produced near interlayered amphibolites. Probably progressive with D_1. Unknown age, probably Proterozoic Y.

D_1, **I_1**, and **M_1** – Isoclinal F_1 folding and deep-seated (~20-25 miles) metamorphism under granulite facies metamorphic conditions producing a penetrative S_1 foliation in metasedimentary and probable metavolcanic units of the Fordham. These deformed units were invaded by a vast suite of syntectonic calc-alkaline intrusives as plutons, sills, and dikes. The intrusives of Proterozoic Y age, cross cut S_1 and enclose screens, xenoliths, and cognate xenoliths of older gneiss.

Note: *The list of relative events summarizes my current understanding of the evolution of the Queens Tunnel Complex (= Fordham Gneiss), based on detailed mapping of the as-built tunnel. The relative time of Deformational (D_n), Igneous (I_n), and Metamorphic (M_n) events is based solely on crosscutting field relationships. The events are numbered from oldest (n = 1) to youngest by subscript from the base upward. Ongoing petrographic and geochemical investigations will refine this table.*

Brittle faults of the Queens tunnel and the Woodside rhyodacite dike swarm

Found exclusively beneath the area of Woodside, Queens, a swarm of five thin sub-parallel rhyodacite dikes, all displaying igneous textures, were penetrated during construction of the Queens Tunnel. The dikes are Permian in age (~295 Ma) based on unpublished Ar_{39}/Ar_{40} data of Dr. Sid Hemming and crosscut folded Proterozoic Y granulite facies rocks of the QTC with which they are genetically and temporally unrelated. The rhyodacites are reddish, glassy to aphanitic igneous rocks with no metamorphic fabric and low average density (2.58 g/cm^3). They occur 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 1.0 m and taper off to thinner dikelets. The injection of a suite of Permian rhyodacite dikes that are chemically, texturally, and temporally unrelated to their bedrock hosts, mark an anomalous geological event that adds a new chapter to the Paleozoic evolution of the NYC area and provides an important time-stratigraphic marker for geological interpretations.

Over 300 faults have been mapped and studied in the Queens Tunnel over the five-mile extent and the data from these features (Invert Station, Tunnel Bearing, Discontinuity Type, Orientation, Width, Filling, Roughness, Seepage, and Miscellaneous Observations) are presented in spreadsheet form on the GANJ 2015 website[1]. Five generations of brittle faults are superimposed on polydeformed bedrock units of the Queens Tunnel Complex often causing brittle reactivation of ductile faults and pre-existing brittle faults. Brittle faults are typically zones of fault breccia and clay-rich gouge with zeolites ± calcite ± pyrite ± epidote mineralization, and quartz veining. They have created extended areas of high strain prone to stress relief in the form invert heave, rock-wall popping, and jointing. In areas of fault convergence, the brittle faults and sub-parallel regional joints are a persistent cause of blocky ground conditions and related detrimental effects on TBM tunneling (Merguerian and Ozdemir, 2003).

A contoured stereonet plot of brittle faults shows that they cluster into three focused groups (A, D, and E), with A and D more abundant and overlapping with less abundant group B and C structures (fig. 7). Group A include moderately SW-dipping faults (A) and Group D include steeply dipping brittle structures and rhyodacite dikes striking parallel to the regional Appalachian grain. Sub horizontal, reactivated low-angle faults and fractures of Group C are relatively less abundant, relatively young, steeply-dipping, NNE-trending faults that cut Group D dikes. Group E are the youngest structures, are about half as abundant as those in Groups A and D, and strike NW, with oblique and strike slips. Group E structures were seen interacting with both older and younger structures as we will see below.

[1] www.ganj.org/2015/Data/2015_NJGWS_GCH_GANJ32_Merguerian-QWT-stations.xlsx

A preliminary Google Earth (GE) visualization of these various structures was done in conjunction with Gregory Herman of the NJ Geological & Water Survey (NJGWS) for this meeting. He supplemented an existing MS Excel worksheet having structural-feature locations, classifications and orientations and used to produce the GE KMZ[2] theme for this meeting. The various groups of ductile and brittle structures were organized for input into a NJGWS custom-software tool used for automatically positioning and annotating planar objects as components in a KMZ file (see chapters 1 and 5.) For this effort, each representative class of structure was evaluated and represented using scaled 3D planar objects. For example, pegmatite dikes (I_5) are shown in figure 8A, and brittle faults of Group D and E are combined together as brittle faults shown as red ellipsoidal planes in figure 8B.

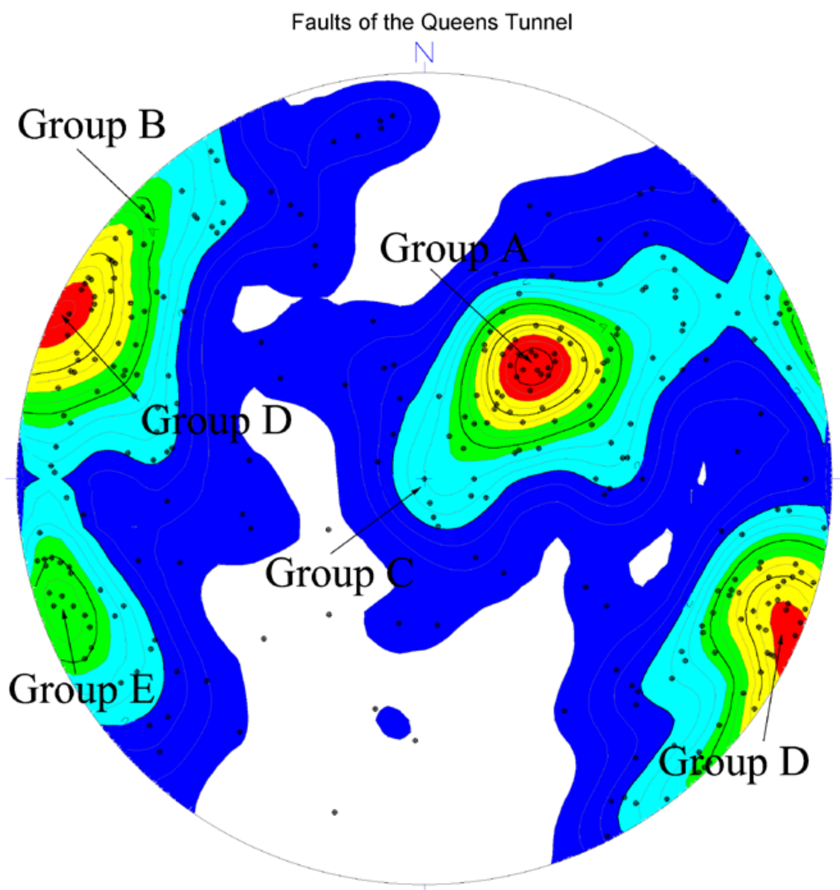

Figure 7. Lower-hemisphere, equal-area stereogram showing the poles to 306 faults mapped in the as-built Queens Tunnel. **Group A** faults strike NW and dip gently SW, **Group B** faults are moderate to steep and strike ENE, **Group C** are sub-horizontal fractures and faults, **Group D** constitutes the NNE-trending fault system of the Queens Tunnel, and **Group E** are the youngest NNW-trending strike-slip faults.

Note in figure 8 how the NNE (Group D) and NW-trending (Group E) faults predominate along both legs of the tunnel. This nicely illustrates in 3D the complimentary orientations of these nearly orthogonal, regional brittle structures. The visualization methods used in GE to generate such features will be covered in this year's teacher's workshop (Chapter 1).

[2] www.ganj.org/2015/Data/2015%20GANJ%2032%20CM%20GCH%20NYC%20Queens%20Water%20Tunnel.kmz

The Group A faults trend ~N46°W with predominately gentle dips and exhibit both normal and reverse offset senses (fig. 9). They are commonly outlined by pegmatite dikes and reactivate NW-trending (D_4) ductile faults (table 1). The brittle Group A faults also occur throughout the entire tunnel in the absence of the ductile faults. The faults are laterally continuous undulating features that persist over 100 m in some tunnel reaches (fig. 10). They vary from tight splays to open features outlined by gouge and crush breccia up to 0.5 m thick. In reactivated zones anastomosing seams of breccia fracture associated granitic intrusives producing local contact dislocations. Group A faults abruptly terminate by ramping steeply into the crown or invert of the tunnel bore. As such, over the course of the tunnel they exhibit variable dip but average ~35°. They dip predominately toward the SW, but a few faults form a conjugate set dipping NE. They are cut by all other faults in the Queens Tunnel (Group B through E). As a result of the persistence of these faults and the development of non-cohesive broken rock as a fault filling, this amalgamated family of ductile and brittle faults exhibit moderate to heavy water inflow and tunnel perimeter instability.

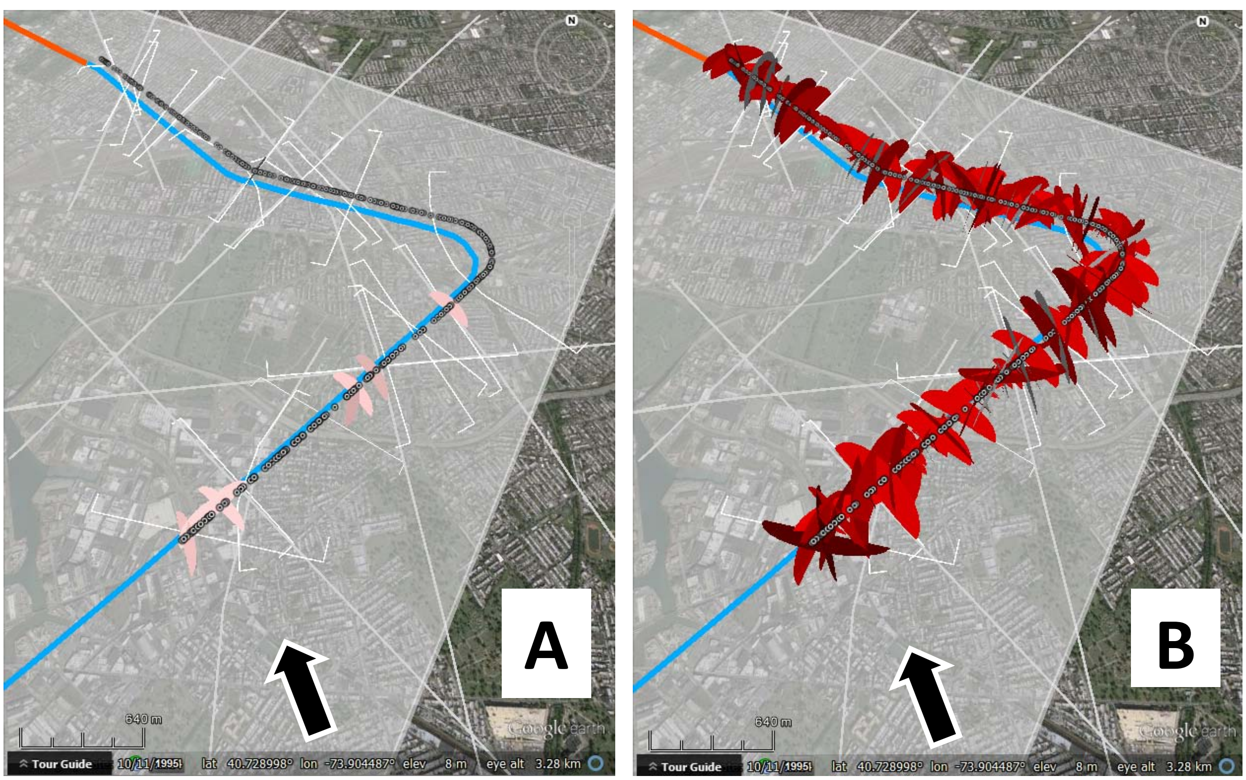

Figure 8. GE views of structures mapped in part of the Queens Tunnel. Data from Merguerian (2000). **A**. Pink ellipses show locations of pegmatite veins. **B.** Red ellipses show brittle fault planes. GE KMZ file available through the GANJ web site, and visualized by G. C. Herman.

Group B, NE-striking faults are minor in total number but can show significant offset. They trend ~N60°E and exhibit moderate to steep dips toward the SE, commonly reactivating NE-trending D_3 ductile fabrics (table 1) and cutting Group A faults. They vary from tight features to open features up to 15 cm in thickness and typically consist of broken rock with a fissile to soft consistency. They cut Group A faults and cut through D_4 zones of biotitization, K-feldspar metasomatism, and granitization. Providing an important relative time control for the fault sequence, one of the Group B faults is truncated by a late Paleozoic rhyodacite dike (fig. 12). Group C, minor brittle faults and fractures can extend for great distances in the Queens Tunnel. They typically show little or no offset and tend to cut or reactivate sub horizontal to gently dipping portions of Group A faults. A number of coincident poles at the

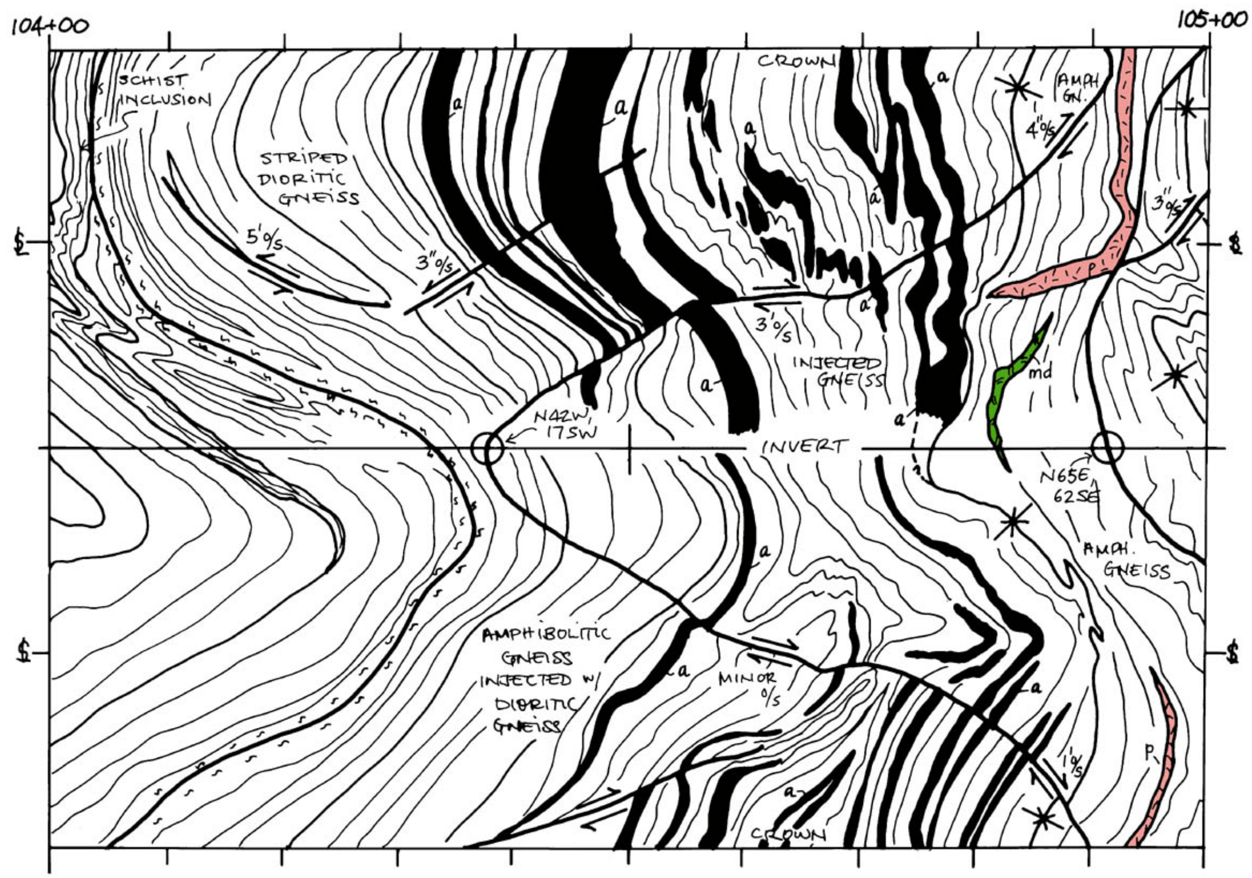

Figure 9. Geologic map of the Queens Tunnel showing Group A fault oriented N42°W, 17° SW that cuts the invert at Station 104+38 (tunnel bearing is N22°E). The fault is only 0.75 cm thick and exhibits 1.0 m maximum offset. **In this and all subsequent map figures the tunnel invert is shown along the center of the map and the tunnel walls curl upward into a cylinder to join at the crown.** Stationing increases from Shaft 19B (to left) to Shaft 16B. The position of the tunnel springline is shown at the map edge. This map covers 100 linear feet of the Queens Tunnel. (Original map scale 1”=10’; tunnel diameter 23' 2".)

center and those clustered near the center of the stereonet (fig. 7) mark the Group C features found throughout the tunnel.

Group D, the 2nd youngest brittle set of NNE-striking, brittle structures, parallel the Appalachian grain and S_3 axial surfaces in NYC and constitutes about a third of all mapped brittle faults (~300 mapped in the 5-mile tunnel segment). They form a system of geologically young dip-slip faults and related joints with an average N21°E strike and have steep dips (figs. 7 and 8).

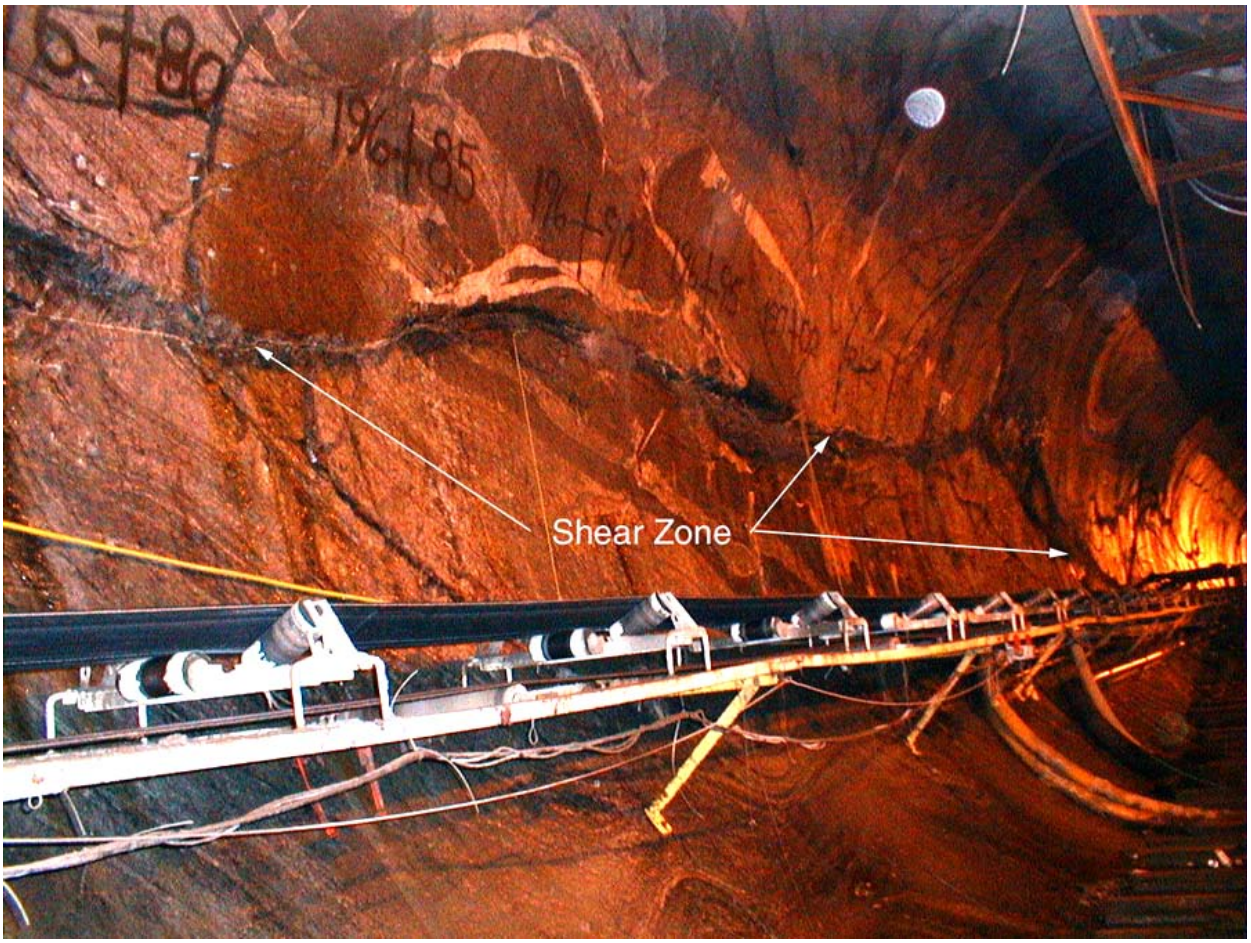

Figure 10. View of migmatitic amphibolite, dioritic gneiss, and minor biotite schist highly fractured because of composite movement along a SW-dipping Group A fault. The fault is a continuous gently dipping feature for 107 m that originates at Station 195+25 and continues on both tunnel walls to Station 198+50. Here it steepens and disappears into the crown of the tunnel in a zone of ramping imbricate fault splays. Fault gouge and -breccia vary in thickness from 0.4 m thick in areas of fault splay intersection near the central reach of the zone to a hairline fracture at the end. (Digital image by C. Merguerian, 18 November 1999.)

Both normal and reverse slips were recorded. Dip-slip slickensides show reactivation or evolution into oblique-slip mechanisms, presumably reflecting overprinting by Group E structures. Group D faults have thick seams of clay, fault breccia and clayey gouge that vary from 1 cm to 5 m. Minerals found healing the NNE- trending faults show a clear paragenesis of apophyllite and/or heulandite followed by two generations of stilbite (yellow to orange followed by translucent). The stilbite is overgrown with spheres and inter-penetrant cubes of pyrite, calcite, and locally, clear cubic crystals of chabazite (figs. 11A and 11B; table 2).

Figure 11. Photographs of some secondary minerals that infill some fracture interstices in the Queens water tunnel.

Top photo shows orange stilbite with pyrite and calcite overgrowths in Group D faults that form broad zones (up to ~76'- wide) in fractured gneiss. Faults in this zone are oriented N19°-22°E/77°NW to vertical, and N35°E/68°SE, Note hand lens for scale.

Bottom photo shows a fracture with about a 1" interstice that is healed with radiating stilbite (orange) followed by calcite (white) in a Group D fault having ~2 m of offset and a 3 m-wide breccia zone orientation N29°E/72°SE. About the same scale noted above.

Table 2. Selected Queens tunnel fault/fracture mineral fillings

Station 077+85 – Upon a substrate of heulandite, cream-colored stilbite in hemispherical masses 2 cm wide and as felted crystalline masses of single sheaf-like crystals. The stilbite is overgrown by calcite and by pyrite. Mineralization occurs in a NS-trending Group D reverse fault cutting interlayered garnet-diorite orthogneiss and garnet amphibolite. Sampled 9/9/99 and 2/8/00.

Station 162+30, RW – Stilbite forming a base with calcite crystals and cubic, clear chabazite overgrowths in a NNE-trending reverse fault zone. Sampled 1/11/99 and 2/8/99.

Station 165+92, RW – Yellowish stilbite as a base to calcite crystals and drusy pyrite. The stilbite crystals, found in Group D N20°E, 71°SE fault, grew as fibers perpendicular to the fracture. Sampled 1/11/99.

Station 166+65, RW – Yellowish stilbite, calcite, and drusy pyrite crystals in N22°E, 77°NW-trending Group D fault zone. Sampled 1/11/99.

Station 167+00, RW & LW – Major 75'-wide NNE Group D faulted pegmatite zone with box-work open cavities and greenish clay gouge. Megascopically, stilbite blades are overgrown by 2-3 mm spherical masses of pyrite. The multifaceted spherical masses are superseded by calcite crystallization, all on a fractured pegmatite or amphibole-gneiss matrix. Sampled 10/6/98, 11/24/98, and 1/12/99.

Station 169+36, RW & LW – Open cavities in 1'-2' wide Group D fault zone (N35°E, 68°NW) through amphibolite in garnet schist containing deep orange stilbite. The stilbite occurs in cavities a few cm in size as rounded sheaf-like clusters. Micro-scale pyrite cubes coat the stilbite. Some late-stage clear acicular stilbite blades occur locally. Sampled 1/12/99.

Station 190+15, RW – Light yellow crystalline stilbite crystals occur in gouge-rich fractured pegmatite. The stilbite crystals are overgrown on massive calcite. Two generations of small, clear crystals (apophyllite and younger analcime) occur next. The analcime crystals are particularly striking because of their facet reflections and clarity. Locally, cm-scale pseudo-cubic calcite crystals are found to overgrow the crystallized matrix. Sampled 1/20/99 and 6/7/99.

Station 190+52, RW – Clear interpenetrating calcite crystals about 1 cm in size in N11°E, 67°NW Group D fault zone overgrow stilbite. Stilbite crystals form a basal substrate found overgrown with massive stilbite then the calcite. Late pyrite cubes here overgrow a second generation of clear stilbite blades. Sampled 6/7/99.

Station 214+25, LW – Radiating masses of orange-colored stilbite surrounded by white calcite in fracture fillings related to a Group D fault oriented N29°E, 72°SE. The fault, which cuts mafic gneiss, has produced a crush breccia zone up to 3 m wide. Mineralization is found in thin veins a few mm thick to irregular nodules up to 10 cm long, all within the brittle fault fabric. Sampled 6/16/99.

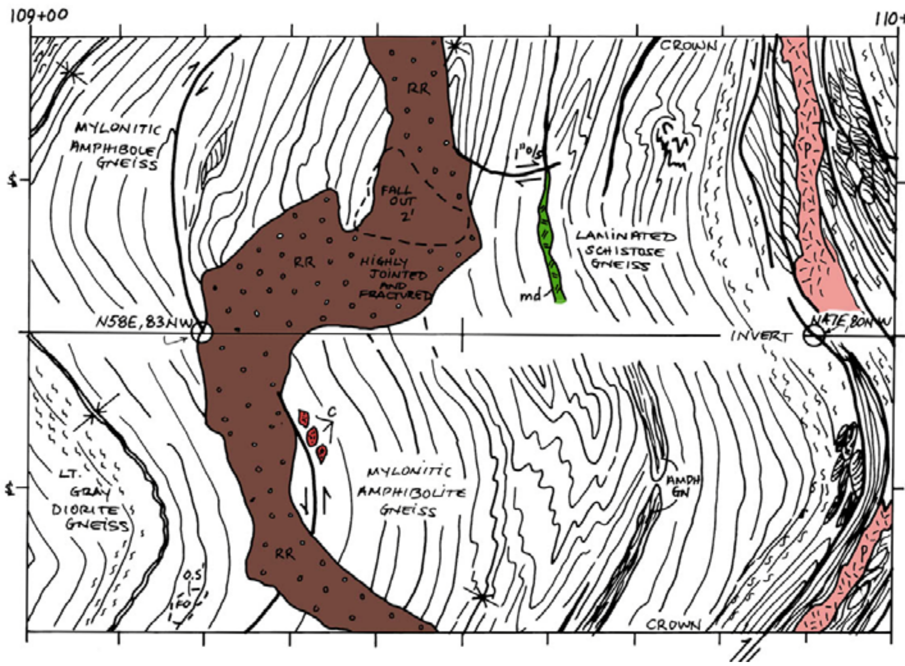

Figure 12. Geologic map showing truncation of N53°E, 83°NW Group B fault by a NW-trending rhyodacite dike of 4 m thickness. (Tunnel bearing is N09°W; Original map scale 1”=10’; tunnel diameter 23' 2".)

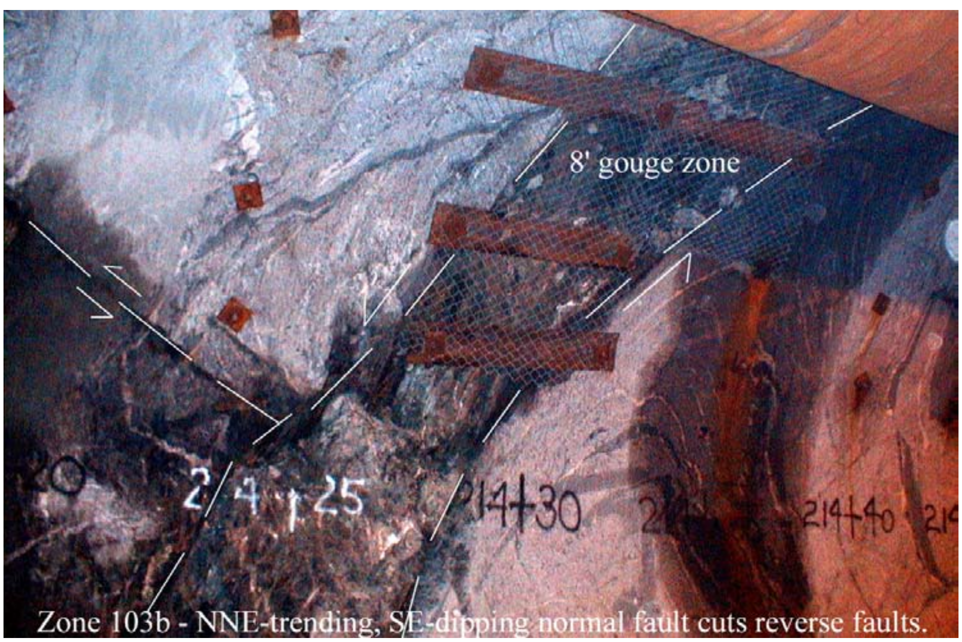

Figure 13. The geology of this disturbed interval (Station 214+30, left wall) is dominated by a major NNE-trending SE-dipping normal fault exposing a 3 m thickness of clay-rich crush breccia. This Group D fault displaces older low-angle reverse faults (Group A) in both the footwall and hanging wall. Fault splays of various orientation and offset sense are found adjacent to the NNE-fault. (Digital image by C. Merguerian, 18 November 1999.)

This group comprises a major fault system that cuts the mapped segment of this tunnel beginning to end, but is most densely concentrated along the NW tunnel leg just beyond the major tunnel bend where orthogonal geometric relationships are easy to spot (see fig. 8B.) Here, the NNE faults crosscut the tunnel at a high angle and contributed to tunnel perimeter instabilities encountered during mining, especially when found in combination with other fractures. They cut the rhyodacite dike swarm and most other geologic features of the tunnel including Group A faults (fig. 13).

The Group E (or Manhattanville) structures are the youngest group of brittle faults and fractures striking NNW from ~N20°W to ~N50°W. They are mostly steeply dipping and show predominately strike-slip offset (figs. 14 and 15). They crosscut every geological feature in the tunnel and mark the youngest structural event to be recorded. These faults dip steeply with sub-horizontal slickensides, flower structure, and little mineralization with the exception of quartz veining. Areas cut by the Group E faults are typically highly fractured and show evidence of high strain in the form of overstress phenomenon including invert heave, spalled rock slabs and rock popping from the crown and tunnel perimeter. These NNW-trending faults are best developed near the western 1.5 km of the tunnel.

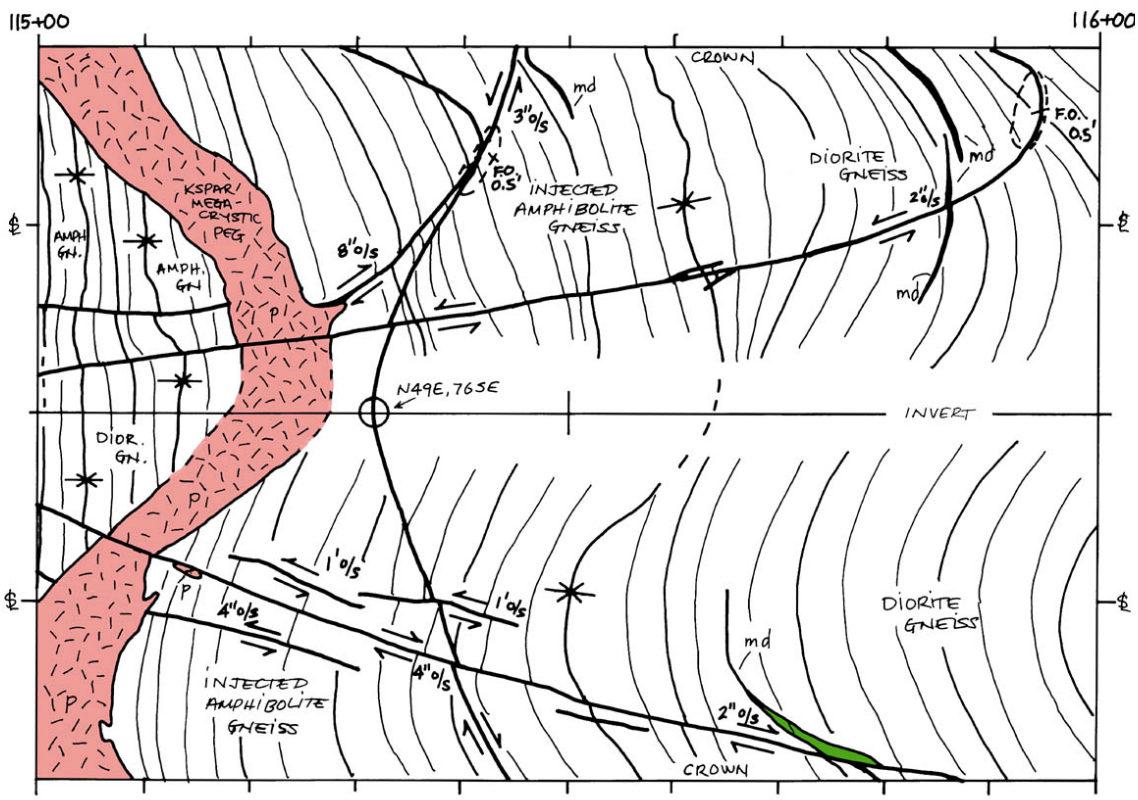

Figure 14. Map showing a NNW-trending left-lateral strike-slip fault of Group E that eventually cuts the tunnel invert at Station 114+90. The fault is oriented N48°W, 64° SW and is a relatively thin (~3 cm) feature.

This western tunnel area marks an extension of the famous "125th Street [Manhattanville] fault" of New York City and parallels many similar faults in the NYC area. Indeed, the Group E faults are part of a regional fracture set along which a recent (17 January 2001) epicenter for a Magnitude 2.6 earthquake occurred[3] (fig. 3).

By contrast to the five-fold fracture history found in the basement rocks of the Queens Tunnel Complex, the Paleozoic cover rocks show a simpler fracture history with an older 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 Group E "Manhattanville" fault set.

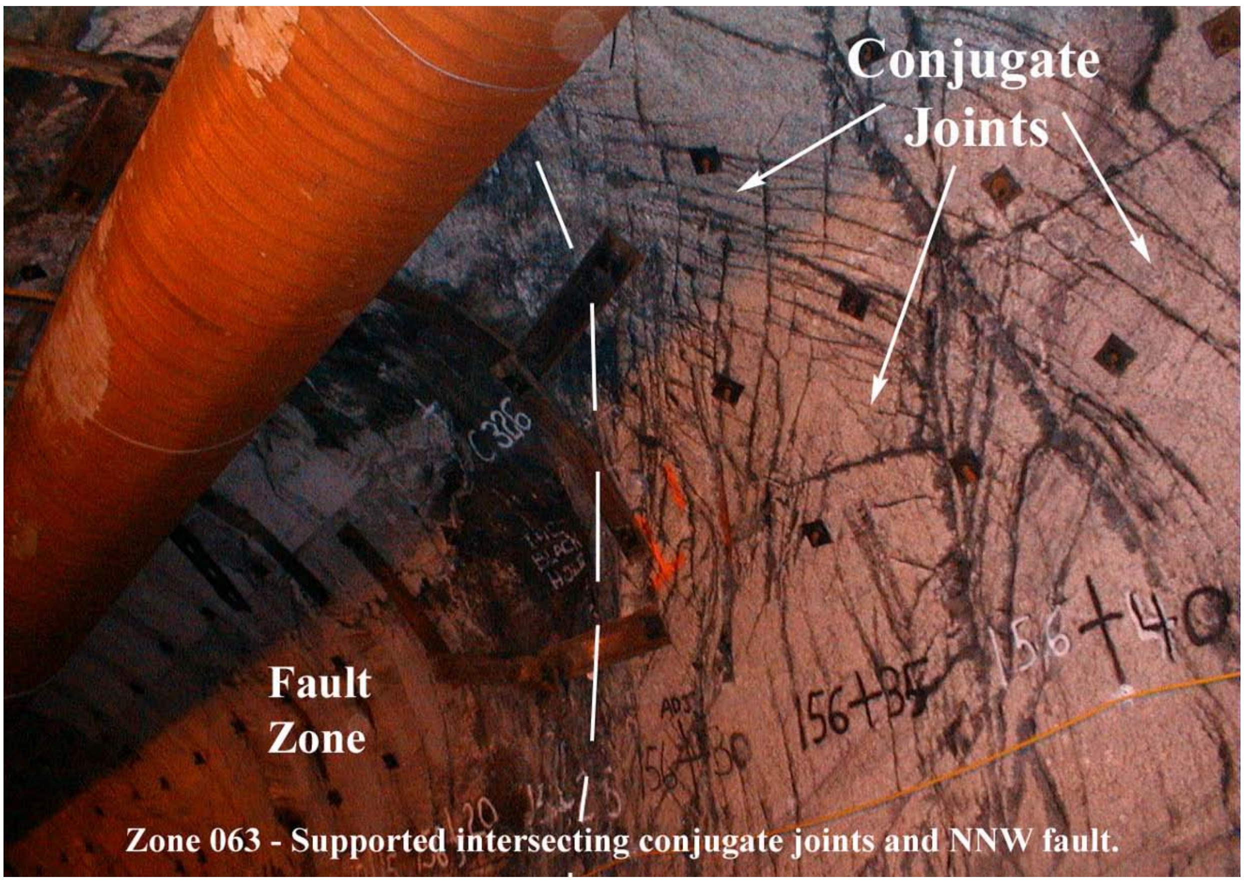

Figure 15. Left wall view of a N20°W fault of Group E that cuts invert at 156+35 with a 0.5 to 1.0 m thick crush breccia and adjacent area of intersecting conjugate joints (flower structure). Tunnel bearing is N41°W; Original map scale 1"=10'; tunnel diameter 23' 2". (Digital image by C. Merguerian, 30 December 1998.)

Intersecting brittle faults are a major contributing factor to the localization, mechanical properties, and alteration of disturbed ground zones in TBM tunnels. Although fracturing generally aids in the TBM excavation of rock, intersecting fractures amplify crown and sidewall instability, cause slippage of TBM grippers, downtime for installation of additional local support and ring steel, and induce damaging water inflows. Such was the case in the East Side Access feature. TBM boring phase both before and after the 90° tunnel bend where significant machine damage and utilization decrease occurred as a result of Group D and Group E fault intersections.

Geology and brittle faults in the East Side Access tunnel

My involvement in the East Side Access project as site geologist for the contractor Dragados-Judlau JV began in 2001 and ended in 2010. This project was to divert a portion of Long Island Railroad trains via curved tunnels to a newly excavated cavern beneath Grand Central Terminal in midtown NYC (fig. 16). Two existing tunnels beneath the East River to 63rd Street constructed in 1980 provided important access from Long Island City for project workers, equipment, TBM launch and maintenance. Two similar open beam TBMs were employed for this project and they were used to punch as many as 8 parallel tunnels into the Paleozoic cover rocks found along the alignment. Except for poor utilization in disturbed ground areas underlain by intersecting faults, excellent penetration rates were experienced because well-layered, gently-inclined micaceous Hartland rocks were found to occupy the much of the tunnel horizon.

Investigations of a number of zones where fault intersection played a role in tunnel perimeter failure allowed for recognition of both NNE- and NW-trending faults in the subsurface Paleozoic cover rocks of the Hartland formation. Two areas in particular were studied. In late 2007, in the EB-2 tunnel between stations 1066+45 and 1067+20, unusual ground behavior took the form of voids which opened up in the crown and sidewalls of the tunnel that caused extensive fallout and downtime for support installation and mucking operations (fig. 17). The voids were over a cubic meter in dimension, laterally continuous and extended upwards to 3-4 m. They contained angular, cobble- to fist-sized blocks of altered slickensided incohesive fault rock and associated clay gouge. The voids were distributed on all sides of the tunnel requiring major downtime during installation of ring steel zone for stability and safety.

In October 2009 a second very similar fractured zone was encountered roughly two years after the zone described above was mitigated and passed. Here, an extensive tunnel reach ~291' in length of the westbound WB-1 tunnel was excavated through nearly identical disturbed ground that was found to unravel fault rock blocks of varying size with little to no stand up time. This produced laterally extensive open voids in the crown and side walls, buried the TBM platforms with loose rock and created interference with support operations. This disturbed ground zone also required pervasive ground support, mucking, and remediation. In both areas, the rock was extremely altered, clay-rich, friable, soft and prone to heaving.

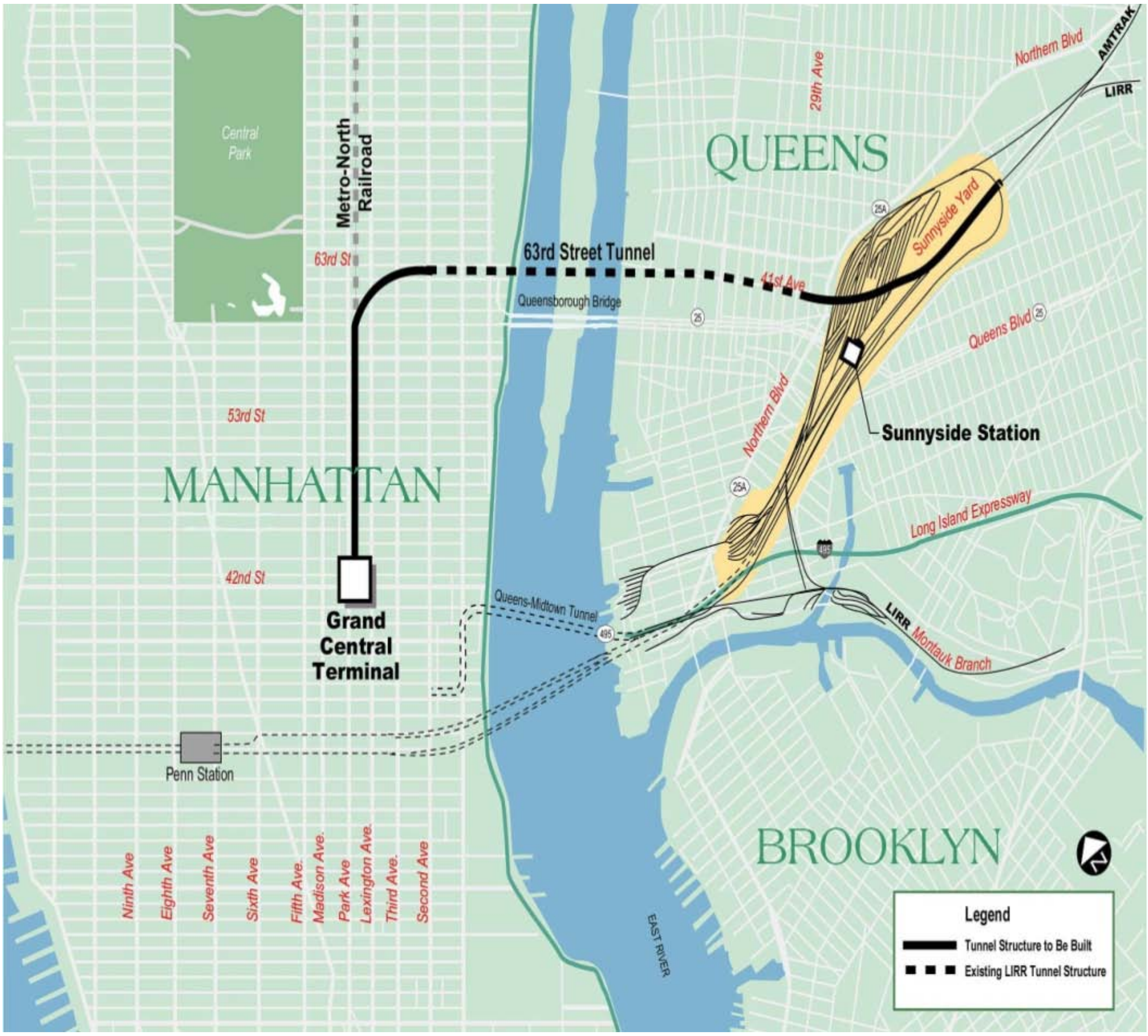

Figure 16. Index map showing the tunnel alignment of the East Side Access Project that will eventually divert MTA Long Island trains from Sunnyside Yard in Queens across the East River via the 63rd Street tunnel into Manhattan. From there the tunnel bends 90 degrees southward to Grand Central Station. (MTA Public Document.)

Even the more quartzofeldspathic granofels interlayers were found to split into thin slabs and were mechanically weak showing clay squeezing and breakage with mild finger pressure. Rock alteration and weakness was the result of pervasive hydration alteration of feldspar and mica to clays which created a weak rock mass not capable of maintaining TBM gripper pressure or load. Similar to the previously described EB-2 zone, this geological condition was the result of a spatial confluence of geological features, including sheared foliation and NNE- and NW-trending brittle faults and joints. A view of a NE-trending fault in this area is shown in figure 18A and the type of ground condition is shown in both figures 17 and 18.

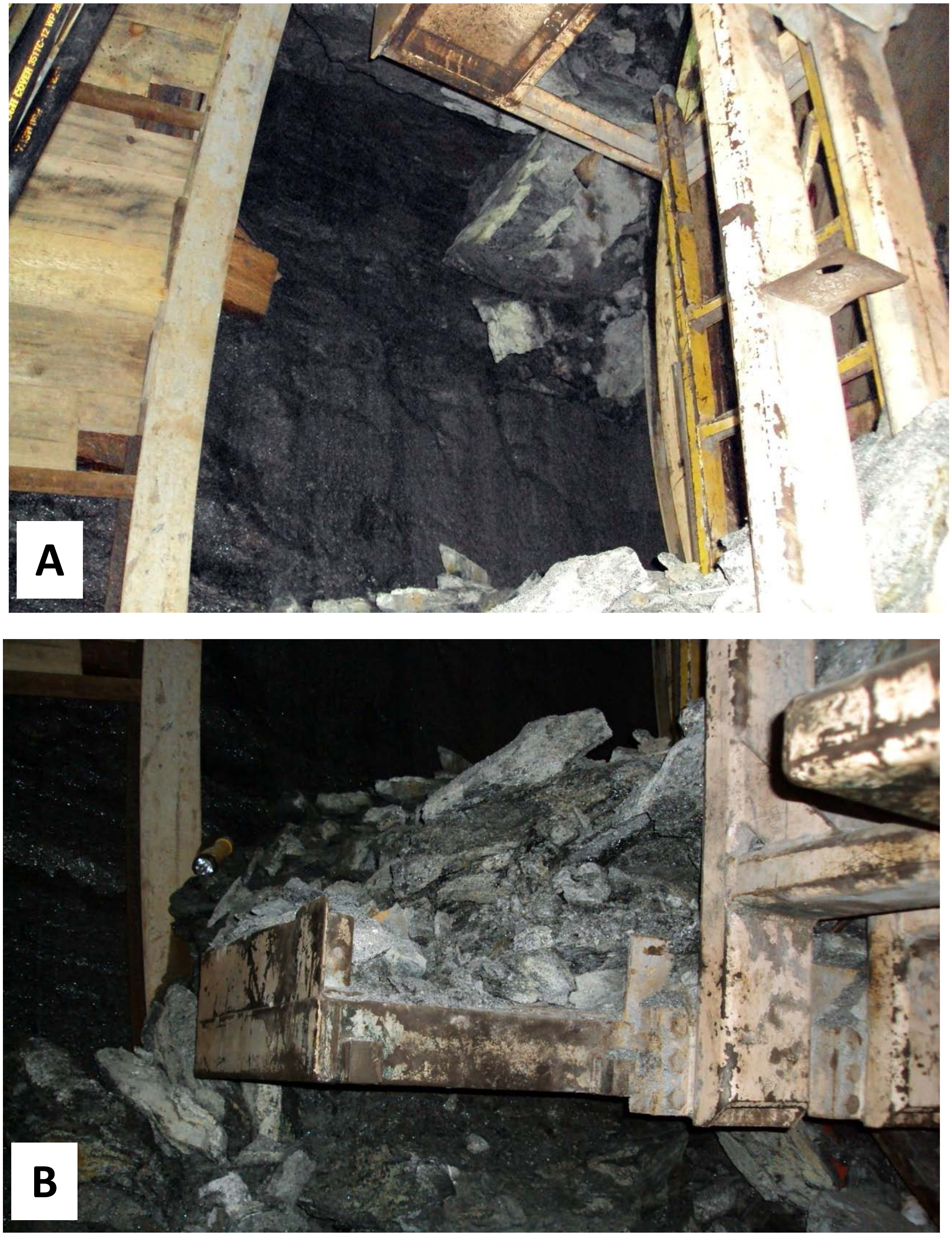

Figure 17. Two views of mucking operations on 09 Dec 2009 showing the extent of poorly-sorted blocky fall out in the left wall rib during mining operations. Upper image (**A**) shows suspended large blocks. Lower image (**B**) shows the magnitude of small rocks and weathered clay-rich matrix of fault breccia and gouge associated with the NE-trending fault that traverses the zone. (Progress Photos 28 and 29 provided by Dragados-Judlau JV.)

Figure 18. Photographs inside the East Side Access tunnel**.**

A. View of N41°E, 85°SE fault (steep through image center) that splays into left wall and crown. This steep Group D fault, together with steep NW-trending cross fractures and gently inclined sheared rock fabrics produced a 291' reach of disturbed ground in the WB-1 tunnel. (Digital image EV010560 taken 01 December 2009.)

B. View of the north wall of EB-2 near Station 1066+70 showing open voids filled with blocky rock and clay behind the support. The voids are scattered throughout the disturbed ground zone and consist of loose angular cobble-sized to fist-sized blocks of highly altered and slickensided rock. (Digital image taken December 20, 2007.)

The redraft of the 1865 Viele map (fig. 19) shows the position of the tunnels in red (EB-2 and WB-1). Note that three NW-trending faults project into the EB-2 tunnel alignment southwest of Station 1066+00. The continuation of mining during 2008 and 2009 looped southward from the area of Station 1066+00 and proved to be an unfortunate geometric situation as the same NE-trending fault zone that affected the EB-1 tunnel in late 2007 traverses southwestward to intersect the WB-1 tunnel starting at Station 1055+71. The width of the disturbed ground zone in EB-2 fault zone along the roughly E-W segment was much less since the fault crossed the tunnel line at a high angle. In the 2009 disturbed ground zone the fault cuts the tunnel at an oblique angle (11°) resulting in an extended zone of tunnel perimeter failure.

To summarize, in the East Side Access excavation unanticipated geological features that converged in these zones produced an extensive reach of open voids, chimneys, and channels that exhibited unraveling with exceedingly short stand up times and deep weathering. This was caused by the presence of a hitherto unknown NE-trending fault zone intersected by NW-trending faults and joints. Because major water courses parallel the NW-trending faults and to a limited extent a NE-trending fault that connects both zones (fig. 19), I suggest that percolating ground water conditions over time affected the fractured, clay-rich ground conditions that plagued the construction effort.

Manhattanville and Mosholu Faults

The venerable 125th Street "Manhattanville" fault has been recognized since Merrill et al. (1902) folio mapping of New York City and in the Berkey (1911) analysis of the New York City Aqueduct (fig. 20). The fault was highlighted in Lobeck (1939) and recognized to be a part of a family of NW-trending faults including faults in Van Cortlandt Park (= Mosholu Fault), Spuytin Duvil, Dyckman Street, Harlem River, and faults to the south in Manhattan (fig. 21). The NW-trending Group E faults of the Manhattan Prong have offset mapped geologic contacts and localized historic seismicity in NYC. Two of these Group E fractures deserve mention in this connection: (1) the famous 125th Street "Manhattanville" fault and (2) the Mosholu fault in the Bronx. Thick zones of fault breccia were diagrammed in Berkey (1948) and redrafted by Fluhr (1969) where a broad U-shaped valley covers 500' of decayed rock above the fault zone (fig. 22).

In 1985, I studied the 125th Street fault during construction of a drill and blast section of NYC Water Tunnel #3 project beneath Amsterdam Avenue where a complex zone of highly crushed fault breccia more than 90 m wide outlined the fault zone (fig. 23). Here, the 125th Street fault strikes N35°W and dips 55° to 75° SW and cuts across and fractured the NE-striking Manhattan Schist (Ꞓ-Om). Where the fault crosses the crown of the tunnel many 2 to 3 m

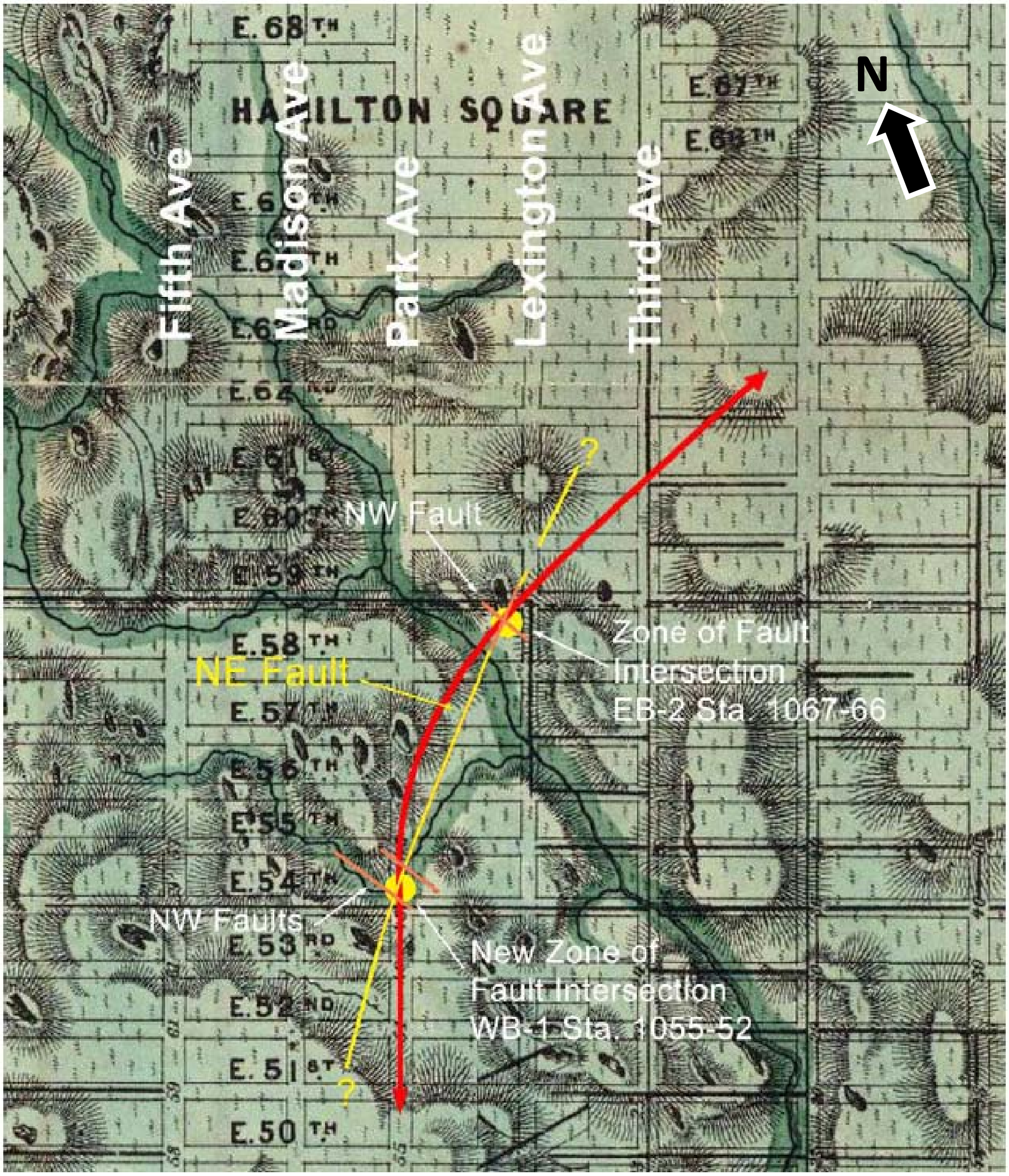

Figure 19. Sanitary and Topographic map of Viele (1865) with the trace of the EB-2/WB-1 tunnels from E. 62nd to E. 51st streets added (red). Note the NW- (orange) and NE- (yellow) trending faults plotted based upon field data (Merguerian and Merguerian, 2004) and by the interpretation of surface drainage patterns. The initial area of disturbed ground from Stations 1067+20 to 1066+45 is plotted in yellow (upper yellow circle). The new zone of intersecting faults and extensive fall out is shown between 54th and 54th streets beneath Park Avenue (Stations 1055+71 to 1052+80; lower yellow circle). Note how drainage patterns are governed by NW- and NE-trending faults and associated fracture zones and how the NE-trending fault extends from the northern disturbed ground zone (upper yellow circle) to the new zone of disturbed ground (lower yellow circle). Main avenues trend ~N30°E so north is tilted to upper left.

Figure 20. Old maps showing the location of the Manhattanville fault, highlighted as a white dashed line.

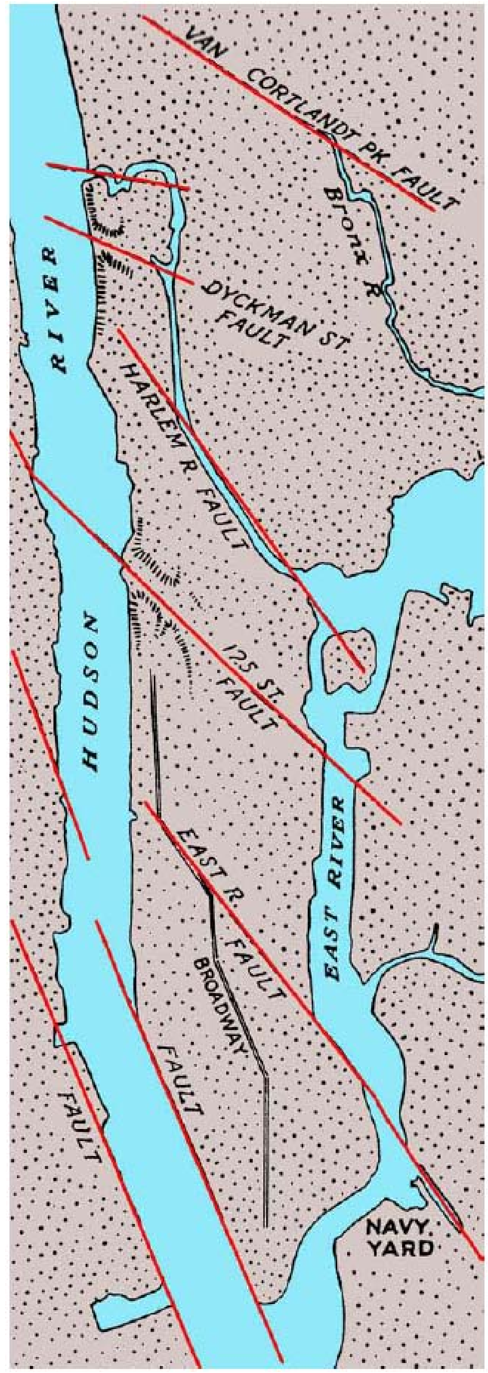

Figure 21. Colorized map of Manhattan showing major faults inferred on the basis of subsurface data in water tunnels and physiographic relationships. (A. K. Lobeck 1939.)

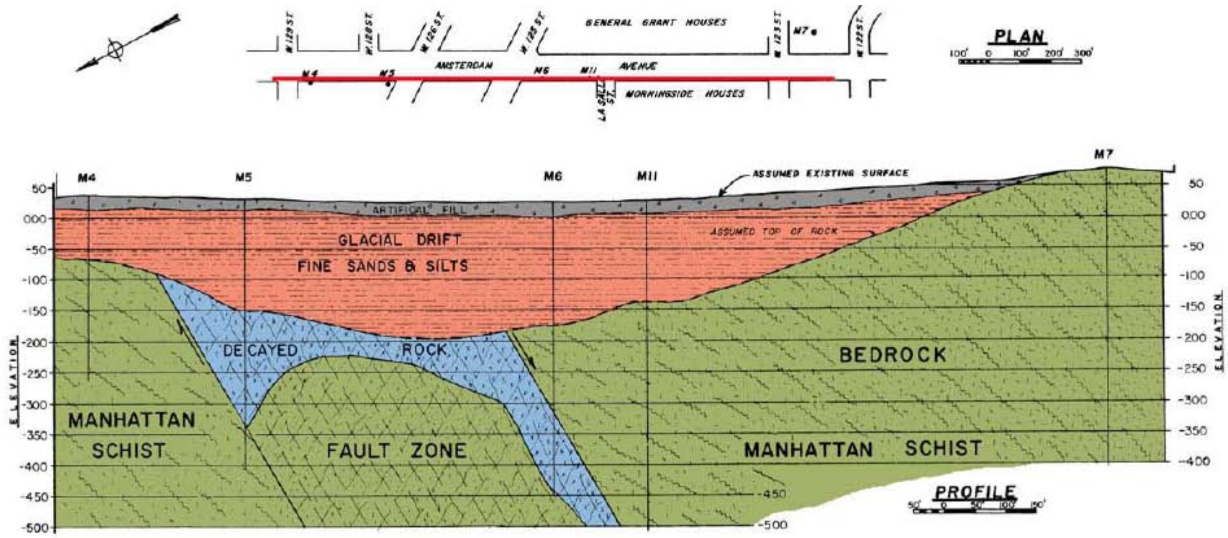

Figure 22. Geological section across the broad U-shaped valley consisting of glacial drift atop the 125th Street "Manhattanville" fault zone. (Colorized from Fluhr 1969, Fig. 4.)

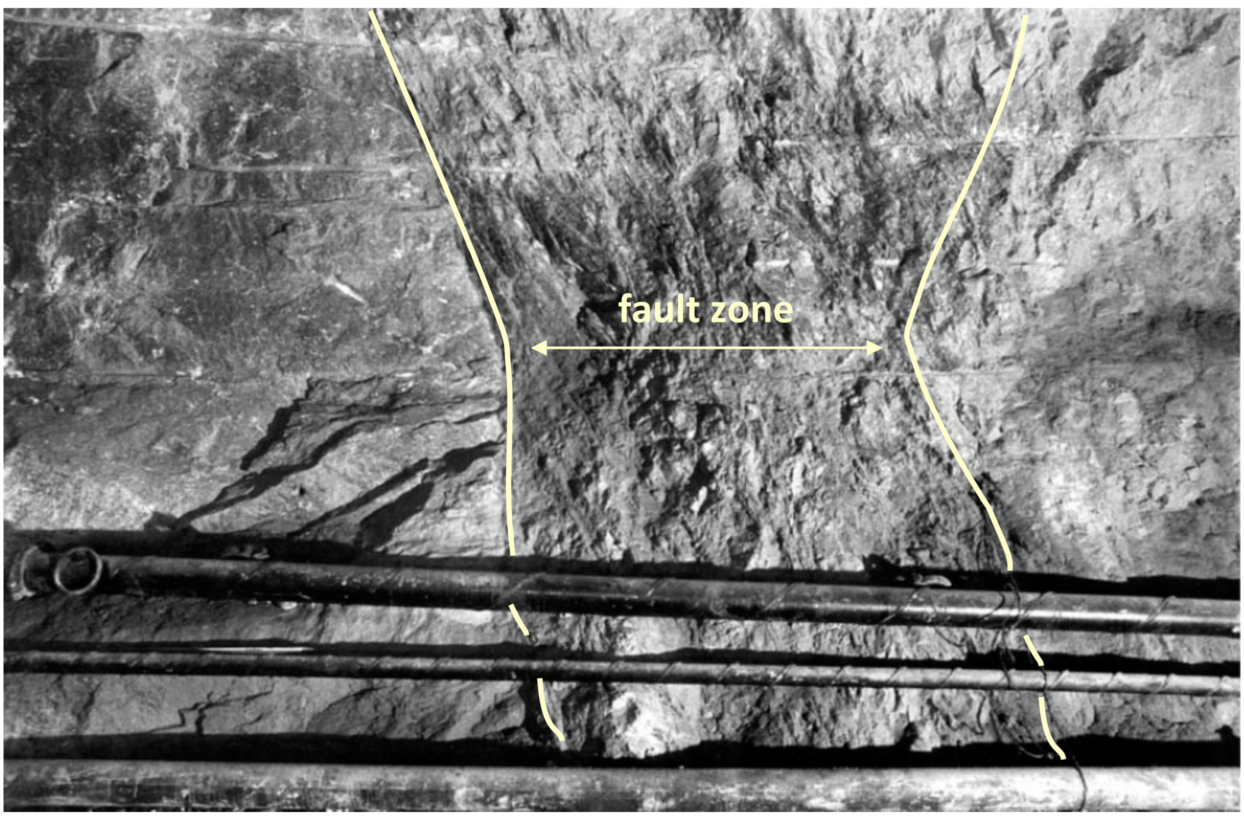

Figure 23. Photograph of the 125th Street fault as exposed in the subsurface of Manhattan in the water tunnel built roughly 250 m beneath Amsterdam Avenue. Note the sharp demarcation of the fault. The photo covers roughly 7 m in vertical dimension and shows the presence of compressed air and water conduits along the bottom. (Carl Ambrose Photo, NYC Bureau of Water Supply.)

blocks of the Manhattan Schist, which remained internally coherent within the broad zone of cataclastic rock, showed a minimum of 90˚ rotation about a vertical axis. The blocks remained internally coherent within an otherwise broad zone of cataclastic rock and fault breccia. Clearly, this observation indicates that along the 125th Street fault, much of the motion has been strike slip. Indeed, slickenlines measured in the tunnel indicate that right-lateral, normal, oblique slip was the most-recent offset sense and that a minimum of 18 cm of slip has been observed along one fault surface (Eileen Schnock, DEP, personal communication). Mapped offset of the prominent Manhattan Ridge in northern Manhattan indicates more than 200 m of composite right-lateral slip along the 125th Street fault valley, a U-shaped valley greatly modified and enlarged by Pleistocene glaciers flowing from the NW and presumably infilled by a younger glacier flowing from the NE (Sanders and Merguerian 1998).

Pelham Bay Park, Bronx, NY

Many excellent examples of brittle faults of contrasting type and offset sense can be found in the bedrock exposures half way up the rock terrace on South Twin Island in Pelham Bay Park in Bronx, NY. Many brittle faults are found in the area including Group D and E faults. Figure 24 shows an eastward view of two brittle faults outlined by quartz veins. Note how the N70°W-trending left-lateral strike slip-fault offsets a quartz vein in the background. This quartz vein was injected into a N30°E fault developed parallel to a sheared foliation in the bounding Hartland gneiss.

A few hundred feet to the south, another NW-trending Group E fault is exposed. This fault trends N66°W and dips 82°SW and shows roughly 0.5 m of composite right-lateral strike-slip offset of an isolated quartz vein. The area around the fault is highly fractured because of a close family of joints oriented N67°W/77°SW. Thus, as found in Central Park (discussed below), both right- and left-lateral offsets occur within close proximity of one another.

Croton Water Treatment Plant, Bronx, NY

Following the excavation of tunnels originating within Van Cortlandt Park for the construction of the Croton Water Treatment Plant in Bronx, NY, project geologists were able to identify and map the contact between the Yonkers Gneiss (Zy) and the Fordham Gneiss (Yf) formations in the side-wall of the TBM tunnel excavations (Isler, Vellone, Merguerian and Merguerian 2009). Based upon analysis of mineralogical differences between the two formations and observations of the textural and megascopic composition of the rock surfaces

Figure 24. Eastward view of N70°W, 62°NE left-lateral Group E fault (lined by milky quartz vein in foreground). This fault cuts an older Group D NNE-trending fault and parallel foliation (N30°E, 80° SE) in the bounding Hartland gneiss.

exposed during tunneling operations, the contact of the Yonkers gneiss has been re-drawn from its southern limit as shown on Baskerville (1989, 1992) and Fluhr and Terenzio (1984) to extend southward to contact the Mosholu Fault at the southern end of Van Cortlandt Park (fig. 25). The Mosholu fault has ruptured along the Yonkers-Fordham boundary where the Yonkers may have acted as a resistant block and controlled the fault trend and/or location. By contrast to the prediction for a thick fault zone (~350 m wide) by pre-mining geophysical instrument measurements, the actual fault was mapped as a surprisingly narrow (~3 m) zone of dark greenish-black slickensided rock with clay and chlorite coating shear surfaces (figs. 26 and 27). Offset sense is right-lateral strike slip based on mapped contacts (Baskerville 1994) but this is based on very limited exposure. Dan Vellone (personal communication) did much of the mapping at the tunnel. He reports that in the Low Level Service TW tunnel there was 30 cm of offset measured at Station 18+40 and 60 cm of offset at Station 27+98 (fig. 27). The High Level Service TW tunnel exhibited 30 cm of vertical offset at Station 17+06 and ~1 cm of offset at Station 34+55.

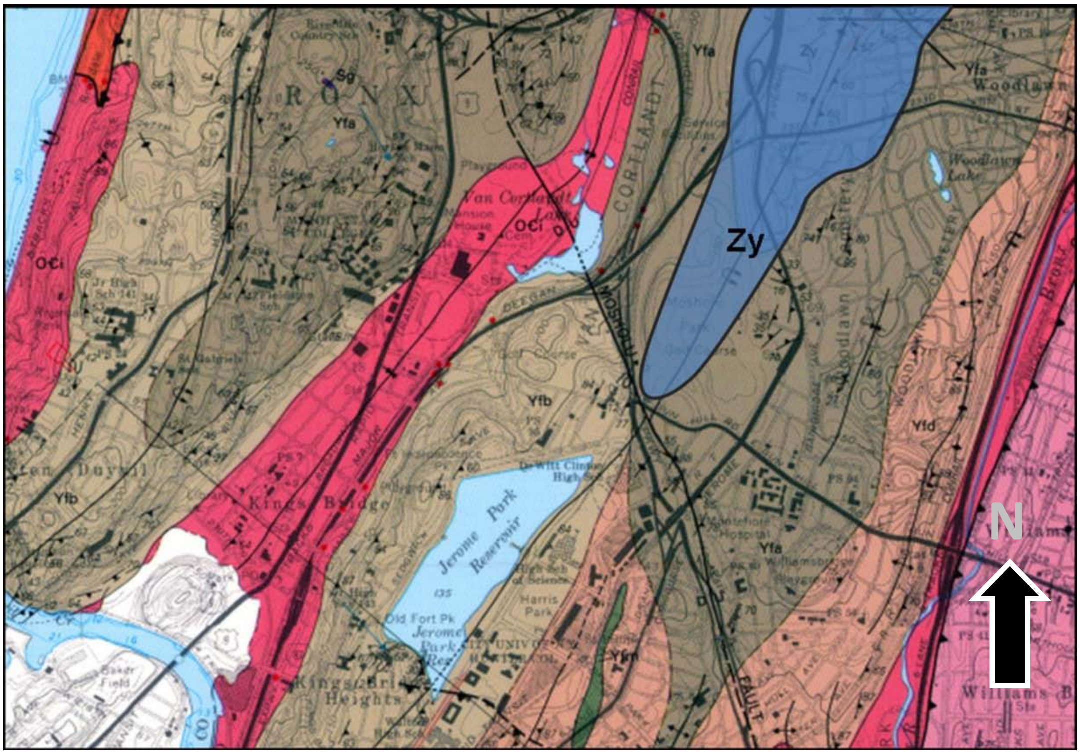

Figure 25. Bedrock map of the tunnel alignment with proposed southward revision of the geologic contact between the Yonkers (Zy - blue) and Fordham (Yf – brown and tan) gneisses based upon observations following the excavation of two tunnels advanced using tunnel boring machine (TBM) methods. (Basemap after Baskerville 1992.)

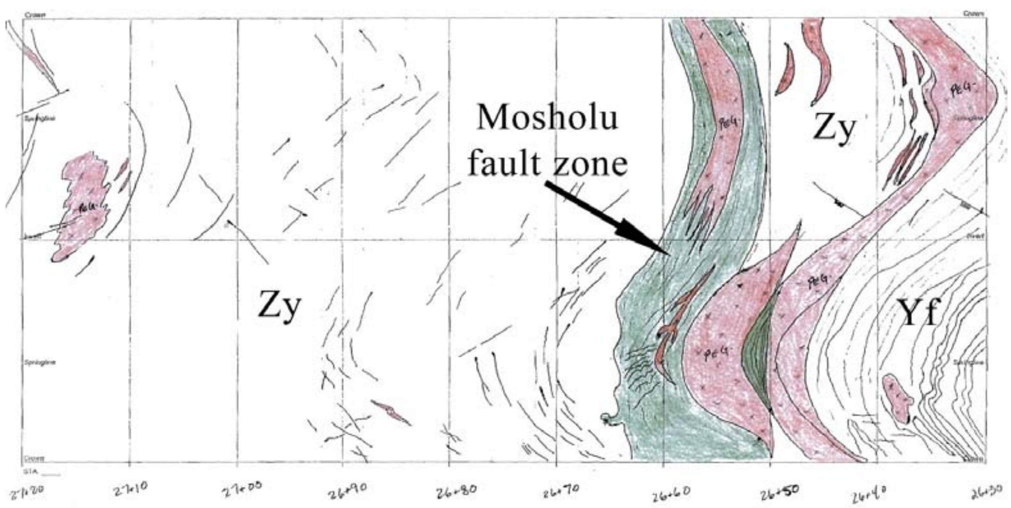

Figure 26. Full-periphery geologic map of the low-level treated water tunnel Station 27+20 to 26+30 that shows jointed Yonkers Gneiss (Zy) in contact with complexly deformed Fordham Gneiss (Yf) along the Mosholu fault zone (green). Younger pegmatite injections are shown in pink (Isler and others 2009; fig. 4).

Figure 27. View of chloritic fault gouge and breccia zone associated with the Mosholu fault in the low-level treated water tunnel (Station 26+60). (Digital image by Dan Vellone.)

Toward the SE, the Mosholu fault extends into the New York Botanical Garden grounds through competent rock (fig. 28).

Central Park, NYC, NY

Hartland, Manhattan and Walloomsac rocks bearing both ductile and brittle structures crop out within Central Park in NYC. A new bedrock map (fig. 29) has modified the position of Cameron's Line and has adjusted the position of bounding lithotypes - the Manhattan and Hartland formations. Cameron's Line shows strong deformation by S-plunging F_3 major and minor folds. The complex sequence of structural events established from other parts of New York City is identical to the structural sequence mapped in Central Park, with three phases of superposed ductile folds crenulated by open folds.

Two generations of brittle faults cut Central Park. They conform to the Group D and Group E faults found in the Queens Tunnel and elsewhere in the city. In some Group D fault surfaces, dip-slip slickensides show overprint by oblique-slip reactivation, the presumable result of younger (Group E) faults. The Group E faults trend N20°W to N50°W, exhibit steep dips and show predominately strike-slip offset. Both right-lateral and left-lateral Group E faults cut the park in three areas.

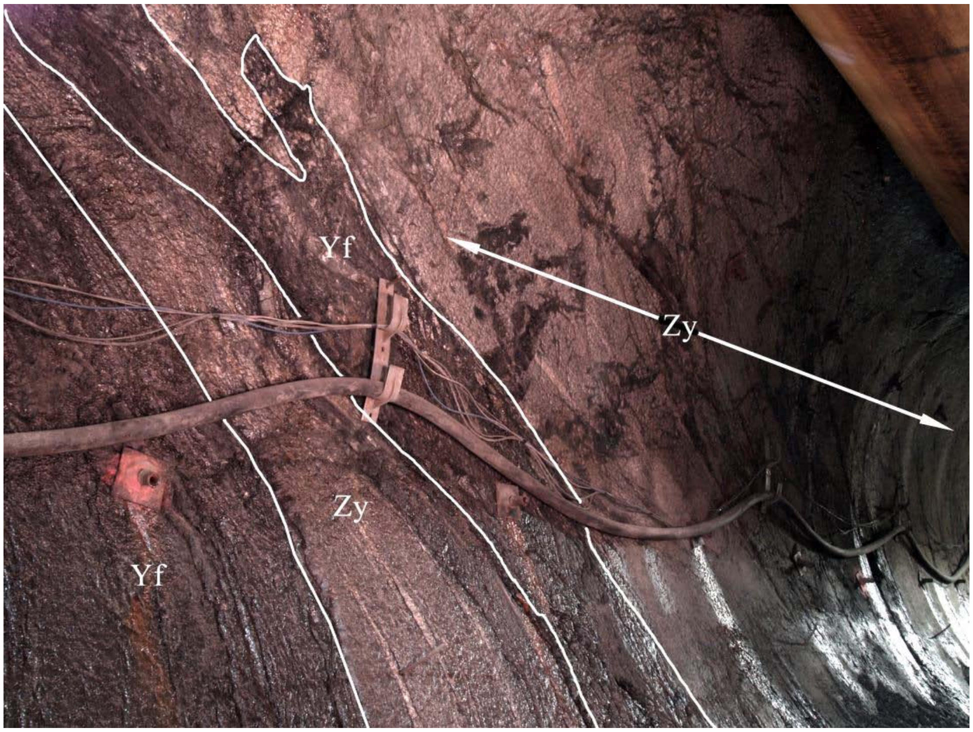

Figure 28. View of southeast wall of high-level treated water tunnel showing permeated and deformed contact of Fordham Gneiss (Yf) with Yonkers Gneiss (Zy). (Digital image of Station 26+95 and annotations by C. Merguerian.)

The 125th Street or Manhattanville fault cuts the NE corner of the park, skirting the Harlem Meer and producing joints oriented N52°W, 75°SW; N19°W 88°NE; and N22°W, 74°NE across the south shore of the meer where gently inclined slickenlines can also be found. Both regional map offsets and the slickenlines indicate right-lateral offset. Two areas south of this locality show evidence for a reversal to left-lateral strike-slip faulting. Near 101st Street and the East Drive, four quartz-healed Group E faults are oriented N12°W, 90° to N39°W, 80°SW-90° with intervening curved splays and healed quartz stringers (colored yellow in fig. 30). From N to S, offsets of 9 cm, 30 cm, 1 cm, and 50 cm (south of outcrop sketch) are the major slip surfaces in the exposure that shows well over a meter of composite offset (fig. 31) and locally up to 0.5 cm of gouge. They cut N44°E sub-vertical isoclinally folded gneiss and amphibolite of the Manhattan formation and offset an isoclinal fold hinge in amphibolite plunging 12° into S45°W.

The most southerly fault in Central Park, adjacent to Eighth Avenue (fig. 29) near the Ladies Pavilion on the west side of The Lake, is oriented N45°W, 90° to N34°W, 81° SW and shows minor left-lateral offset in highly jointed Hartland granofels (fig. 32). Thus, two near orthogonal fault sets cut Central Park, the Group D and Group E faults found elsewhere in NYC. They produce a chocolate block type of brittle fracture pattern in the bedrock units as shown in the magnificent exposure at Umpire's Rock, just south of the ball field. Here, two crosscutting fault generations occur. The older set trends N32°E, 90° with thick gouge and 3 m thick fault breccia at east edge of the sculpted exposure that has been modified by glacial plucking. The field image shows one of the NE-trending faults and shows a NW-trending fracture cutting the exposure at a high angle (fig. 33).

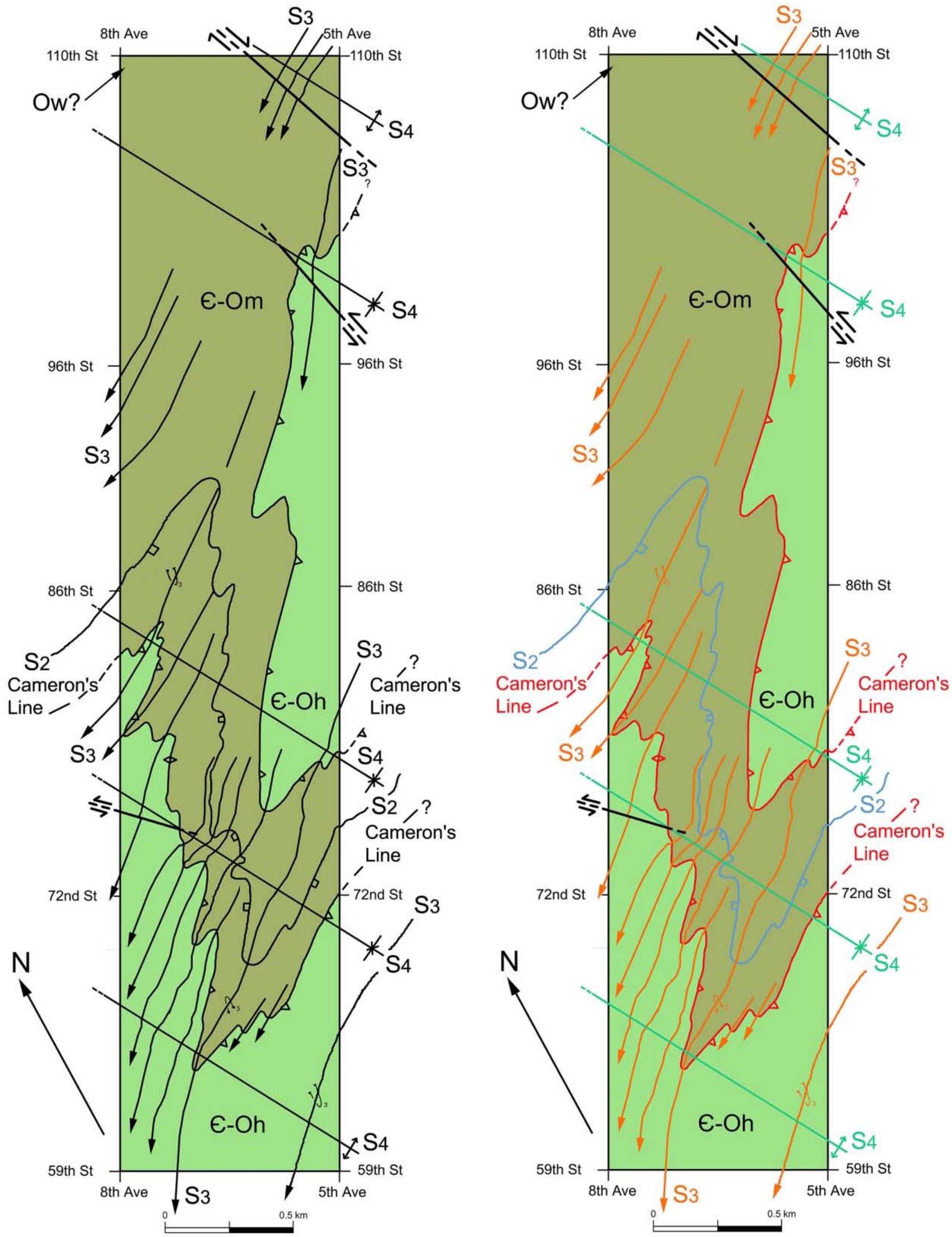

Figure 29. Preliminary bedrock geological maps of Central Park showing ductile and brittle faults and the axial traces of the major structural features, based on re-mapping by Merguerian and Merguerian (2004).

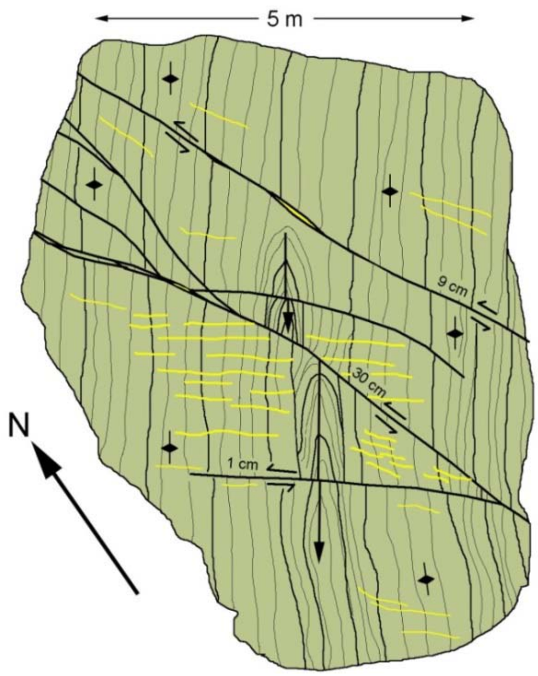

Figure 30. Field-sketch map showing Group E faults in northern Central Park near projected intersection of 101st Street and the East Drive. Yellow lines are healed quartz-filled fractures showing no offset.

Figure 31. Photo looking southward along main fault from center of previous figure. Here a N12°W, 90° left-lateral fault offsets by 30 cm an isoclinal fold hinge in Manhattan amphibolite plunging 12° into S45°W. Foliation and layering in the Manhattan are oriented N44°E/83° NW-90°. Pocket knife at top of image for scale. (CM Stop N537.)

Mt. Morris Park, NYC, NY On the north and south, this small NYC park is a bedrock knoll bounded on the north and south by strike-slip faults. For bedrock enthusiasts low-angle truncation of layering and foliation in the Inwood and Walloomsac by allochthonous garnet sillimanite gneiss of the Manhattan along the St. Nicholas thrust displayed along the knoll's eastern edge (Merguerian and Sanders 1993). At the south end, a slickensided fault surface oriented N75°W, 72°SW exhibits right-lateral oblique-slip offset with slickenlines plunging 28° into W and at the north end of the park another fault is oriented N25°W, 84°NE and shows slickenlines pitching 10°.

Figure 32. Southeastward view of left-lateral N34°W, 81°SW fault zone in Hartland granofels and schist where minor left-lateral offset was detected.

Figure 33. Umpire Rock in Central Park showing two near orthogonal faults. The Group D fault extends from the lower left foreground back into the image and is oriented N32°E, 90° with an eroded 0.5 m gouge zone. This fault is cut by a Group E fault trending ~N50°W, 90° across the image. The outcrop shows another Group D fault defining the east edge which shows a 3 m thick fault breccia modified by glacial action.

New York Botanical Garden, Bronx, NY

Mapping of rocks in the New York Botanical Garden in 2011 showed that Inwood, Walloomsac, Manhattan and Hartland rocks have been imbricated by juxtaposition along the St. Nicholas thrust and Cameron's Line. The overall structure in the park shows an overturned synform of the Inwood-Walloomsac strata with Manhattan and Hartland rocks nestled in the core. The Rocks are cut by the right-lateral Mosholu fault (fig. 34). The trend of the Mosholu fault in the Bronx is similar to that of the 125th Street fault (~N24°W) and its sense of offset is identical. However, the degree of glacial modification is not as great on the Mosholu fault as found along the 125th Street fault, which has been severely modified by glacial action (fig. 22).

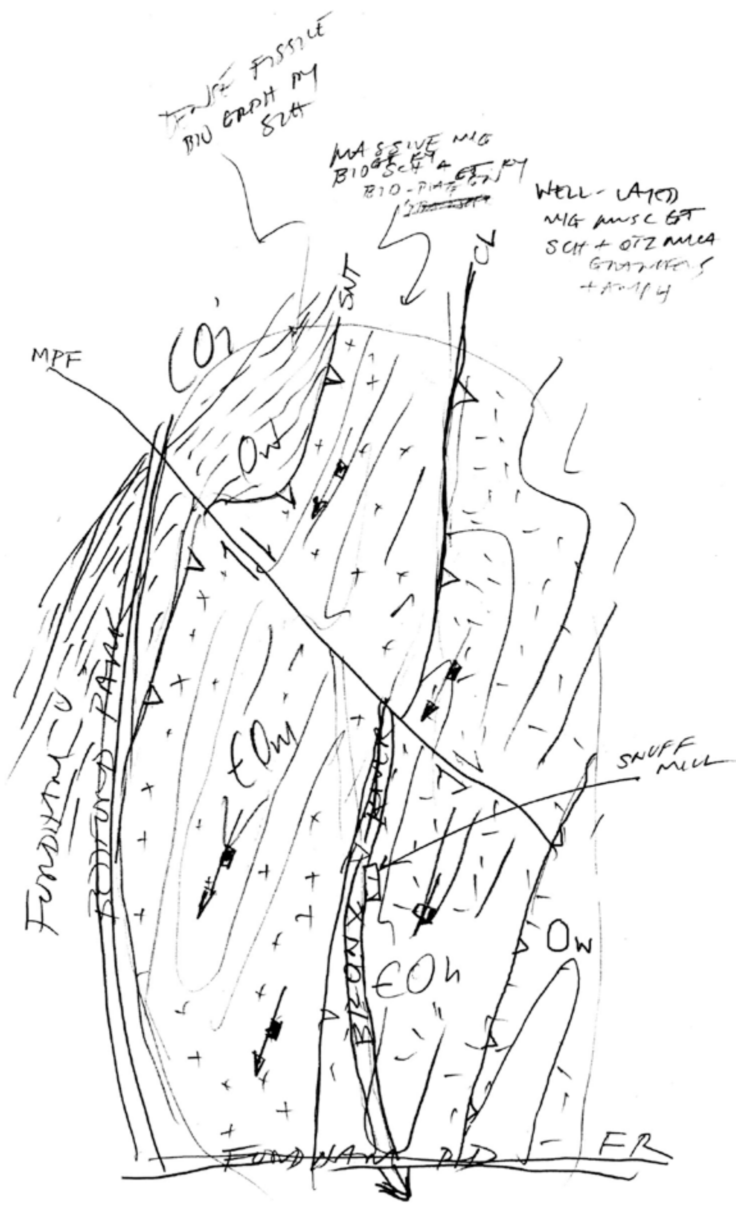

Figure 34. Sketched geological map of the New York Botanical Garden (north to the top) showing a SE-dipping series of thrust slices of Manhattan (Ꞓ-Om), Hartland (Ꞓ-Oh), and Walloomsac (Ow) rocks. The Manhattan is thrust against the Walloomsac and Inwood (Ꞓ-Oi) along the St. Nicholas thrust (SNT) in the NW part of the park. The overall structure is synformal with Manhattan Schist at the center of a SE-plunging F_3 synform whose truncated SE-limb is marked by Cameron's Line (CL) near the course of the Bronx River. Farther SE, a secondary thrust places an imbricate slice of Walloomsac (Ow) against Hartland rocks (Ꞓ-Oh). The thrust zones are marked by imbricated lithologies and broad zones of mylonite ± migmatite. All of the bedrock units and ductile faults are cut by the NW-trending, right-lateral Mosholu fault. (Merguerian, unpublished data.)

Hypotheses on the origin of the Snuff Mill gorge and diversion of the Bronx River

Northeast of the NW-SE-trending Mosholu fault, the Bronx River flows SW in a wide NNE-SSW-trending strike-valley lowland underlain by Inwood Marble (fig. 35). Southwest of the fault is the NNE-SSW-trending Webster Avenue lowland, another equally wide valley underlain by the Inwood Marble, that is offset to the west from the former and lacking a modern-day river but in which the Bronx River undoubtedly flowed in the past.

Just at the point where the NNE-SSW-trending marble lowland has been offset, the Bronx River leaves it and flows southward across resistant gneiss and schist of the Hartland formation in the narrow N-S-trending Snuff Mill gorge. This condition marks a first-order drainage anomaly. If the river did indeed follow the marble lowland SW of the Mosholu fault, then some kind of blockage must have prevented it from continuing to do so. During the time when the river's course to the SW down the Webster Avenue lowland was blocked, the water would have been backed up to form a lake. In such a lake, one would expect that some fine sediment would have been deposited. After a new course to the south through the Snuff Mill gorge had been established, outfall water from the lake would have been locked into this new course across the Hartland, so that even if the locked Webster Avenue lowland became available, the river would not seek to re-occupy it.

Several geologic consequences would be associated with diversion of the Bronx River out of the presumably ready-made course underlain

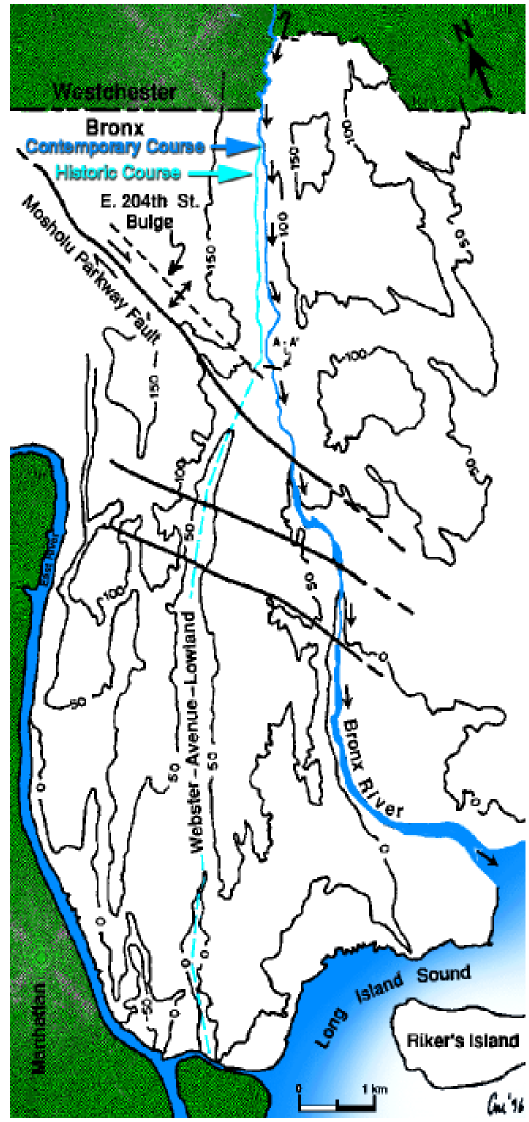

Figure 35. Bedrock contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including the northernmost Mosholu, Bedford Park, and Fordham faults, the E. 204th Street Bulge, the area of the Snuff Mill gorge and section A-A' (fig. 36). The Webster Avenue Lowland marks the previous course of the Bronx River. (Subsurface and fault data from Baskerville (1992), and from engineering records of the NYC Subsurface Exploration Section; bedrock contours in feet).

by the Inwood Marble along the strike-parallel Webster Avenue lowland (fig. 35).

The records archived in the New York City Office of General Services, Subsurface Branch, contain evidence bearing on the diversion of the Bronx River. Figure 36 shows a profile section culled from borings taken across the Bronx River valley from E. 205th Street across to Burke Avenue at a point upstream from the inferred blockage/diversion. Several noteworthy features of these boring records stand out.

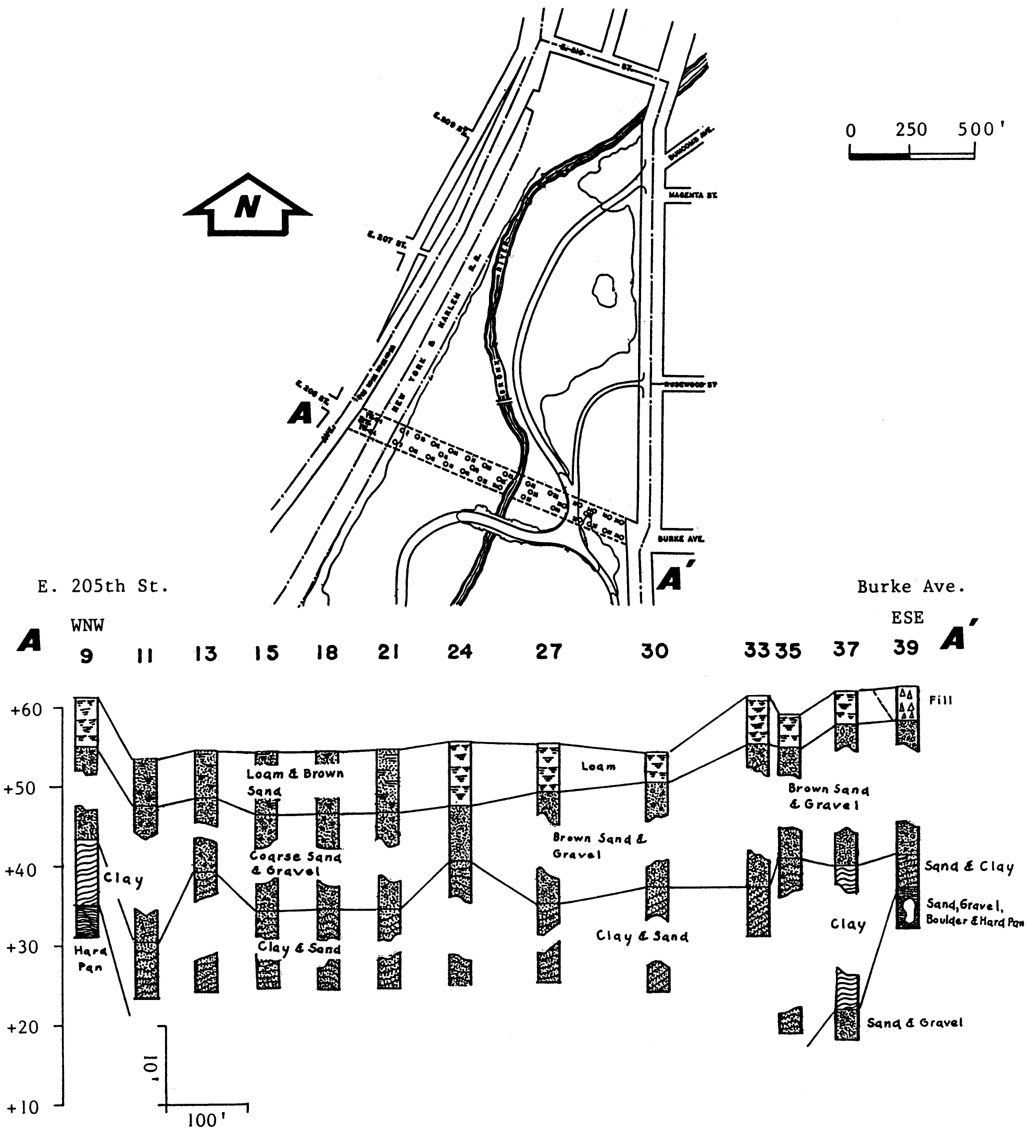

Figure 36. Index map and subsurface stratigraphic section from E. 205th Street east-south-eastward to Burke Avenue in the Bronx, upstream of point of diversion of Bronx River based on records of borings assembled in the 1930s by the WPA rock-line map of the Bronx. Line of section (A-A') also shown on figure 35. Index map shows locations of borings and section A-A'. Stratigraphic correlation diagram using original WPA lithologic symbols for individual boring logs. (Drawn at 10X vertical exaggeration by J. E. Sanders. Elevations are Bronx Highway Datum.)

First, at the bottoms of several borings are what probably should be classified as till ("hardpan," "boulders"). Overlying the putative till is pebbly coarse sand. Next above is thick clay. The clay infers deposition within a lake that formed in connection with the diversion. The clay is both underlain and overlain by coarse +/- pebbly brown sand. Not shown on this section is the deposit of cobbles having an exposed thickness 20 feet in the excavations for the new Bronx River sewer mentioned by Kemp (1897, p. 19).

No clay unit comparable to that found north of the Mosholu fault is present in any of the boring records we have examined along the Webster Avenue lowland, where a capping of artificial fill was emplaced before the railroad and streets were built. The records of sediment in the fill of the Webster Avenue valley contain gray sand below, which is overlain by brown sand. Notably absent is any reddish-brown sediment, key indicators of one- or more pre-Woodfordian glacial episodes. As mentioned above, figure 35 shows contours on the bedrock surface. Note that the Webster Avenue valley is youthful with a narrow, V-shaped profile.

Kemp (1897) inferred that the diversion of the Bronx River was a byproduct of Pleistocene glaciation. Merguerian and Sanders (1997) accepted Kemp's post-glacial age assignment but did so for a reason Kemp did not mention. Namely, had the Snuff Mill gorge been in existence before the latest glacier arrived in the NYC region, then the ice would surely have changed the profile from its present narrow V-shape to a broader U-shaped valley. The narrow V-shaped profile of the Snuff Mill gorge (fig. 37) and absence of smoothed-, polished- and striated rock surfaces on the jagged fresh bedrock exposed in the valley walls by contrast to glacially polished and striated rock on the upland surfaces away from the gorge are powerful arguments in favor of a post-glacial age for the Bronx River diversion, erosion and downcutting of the Snuff Mill gorge. Merguerian and Sanders (1997) considered the NW-trending Group E faults of NYC, along with the Mosholu and Dobbs Ferry faults in Westchester to be seismically capable faults with a history of offset of geological and geomorphic features. They associate the bedrock bulge in figure 36, right-lateral offset of the Bronx River, and diversion of the Bronx River with neotectonic (post-glacial) seismicity along the Mosholu fault.

Faults and Seismicity in NYC

NYC paleozoic cover rocks are cut by two main sets of brittle faults trending ~N30°E [paralleling the long axis of Manhattan] and ranging from N20°W to N50°W [diagonally across Manhattan] with steep to moderate dips toward the SW. Proterozoic basement rocks show a more complex brittle fault history. The NNE-trending faults, which locally reactivate annealed ductile fault zones (Cameron's Line and the St. Nicholas thrust) are steep- to vertical and show dominantly dip-slip motion. The NW-trending faults show complex movement dominated by strike-slip offset followed by dip-slip or oblique-slip reactivation. The NW-trending faults have produced map-scale offset in NYC and geomorphic evidence from the Bronx River implies post-glacial ground rupture.

Figure 37. View of Snuff Mill gorge showing non-glaciated bedrock exposures along V-shaped course of the Bronx River through non-glaciated Hartland rocks. (CM digital image taken 02 June 2011.)

North of NYC, contemporary seismicity along the NW-trending Dobbs Ferry fault in late October 1985 included two small (~4.0) tremors and many aftershocks. As shown in figure 38, more robust earthquakes in and around the vicinity of NYC were recorded in 1884, 1783, and 1737. Unequivocal post-glacial ground rupture is difficult to demonstrate in NYC where most bedrock faults are deemed (especially by seismologists) to have formed at depth and then later elevated to the surface. Yet, the Bronx River, which formerly flowed SSW in an open valley underlain by the Inwood Marble, shows diversion away from its "pirated" marble valley along the NW-trending right-lateral Group E Mosholu fault.

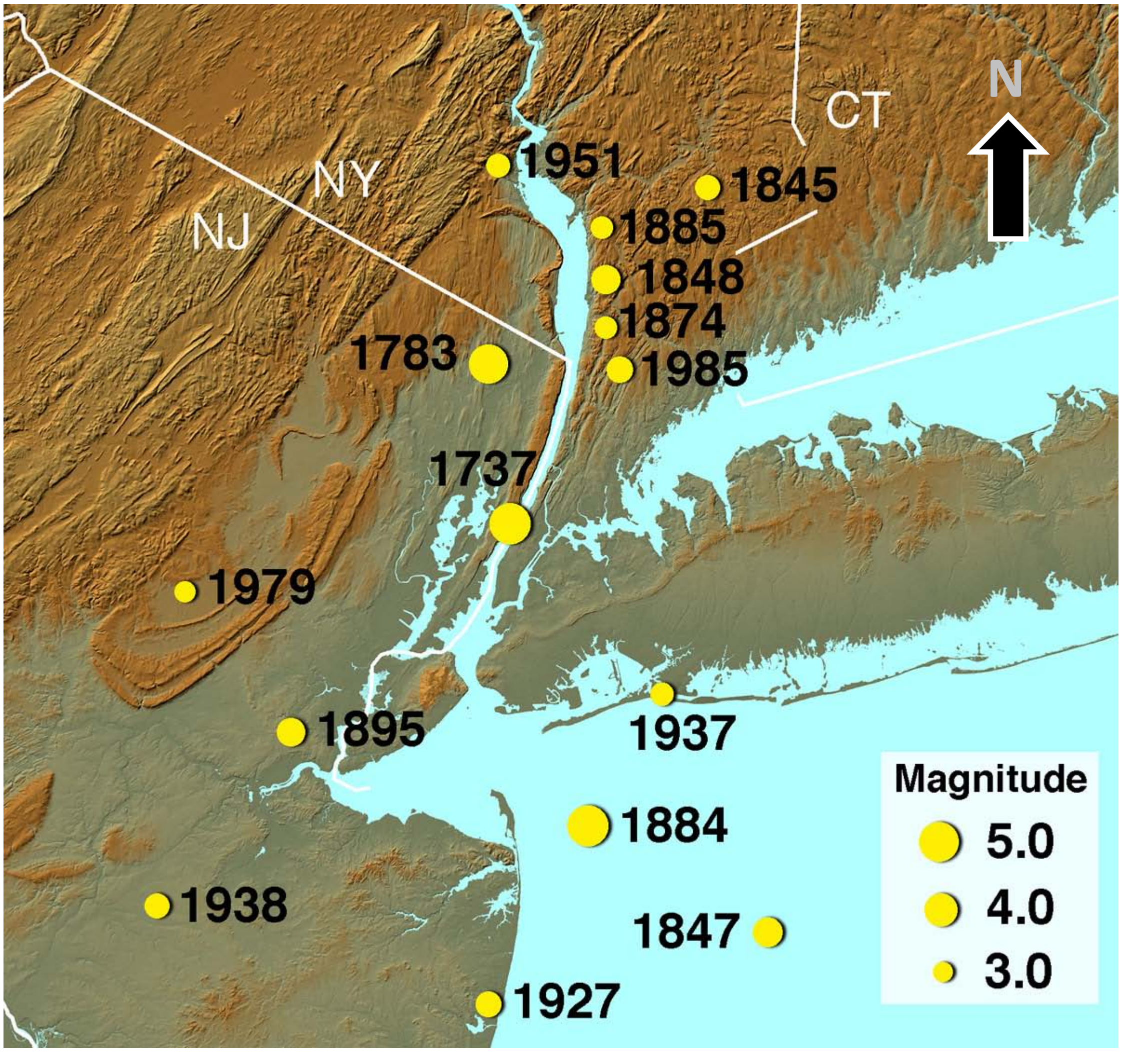

Figure 38. Map showing historic seismic activity in the vicinity of New York City showing a diffuse zone of seismicity and the position of M3 and greater events before 1986. (From Bennington and Merguerian 2007.)

Merguerian and Sanders (1997) did not prove that the surface displacement of the bedrock adjacent to the East 204th Street bulge accompanied an earthquake generated along the Mosholu fault, nor did they prove that surface rupture took place. However, in many seismically active zones, surface displacement, such as the bulging mentioned above adjacent to the Mosholu fault, typically is associated with earthquakes (for example, the Palmdale Bulge along the San Andreas fault in California). No surface offset has been previously reported in connection with any of NYC's strongest earthquakes of 1737 (~M5.2), 1783 (~M4.9), and 1884 (~M5.2). Yet, the August 1884 earthquake produced 4 m long by 3 m deep soil openings, cracked buildings and chimneys in Brooklyn and was felt over a hundred miles from the epicenter, which was located in the New York Bight. Equivalent seismic shaking in NYC today would likely cause failure of older masonry walls, shatter glass windows in skyscrapers and rupture water and gas mains as soils liquefy during ground shaking.

The epicenter of a small earthquake (~2.4 Richter) localized in NYC on 17 January 2001 plots adjacent to the trace of the 125th Street fault near 102nd Street and Park Avenue in Manhattan. Later that same year, on 27 October 2001, another similar earthquake (~2.6 Richter) struck NYC with an epicenter near 55th Street and Eighth Avenue. The two epicenters are plotted on figure 39 to show that they are parallel to Group E Central Park faults (shown in red with offset arrows) as described above.

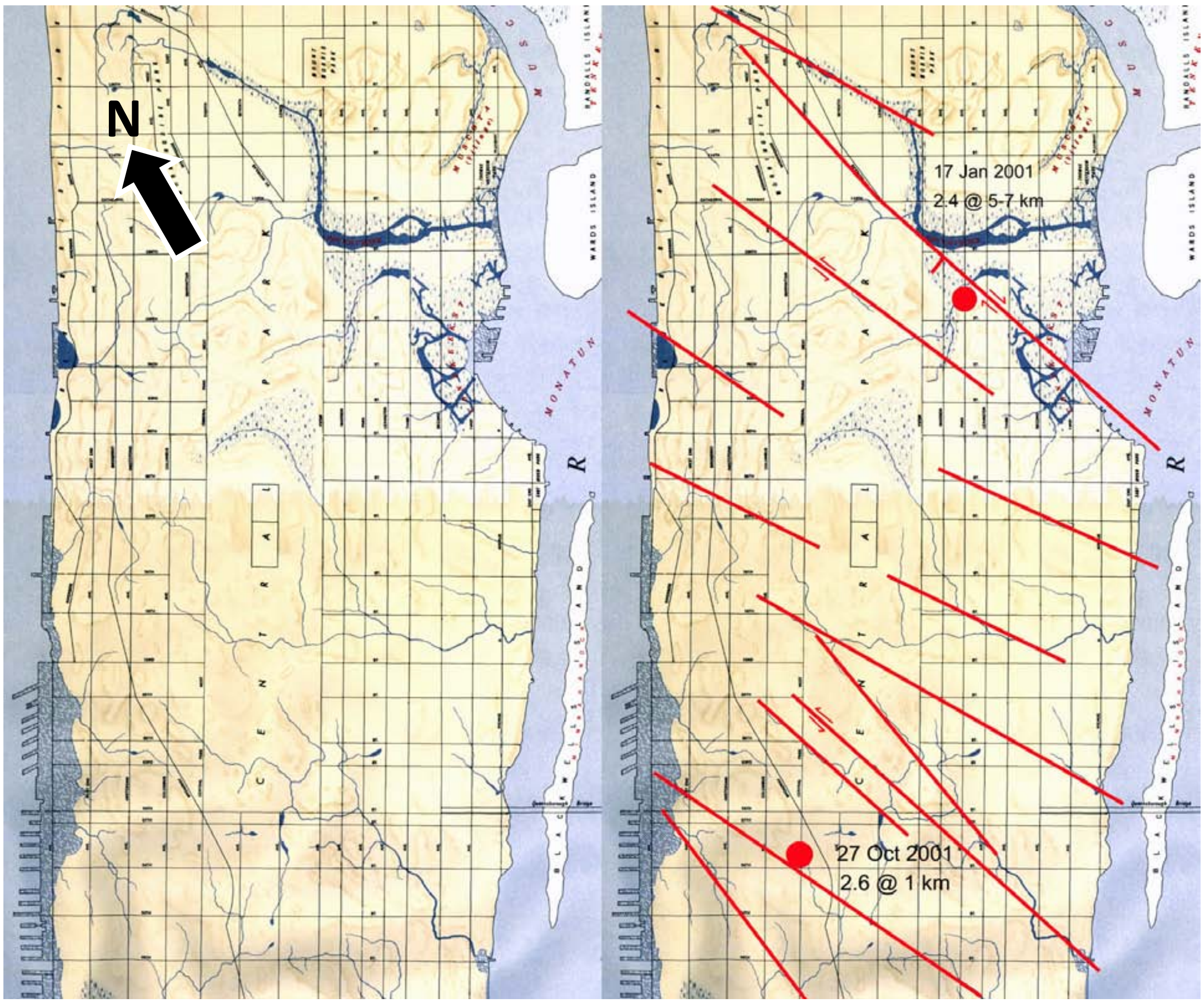

Figure 39. Old topographic map of Manhattan (McCoun 1609) showing pre-industrial era drainage on left following structural weaknesses (typically faults) in crystalline rocks. Note the pronounced NNW- to NW- trend of creeks and streams. The map on the right includes mapped fault with arrows showing slip directions in Central Park Other faults are inferred from stream patterns and topography. Epicenters of two small earthquakes in 2001 beneath Manhattan Island are also shown.

Because the contemporary stress regime in the lithosphere is oriented N64°E and also about NW-SE (Sykes and others, 2008), NYC faults are well-oriented to exhibit neotectonic activity. Arm waving aside, perhaps the Group E fractures may result from Atlantic Ocean ridge push with transform- fracture propagation into the edge of the continental crust (fig. 40). This model, proposed over twenty years ago at a GSA meeting while the audience snoozed loudly, is deemed a possible mechanism for neotectonic reactivation of these young brittle features though other mechanisms or combinations of mechanisms are clearly possible given the numerous potential inputs of neotectonic overprint.

Thus, given the modern stress regime, the presence of Group D and Group E faults in the NYC area portend seismic risk. Given the known history of time-separated moderate intensity seismic activity in New York City, the potential that a damaging earthquake may affect this densely populated area should not be ruled out. Because earthquakes *have* happened here, *can* happen here, and *will* happen here, effective pre-emptive planning to mitigate seismic hazards is an urban necessity.

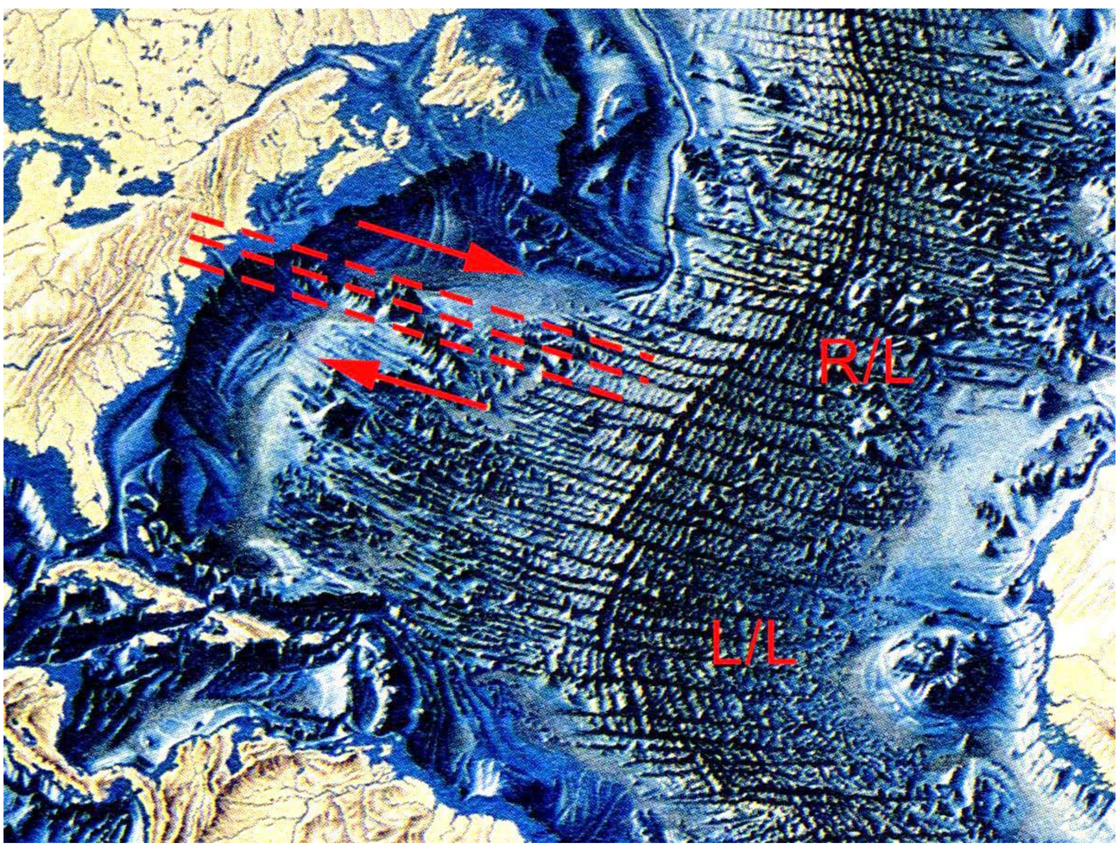

Figure 40. Contemporary NYC seismicity seems to be localized along NW-trending brittle faults. As diagrammed above, the right-lateral and left-lateral offset sense of active NYC faults may be caused by varied offset along the transcurrent faults that segment the mid-ocean ridge of the Atlantic Ocean basin. (Base map from Heezen and Tharp 1968.)

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