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STRATIGRAPHY, STRUCTURAL GEOLOGY, AND DUCTILE- AND BRITTLE FAULTS OF THE NEW YORK CITY AREA

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INTRODUCTION

Field- and petrographic studies of the Paleozoic metamorphic rocks of New York City suggest a new interpretation of the stratigraphy and structure of the region and has delineated a number of ductile- and brittle faults. The belt of rocks originally lumped together as the Manhattan Schist is now interpreted to consist of three mappable units structurally imbricated by two major ductile faults, the St. Nicholas thrust and Cameron's Line. NE- and NW-trending brittle faults cut the ductile faults and metamorphic tectonites. Future seismicity may be concentrated along the NW-trending faults which, indeed, show the greatest amount of offset.

The crystalline rocks of New York City are largely obscured by urbanization and surface sediment deposits which inhibit direct examination of bedrock. Over the last 15 years, my studies of New York's bedrock have involved examination of over 500 natural exposures, site visits to roughly 100 open-pit construction sites during the building boom of the 1980s, subsurface study during ongoing construction of City Water Tunnel #3, and study of Hofstra University's Metropolitan New York Drill Core Collection. These data, together with subsurface information from existing reports, engineering boring logs, and data from the construction of City Water Tunnels #1 and #2, have allowed a new interpretation of the stratigraphy and structure of the New York metropolitan area. The following is a progress report on these studies. Included as Figure 1 is a new interpretation of the bedrock geology of southern Manhattan, western Queens and Brooklyn. Figure 2 outlines the geology of New York and Bronx counties and provides a cross-section to illustrate the complex geology of the region.

REGIONAL GEOLOGY

New York City is situated at the southern terminus of the Manhattan Prong, a northeast-trending deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward to form the crystalline terranes of western New England. Southward from New York City, the crystalline rocks of the Manhattan Prong plunge beneath Mesozoic rocks and overlying Cretaceous and Pleistocene sediments and re-emerge at the surface in the vicinity of Philadelphia, Pennsylvania.

In the vicinity of New York City (Figure 1), the crystalline rocks of the Manhattan prong are separated by complexly deformed, northeast-trending ductile thrust faults mapped as the St.

Nicholas thrust and Cameron's Line (Merguerian, 1983a; Merguerian and Baskerville, 1987) which separate contrasting sequences of metamorphosed Lower Paleozoic strata formerly lumped together as the Manhattan Schist formation. Structurally above Cameron's Line, allochthonous rocks of the Hartland Formation (Ꞓ-Oh) consist of amphibolite facies gneiss, schist, amphibolite, and garnet-quartz granofels. This terrane, which extends to underlie the

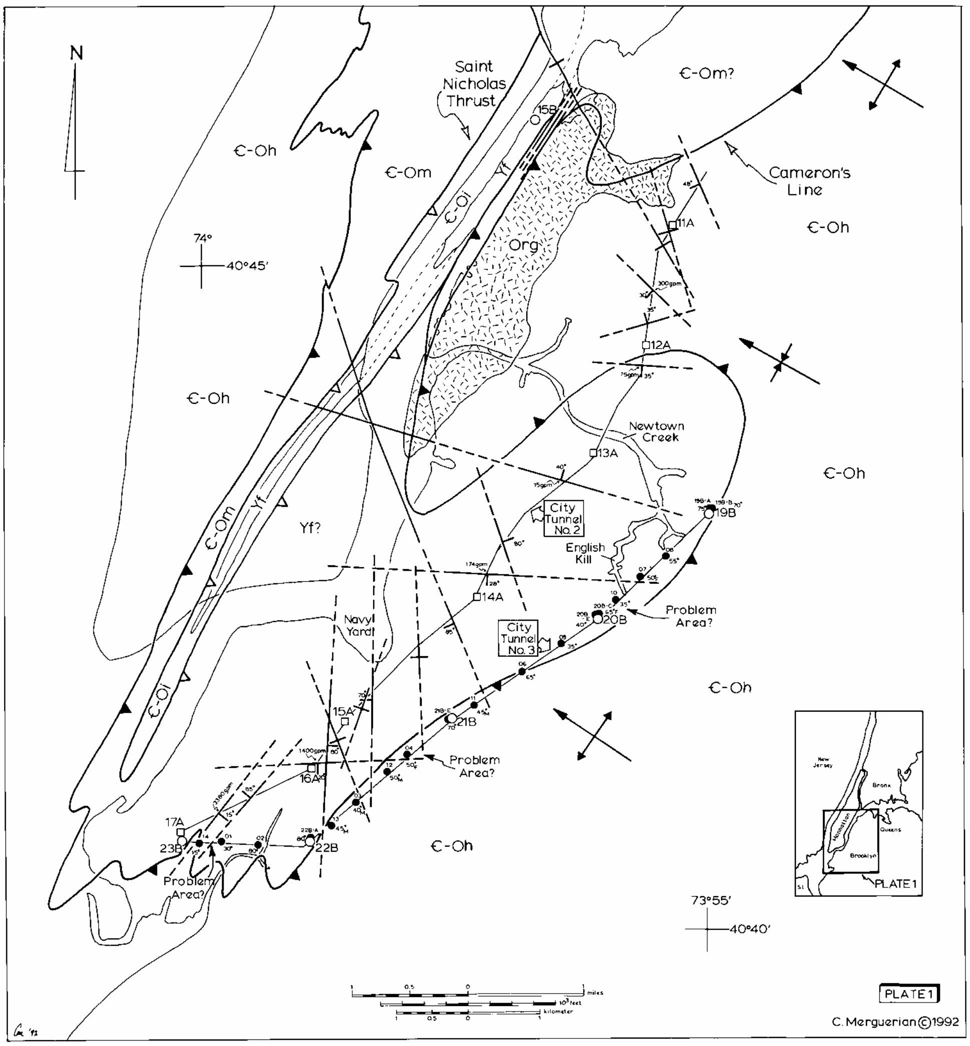

Figure 1 - Interpretive geologic map of western Brooklyn, western Queens, and southeastern Manhattan, originally compiled at 1:24,000 scale, indicates the positions of the tunnel line and shafts (open squares) of City Water Tunnel # 2 and the construction shafts (filled circles) and proposed tunnel line of City Water Tunnel # 3. Geologic units include Org - Ordovician Ravenswood Granodiorite Gneiss, Ꞓ-Oh - Cambrian to Ordovician Hartland Formation (Upper Schist Unit), Ꞓ-Om - Cambrian to Ordovician Manhattan Formation (Middle Schist Unit), Om - Ordovician Manhattan Formation (Lower Schist Unit), Ꞓ-Oi - Cambrian to Ordovician Inwood Marble Formation, Yf - Proterozoic Y Fordham Gneiss Formation. Sources include: Berkey (1910, 1933), Ziegler (1911), Merguerian, unpublished data, Merguerian and Baskerville (1987), Chesman (1991), and Baskerville (1992).

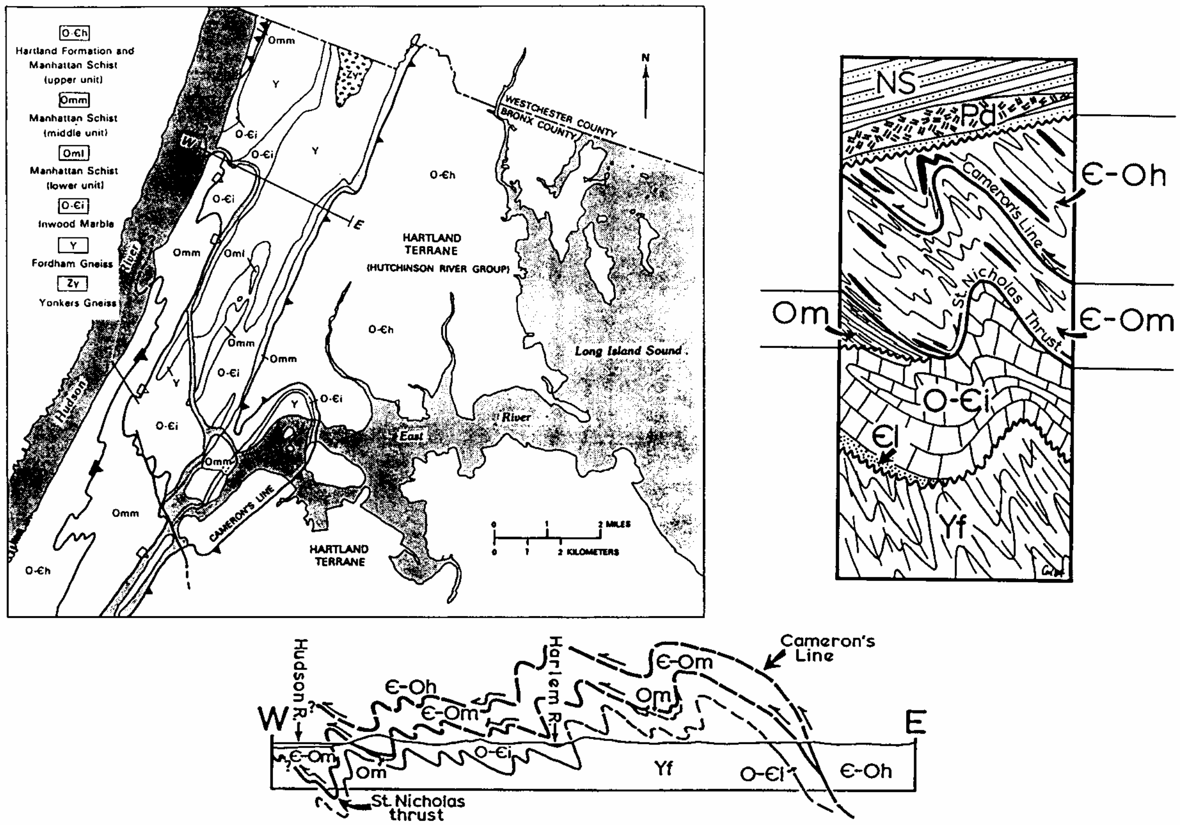

Figure 2 - Geologic map of Manhattan and the Bronx showing a new interpretation of the structure of the Manhattan Schist (adapted from Merguerian and Baskerville, 1987). Notation very similar to figure 1 and inset which shows a new interpretation of the stratigraphy of the region. The east-west geologic section shows the distribution of various tectonostratigraphic units in New York City and geometry of the deformed ductile faults (Cameron's Line and the St. Nicholas thrust).

crystalline highlands of western Connecticut, marks the eroded remains of former slope-rise and deep-water oceanic sediments and interlayered volcanic rocks deformed in a deep-seated, continentward-facing subduction zone during the Taconic orogeny (Robinson and Hall, 1980; Merguerian, 1983b, 1985). The St. Nicholas thrust separates an upper metamorphosed slope-rise facies of the Manhattan Schist (unit Є-Om - described below) from structurally lower basement-cover rocks which (moving upsection) includes the Proterozoic Y Fordham Gneiss (Yf), the very local unconformably overlying Cambrian Lowerre Quartzite (Єl), the Cambrian to Ordovician Inwood Marble (Є-Oi), and the overlying Manhattan Schist of medial Ordovician age (Om). This autochthonous sequence is interpreted to represent former 1.1 Ga continental crust (Yf) and overlying 550-450 Ma shallow-water shelf sediments, now metamorphosed into quartzite, marble, gneiss, and schist (Єl, Є-Oi, Om).

STRATIGRAPHY OF THE MANHATTAN SCHIST(S)

The Manhattan Schist formation can be subdivided into three lithologically distinct, fault-bounded units of kyanite- to sillimanite metamorphic grade (Figure 2). The structurally lowest unit (Om) crops out in northern Manhattan, the western Bronx, and has been identified in the subsurface of western Queens and Brooklyn. This unit consists of brown- to rusty-weathering, fine- to medium-grained, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet gneiss and schist containing interlayers, centimeters to meters thick, of calcite+diopside marble.

Both the lower schist unit (Om) and the Inwood Marble (Ꞓ-Oi) are structurally overlain by the middle schist unit (Ꞓ-Om) which forms the bulk of the "schist" exposed on the island of Manhattan. The middle schist unit consists of massive to indistinctly layered, rusty- to sometimes maroon-weathering, medium- to coarse-grained, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. Unit Ꞓ-Om is characterized by the presence of kyanite + sillimanite + quartz + magnetite layers and lenses up to 10 cm thick, cm-to m-scale layers of blackish amphibolite, and quartzose granofels. The middle unit is lithologically identical to the Waramaug and Hoosac formations of Cambrian to Ordovician ages in New England (Hatch and Stanley, 1973; Hall, 1976; Mose and Merguerian, 1985). Thus, the rocks of the middle unit are older than the Manhattan Schist (Unit Om) found "in situ" above the Inwood Marble which implies allochthony of the middle unit along the St. Nicholas thrust.

The structurally highest, upper schist unit (Ꞓ-Oh) is a dominantly well-layered, gray-weathering, fine- to coarse-grained, muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and granofels with cm- and m-scale layers of greenish amphibolite+garnet. The upper schist unit, which underlies most of the western- and southern parts of Manhattan island and the eastern half of the Bronx (including Pelham Bay Park), is lithologically identical to the Cambrian and Ordovician Hartland Formation of western Connecticut and southeastern New York. On this basis, they are considered correlative. The regional contact between the Manhattan (Ꞓ-Om) and Hartland Formations (Ꞓ-Oh) is a zone of mylonitic rocks known as Cameron's Line.

STRUCTURAL GEOLOGY

The exposed bedrock of New York City consists of amphibolite facies metamorphic rocks that have been intensely folded (three superposed episodes of folds with local shearing and development of related penetrative fabrics) which resulted in total recrystallization and localized partial melting of the rocks. During the culmination of the first two stages of ductile deformation, the rocks were imbricated by two syntectonic ductile thrust faults (Cameron's Line and the St. Nicholas thrusts), and intruded by late syntectonic calc-alkaline magmas (now preserved as orthogneisses such as the Ravenswood Granodiorite Gneiss - Org in Figure 1).

Cameron's Line and the St. Nicholas thrust developed during two progressive stages of ductile deformation accompanied by isoclinal folding (F1+F2). An annealed, highly laminated mylonitic texture occurs at these thrust zones (Merguerian, 1988). Recrystallized mylonitic layering is marked by ribboned and locally polygonized quartz, lit-par-lit granitization parallel to S2, and quartz veins developed parallel to the axial surfaces of F2 folds. During D2, a penetrative foliation (S2) and metamorphic growth of lenses and layers of quartz and kyanite + quartz + magnetite up to 10 cm thick formed axial planar to F2 folds which deformed the bedrock units into a large-scale recumbent structure that strikes N50°W across Manhattan island and dips 25°SW.

Although the regional metamorphic grain of the New York City bedrock trends N50øW, the overall geometry of map contacts are regulated by F3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25°. S3 is oriented N30°E and dips 75°SE and varies from a spaced schistosity to a transposition foliation often with shearing near F3 hinges. The F3 folds and related L3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz and kyanite lenses and layers into elongated shapes.

These rocks were later effected by at least three, comparatively weak, open- to crenulate folds of the composite foliation (at significantly lower metamorphic grade), resulting in spaced slip cleavage and local northward plunge reversals of F3 hingelines.

Figure 2 presents a simplified W-E structure section across northern Manhattan into the Bronx roughly parallel to the Cross Bronx Expressway (I-95). The section illustrates the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit strata. The major F3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently southward out of the page toward the viewer.

DUCTILE FAULTS

The rocks encountered by borings (filled circles in Figure 1) along the proposed tunnel line of CT #3 include garnetiferous quartzofeldspathic gneiss and subordinate schist, foliated orthogneiss (metaplutonic rock), and subordinate pegmatite. All of the rocks are strongly migmatitic thus resulting in use of the term "injection" gneiss (Berkey 1948; Blank, 1973) for the dominant lithologies in the region. In Figure 1 the position of Cameron's Line is a "best fit" based on lithology, recognition of ductile fault textures, and mixed rocks. Ductile-fault rock textures (mylonitic rocks) are well developed as are zones of mixed rock typical of Cameron's Line. The imbricated lithologies include the Fordham Gneiss (Yf), the middle unit of the Manhattan Schist (Ꞓ-Om), the Hartland (Ꞓ-Oh), and migmatitic gneiss of unknown lithologic affinity. Thus, Cameron's Line juxtaposes Hartland rocks against units of the Manhattan Schist and the Fordham Gneiss, a relationship first reported (Merguerian, 1986) in a water tunnel connecting Manhattan and Queens beneath the East River.

Note that Cameron's Line is strongly folded in the vicinity of western Queens and Brooklyn. The bulbous geometry of Cameron's Line is the result of superposed F3 and younger folds (with possible NW-trending anticlinal and synclinal fold axes illustrated on Figure 1 to the SE of Cameron's Line) that have warped the thrust surface into a subhorizontal flap that has been breached by erosion. Thus, in the area of western Queens, Hartland rocks and the Ravenswood

Granodiorite Gneiss are exposed but in western Brooklyn, rocks of the Fordham-Inwood-Manhattan sequence occur in a structural window beneath Cameron's Line. A similar, structurally lower window (might this qualify as a double-hung window?) exposes the St. Nicholas thrust and underlying units Yf and Ꞓ-Oi in southeastern Manhattan. Tunneling of CT #3, which is slated to begin in early 1994, should better constrain the geometry of the geologic contacts in this area.

Cameron's Line trends westward near Shafts 23B and 17A in southwestern Brooklyn (closed thrust symbol on Figure 1) and must traverse northward into the south part of Manhattan as mapping constrains the position of Cameron's Line to the southern portion of Central Park northward along the western edge of Manhattan. It passes offshore into the Hudson River near 165th Street (Figure 2). The St. Nicholas thrust (open thrust symbol on Figure 1) follows a somewhat similar geometry as it was also deformed by F3 and younger folds.

BRITTLE FAULTS

All geologists and seismologists agree that earthquakes produce dislocations known as faults and that preexisting faults and joints tend to localize new earthquakes. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of ductile- and brittle faults. In addition to Cameron's Line and the St. Nicholas thrust, a large number of northwest-trending brittle faults are indicated on Figures 1 and 2. One of these, the famous 14th Street fault controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan between 23rd and Canal streets. The fault at 125th Street underlies a broad, U-shaped valley.

Two contrasting sets of brittle faults are superimposed upon isoclinally folded imbricate ductile thrusts (Cameron's Line and the St. Nicholas thrusts) and amphibolite-facies metamorphic rocks in New York City. Field evidence and subsurface data indicate that trends of these sets are: 1) approximately N30°E (roughly parallel to the trend of lithologic contacts and the axial surfaces of F_3 folds) and 2) ranging from N20°W to N50°W (across the NE trend, roughly parallel to the S_2 axial surface of the F_2 folds). Thus, the orientation directions of brittle faults in the vicinity of New York City are the products of emphatic structural control in the form of lithologic layering (S_0), the S_1+S_2 metamorphic fabrics, and the S_3 axial surfaces of major F_3 folds.

The NE-trending faults are steep to vertical and show dominantly dip-slip motion with offset up to 1 m in zones up to 2 m thick. Locally, where they parallel NE-oriented mylonite zones (Cameron's Line and the St. Nicholas thrust), they are cataclastic (broken) and marked by greenish clay-, calcite-, and zeolite-rich gouge up to 30 cm thick. More commonly, they are healed shut by quartz, calcite, or zeolite minerals. Elsewhere, the NE-trending faults are developed parallel to an S_3 transposition foliation or spaced schistosity and/or transposed compositional layering and foliation (S1+S2).

The NW-trending faults exhibit the greatest amount of offset of geological contacts, dip steeply to moderately and show complex movement histories dominated by left-lateral strike-slip offset often followed by secondary dip-slip or oblique-slip reactivation. A case in point was mapped in the east channel of the East River, where a NW-trending, steep NE-dipping left-lateral strike-slip fault bearing sub-horizontal slickensides, shows overprint by N- to NE- plunging slickensides. This composite movement has resulted in roughly 7 cm of offset of a quartzose segregation in gneisses of the Hartland. The NW-trending faults are lined by zeolites, calcite, graphite, and sulfides. Composite offsets average a few cms to more than 35 cm but local offset may exceed 100 meters in brecciated zones. The NW-trending faults may have been structurally controlled initially by an anisotropy produced by A-C joints related to southward-plunging F_3 folds and/or by the NW-trending S_1+S_2 metamorphic fabric of the bedrock. Thus, New York City is cut into blocks by the intersection of these two important fault sets. Protracted dislocations along the NW-trending faults may be the result of stress propagated through the continental crust along oceanic fracture zones in response to spreading of the North American plate away from the mid-oceanic ridge of the Atlantic Ocean. Field observations support a conclusion that the NW-trending faults are, by far, the most seismically potential faults in the region. As an example, in the New York Botanical Garden, a NW-trending fault has produced post-Pleistocene diversion of the Bronx River from its former channel.

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