

BRONX RIVER DIVERSION: NEOTECTONIC IMPLICATIONS

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ABSTRACT

Nearly all of the rivers draining the Manhattan Prong physiographic subprovince in New York City and vicinity flow southwestward in wide NE-SW-trending strike-valley lowlands underlain by the Cambro-Ordovician Inwood Marble. For most of its course, the Bronx River flows in such a strike-valley lowland. However, just at the point where the NW-SE-trending Mosholu fault offsets this marble lowland, the Bronx River leaves the lowland and flows southward across the more-resistant gneisses and schists of the Hartland Formation in the narrow N-S-trending Snuff Mill gorge.

Schuberth (1968) advocated that the Bronx River started to erode the Snuff Mill gorge in Miocene time (15 million years ago) by finding a weak zone in the schist along a N-S-trending fault. By contrast, Kemp (1897) made a convincing case for a postglacial age (possibly 13,000 years ago) for the Bronx River's diversion into the Snuff Mill gorge. Subsurface data demonstrate that valley-fill sediments NE of the point of diversion include a clay overlying a probable till. We infer that this clay was deposited in a lake which formed when the Bronx River's former path to the SW was blocked.

We infer that the mechanism of blockage was neotectonic uplift of the East 204th Street bulge, a bedrock barrier situated on the footwall block of the NW-trending, oblique-slip Mosholu fault at the exact point where the Bronx River was diverted. Given the history of time-separated seismic activity in New York City, the possibility that a damaging earthquake will affect this densely populated area should **not** be ruled out.

KEYWORDS

Drainage Anomaly, Faults, Geomorphology, Glaciology, Mapping, Seismicity, Structural Geology.

INTRODUCTION

An important aspect of any earthquake is whether or not the Earth's surface is permanently elevated and/or ruptured. No specific quantitative relationships have been established, but the proposition seems generally true that no surface deformation accompanies small-magnitude earthquakes but may accompany large-magnitude earthquakes. New York City has experienced small-magnitude historical earthquakes none of which has evidently been accompanied by surface deformation and/or ground breakage. We have proposed (Merguerian and Sanders, 1996a) that the diversion of the Bronx River out of its open strike-valley lowland and into the Snuff Mill gorge was the river's response to a surface bulge along the Mosholu fault. If our interpretation of this drainage anomaly is correct, then it implies the existence of a neotectonic uplift sufficiently large to dam- and divert the Bronx River. Here, we elaborate on this inferred neotectonic feature and emphasize its implications for the earthquake-hazard situation for the New York metropolitan area.

GEOLOGIC SETTING

The Bronx, which spreads across four 7.5-minute topographic quadrangle maps of the U. S. Geological Survey (Figure 1A), is situated near the southern end of the Manhattan Prong, which is one of two southwestward extensions of the New England Upland physiographic province of the Northern Appalachians. The Manhattan Prong is a region of low, rolling elongate ridges and valleys that is underlain by metamorphic rocks of Proterozoic- and Early Paleozoic ages that have been folded. Fold axes plunge predominately toward the SW. Deep weathering and - erosion of these folded layers have created the NE-SW-trending valley-and-ridge aspect of the countryside. This ridge-and-valley morphology is limited to the western part of The Bronx. In the eastern Bronx, exposures of bedrock are rare. Parallel elongate topographic features are present, but the hills are composed not of resistant bedrock but of glacial deposits, and the direction of elongation is NNW-SSE. This topographic texture is exemplified by the trend of Throgs Neck and by the alignment of streets in the SE Bronx south of Pelham Parkway and southeast of the Bruckner Expressway (for example in the Hunts Point, Parkchester, and Morris Park sections).

Bedrock Geology

The bedrock underlying the Manhattan Prong (Figure 1B) consists of amphibolite-facies Proterozoic- to Lower Paleozoic rocks that have been deformed into structures that largely trend NE-SW. Because the metamorphism took place at great depth (possibly as much as 30 km), the exposure of these rocks at the Earth's surface is possible only as a result of great vertical uplift and enormous erosion.

In southeastern New York and western Connecticut a steeply oriented, annealed ductile Taconian lithotectonic boundary known as **Cameron's Line** (Rodgers et al, 1959; Merguerian, 1983, 1985, 1987) separates essentially coeval-, but contrasting metamorphosed lithofacies of Lower Paleozoic strata. To the east of Cameron's Line, the Hartland Terrane (**C-Oh** in Figure 1B) consists of well-layered, quartzofeldspathic gneiss, mica schist, amphibolite, and garnet-

quartz granofels. The rocks of this terrane are inferred to represent former deep-water oceanic sediments and interlayered volcanic rocks that were deformed in a deep-seated continent-facing subduction zone. Many workers consider them to be correlatives of the **Taconic sequence**. Allochthonous Taconic rocks, formerly deposited across the slope and rise, are also found to the west of Cameron's line as parts of the Manhattan Schist (**Є-Om**; Figure 1B).

Autochthonous rocks are also found to the west of Cameron's Line and include the Proterozoic Fordham Gneiss (**Yf**), consisting of felsic- to mafic gneiss and orthogneiss with lesser biotite schist and diopsidic calc-silicate rock. In Westchester County, New York, subunits of the Fordham are unconformably overlain by rocks of the **Sauk Sequence** (Hall, 1968) including the Cambrian Lowerre Quartzite (**ЄI**) and the Cambrian- to Ordovician Inwood Marble (**O-Єi**). The Sauk Sequence is disconformably overlain by the **Tippecanoe Sequence**, here represented by the Manhattan Schist (**Om**) of presumed mid-Ordovician age. In marked contrast to the former oceanic parentage of the Hartland sequence, the western basement-cover sequence represents former 1.1 Ga continental crust (**Yf**) and overlying 500-million-year-old shallow-water shelf sediments (**ЄI + O-Єi = Sauk Sequence**) and deeper-water foreland-basin sediments (**Om = Tippecanoe Sequence**), now metamorphosed to gneiss, quartzite, marble, and schist (Figure 1C).

In NYC, belts of rock originally lumped together as the Manhattan Schist and thought to be *in situ* above the Inwood Marble (in sequence-stratigraphic terms, belonging to the Tippecanoe Sequence) consist largely of aluminous rocks (**Є-Om** and **Є-Oh**) more or less correlative with the Inwood Marble, that have been intensely folded, sheared, and structurally imbricated along two major ductile faults (Merguerian, 1994, 1996). Thus, they are not *in situ*, but a part of the allochthonous **Taconic Sequence** (Figure 1D).

Geologic Structure

The earliest phases of deformation included three episodes of superposed isoclinal- to tight folds that prompted the growth of sillimanite and kyanite. Later, at least three lower-grade episodes of folding took place at crustal levels where conditions did not create intense metamorphism but retrograded earlier fabrics.

Two culminative episodes of superposed isoclinal- and shear folds (F_1+F_2) resulted in a composite regional foliation (S_1+S_2) in bedrock units. During D_2 , a penetrative foliation (S_2) formed axial planar to F_2 folds which produced a large-scale recumbent bedrock structure that strikes $N50^\circ W$ across Manhattan Island and dips $25^\circ SW$. Although the S_2 regional metamorphic grain of the New York City bedrock trends $N50^\circ W$, the northeast trends of the map contacts have been determined by F_3 isoclinal- to tight folds that are overturned toward the northwest and plunge SSE to SW at 25° . S_3 is oriented $N30^\circ E$ and dips $75^\circ SE$ and varies from a spaced schistosity to a transposition foliation commonly with the effects of pronounced shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared previously flattened (into S_2) quartz+kyanite lenses and -layers into ellipsoidal shapes.

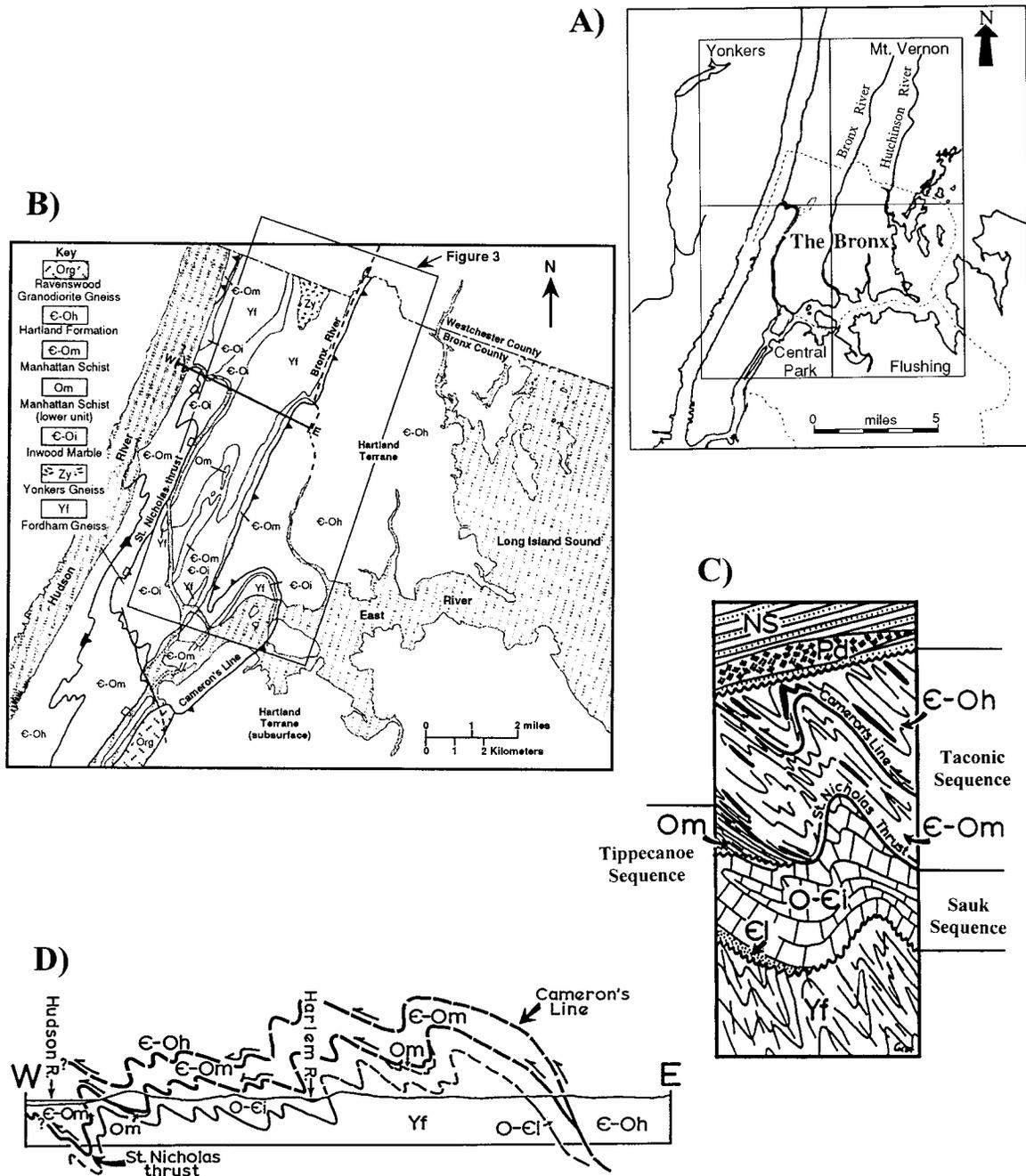


Figure 1. A) Index map showing the U.S. Geological Survey topographic quadrangles that cover The Bronx. B) Geologic map of the south end of the Manhattan Prong showing Cameron's Line, the St. Nicholas thrust and the Hartland Terrane. Rectangle shows location of Figure 3. C) Schematic tectonostratigraphic section of the major bedrock units of the New York City area. Formation abbreviations and ductile-fault contacts described in map 1B and text. D) Geologic section shows stacking of the two folded Taconian ductile faults (Cameron's Line and the St. Nicholas thrust) across the north end of Manhattan island eastward to the Bronx. Line of section shown on 1B. (Adapted from Merguerian, 1996; Merguerian and Baskerville, 1987, fig. 3, p. 139.)

Synchronous with D_2 , foliated rocks of the Sauk, Tippecanoe, and Taconic sequences were imbricated along two major syntectonic ductile thrust faults: (1) the St. Nicholas thrust and (2)

Cameron's Line. The **St. Nicholas thrust**, a Taconian frontal thrust, truncates the Manhattan Schist (**C-Om**) near its base. Moreover, along **Cameron's Line**, the Hartland Terrane (**C-Oh**) is in ductile-fault contact with the Manhattan Schist (**C-Om**). D_2 shearing along these two ductile thrust zones and kyanite-zone recrystallization during D_3 , together produced an annealed, highly laminated mylonitic texture within the affected zones.

Brittle Faults

Two contrasting, near-orthogonal brittle-fault sets cut the ductilely deformed rocks of NYC. A stereonet of poles to 118 surface faults (Figure 2A), shows a bimodal distribution (approximately $N30^\circ E$ and approximately $N45^\circ W$) of moderate- to steep faults although a scattering of gently dipping faults exists.

The NE-trending faults dip steeply to moderately and show dominantly dip-slip motion. Offsets of up to 1 m are present in zones up to 2 m thick. Locally, where they parallel NE-oriented mylonites (Cameron's Line and the St. Nicholas thrust), they are cataclastic and display greenish clay-, calcite-, and zeolite-rich gouge up to 30 cm thick. Commonly, they have been healed by quartz, calcite, or zeolite minerals. Typically, the NE-trending faults are developed parallel to and commonly disrupt an S_3 transposition foliation or spaced schistosity and/or transposed compositional layering and foliation (S_1+S_2).

The NW-trending faults also dip steeply to moderately and show complex movement histories. Figure 2B shows the poles to 14 left- and right-lateral oblique-slip and strike-slip faults. Of these, 80% were left lateral and 20% were right lateral. Commonly these have been reactivated to create secondary dip-slip- or oblique-slip offsets. Minerals present within the NW-trending faults include zeolites, calcite, graphite, and sulfides. Composite offsets along the left-lateral faults average a few cm to more than 35 cm but locally they occur as major faults in brecciated zones. Contacts along the right-lateral faults have been displaced enough (100 m - 200 m) to show offset on 1/24,000-scale maps.

Pleistocene Deposits

A long-standing debate about the Quaternary glacial history of the New York City region is whether the glacial features hereabouts were caused by the advance- and retreat of one continental glacier or by more than one such glacier. A key factor involved in this debate is direction of flow of the glacial ice. One of our chief contributions to knowledge of the local Quaternary record is an emphasis on the features by which the direction of flow of a former glacier can be established. We follow the principle that a continental glacier can be characterized locally by a distinctive flow direction. Application of this principle has led us to resurrect, but to modify in several important respects, M. L. Fuller's (1914) classification of the Quaternary deposits of Long Island that most of our contemporaries have cast aside.

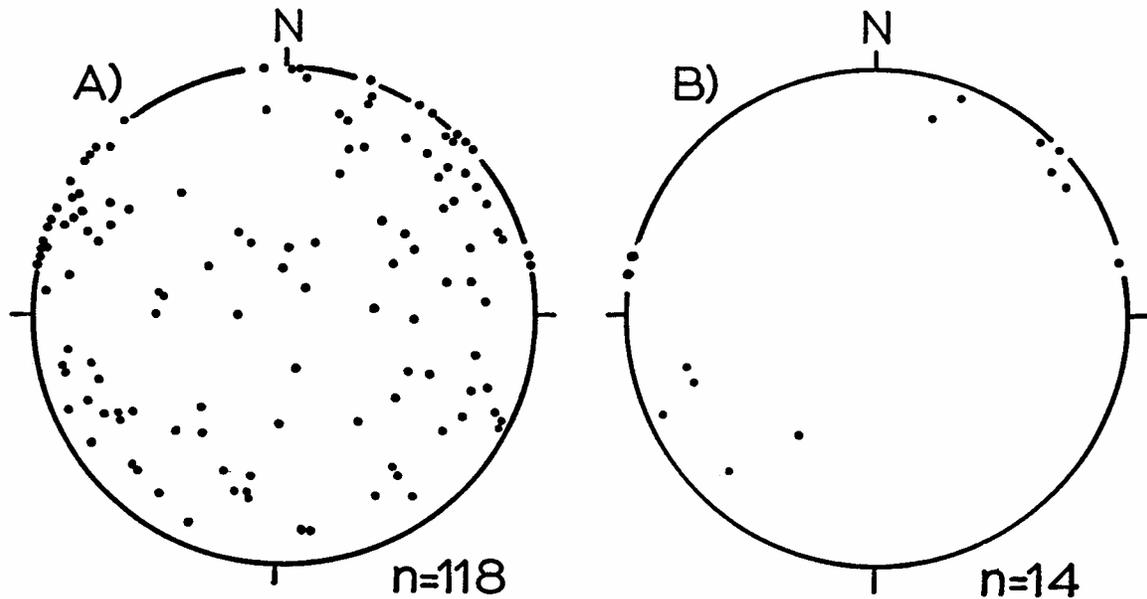


Figure 2. Equal-area stereonet showing poles to mapped surface faults. Northern half of net used for poles to vertical faults. **A)** Poles to 118 faults showing bimodal distribution of NE- and NW-trending fault sets. The dips of the NE-trending set (average trend of N30°E, essentially parallel to the long axis of Manhattan) are steep to moderate. **B)** Poles to 14 strike-slip faults with a dominantly NW trend. The dips of the NW-trending set (average trend of N45°W) are also steep to moderate.

Our proposed classification of the Pleistocene deposits of the NYC region includes products of five glacial advances (Sanders and Merguerian, 1994, 1995, 1996). We designate each of the tills by a roman numeral, starting with I at the top and ending with V at the bottom. According to us, Glacier I flowed from NNE to SSW and did not reach most of Long Island. Glacier II, flowing from NNW to SSW deposited the Harbor Hill Moraine. Glacier III, with several advances and retreats, deposited Fuller's Manhasset Formation and the Ronkonkoma Moraine. Glacier IV flowed from the NNE to the SSW and Glacier V, from NNW to SSE.

HYPOTHESES OF ORIGIN OF THE SNUFF MILL GORGE

Northeast of the NW-SE-trending Mosholu fault (of Baskerville, 1992), the Bronx River flows SW in a wide NNE-SSW-trending strike-valley lowland underlain by Inwood Marble. Southwest of the fault is the NNE-SSW-trending Webster Avenue lowland, another equally wide valley underlain by the Inwood Marble, slightly offset from the former and lacking a modern-day river but in which the Bronx River undoubtedly flowed during the past. Just at the point where the NNE-SSW-trending marble lowland has been offset, the Bronx River leaves it and flows across the more-resistant gneisses and schists of the Hartland Formation in the narrow N-S-trending Snuff Mill gorge. (See Figures 1B and 3.) This is a first-order drainage anomaly.

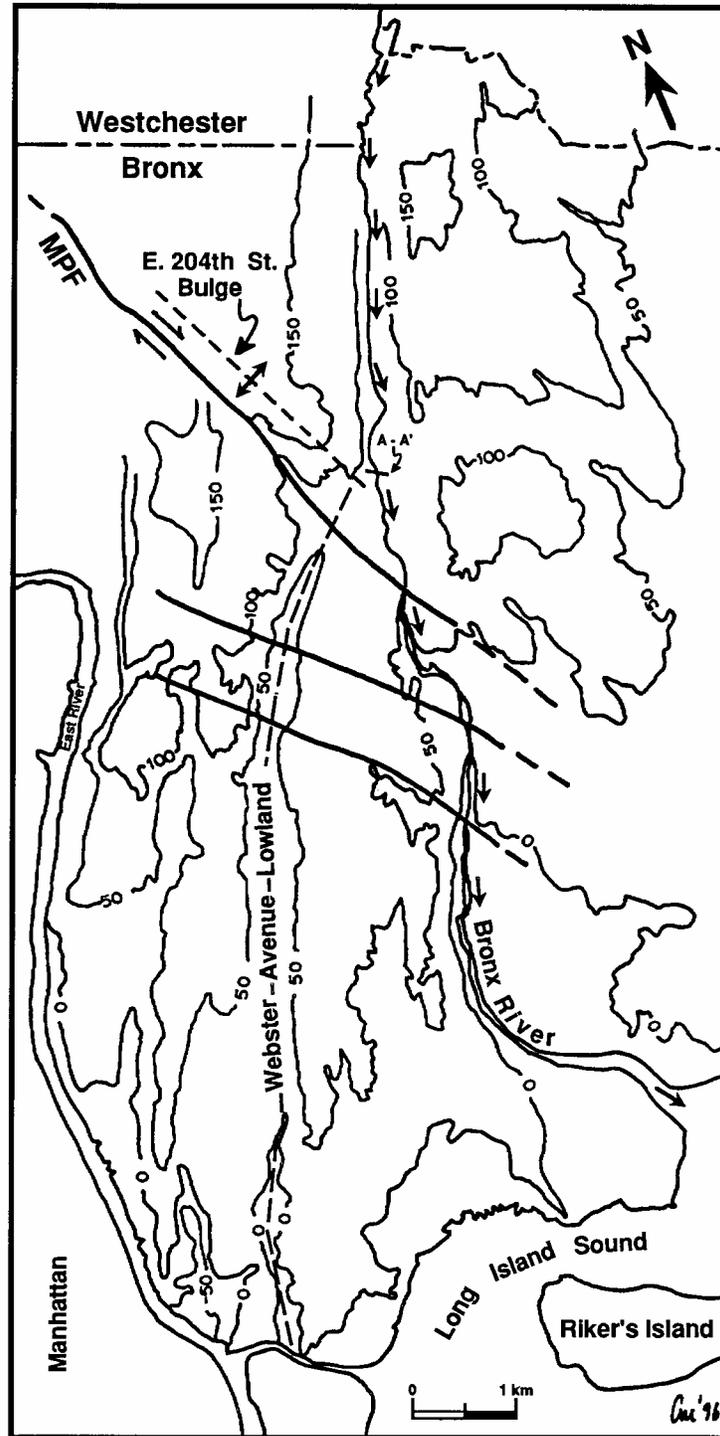


Figure 3. Index- and bedrock-contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including the Mosholu fault (MF), the Bedford Park fault (BPF), the Fordham fault (FF), the 204th Street Bulge, the area of the Snuff Mill gorge, and section A-A' of Figure 4. The Webster Avenue Lowland marks the previous course of the Bronx River. Subsurface- and fault data from Baskerville (1992), and engineering records of the New York City Subsurface Exploration Section.

Schuberth (1968) postulated that the Bronx River started to erode the Snuff Mill gorge in Miocene time (15 million years ago) by finding a weak zone in the schist along a N-S-trending fault. By contrast, Kemp (1897) inferred that the diversion of the Bronx River was a byproduct of Pleistocene glaciation. Kemp's evidence for postglacial diversion effectively refuted the Miocene age proposed by Schuberth. In addition, we have not found the supposed weak zone in the schist along a N-S-trending fault. In evaluating how glacial action might have diverted the river, Kemp (1897) entertained four hypotheses as possible causes: (1) "a gravel bar or a morainal deposit in the old channel somewhere between Bedford Park Station and tide water;" (2) the present gorge is "an old depression from an earlier period, which perhaps a temporary stoppage of the old channel by the ice sheet had caused the river to clear of possible gravel, etc.;" (3) "during the presence of the ice-sheet (*sic*), a sub-glacial, or perhaps in part a supra-glacial stream down the upper valley of the Bronx found its way out over this ridge and began to cut it down; being prevented issuing by the old channel because of the presence of the ice;" and (4) "the present channel has always been the drainage line of the Bronx to which it has consistently adhered, while the westerly depression has been caused by the small stream now occupying it; and that the brook has excavated this valley at a little slower rate than the Bronx has its present one."

Kemp reluctantly preferred hypothesis (3) and concluded that the age of diversion was postglacial. We fully accept Kemp's postglacial age assignment. However, we do so chiefly for a reason he did not mention, namely that 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 transverse profile from its present narrow V shape (See Figure 3.) to a broader U shape and would have polished- and striated its bedrock walls. Therefore, we think that the narrow V profile of the Snuff Mill gorge and absence of glacial polishing on the jagged fresh bedrock exposed in the valley walls are powerful arguments in favor of a postglacial age for the origin of the Snuff Mill gorge.

We add a fifth hypothesis to Kemp's list of four, namely that postglacial local uplift of a bedrock high (E. 204th Street Bulge of Figure 3.) along the NW-SE-trending Mosholu fault blocked the offset marble lowland, dammed the Bronx River, and thus caused a lake to form upstream from the present site of the Mosholu Parkway. Water spilling out of this lake to the south, possibly reoccupying the beginnings of a valley that had been eroded during earlier ice blockage of the Webster Avenue lowland, eroded the N-S-trending Snuff Mill gorge in the New York Botanical Garden, the route the Bronx River takes where it crosses the Hartland Terrane.

Kemp (1897) mentioned a bedrock ledge between the two lowlands, but did not consider tectonic movements among his possible hypotheses of diversion. According to our interpretation of the glacial history, at least three glaciers (Nos. II, III, and V) would have crossed the NNE-SSW-trending lowland and at least two other glaciers (Nos. I and IV) would have flowed **down** the marble lowland. Retreat toward the NNW of any one of the glaciers that flowed to the New York City region from the NNW could have uncovered the part of the marble lowland N of the Mosholu Parkway while ice remained in and blocked the Webster Avenue lowland. This situation could have started the Bronx River flowing across the Hartland Terrane. But the lack of glacial striae or -polish on the bedrock walls of the Snuff Mill gorge and the postglacial age of

the clay in the valley fill on the E. 205th Street-Burke Avenue section (Figure 4) demonstrate that the main cutting of the gorge must have been postglacial.

DISCUSSION

Our field observations support the contention that the NW-trending faults of the Manhattan Prong have indeed been major players in the localization of offset of mapped geologic contacts. Two of these fractures deserve mention in this connection: (1) the famous 125th Street fault in Manhattan and (2) the Mosholu fault in The Bronx.

Merguerian was able to carry out subsurface studies of the 125th Street fault during construction of the Third New York City Water Tunnel project. He found a complex zone of highly crushed fault breccia more than 90 m thick (Merguerian, 1996). Here, in a zone of highly fractured Manhattan Schist (**C-Om**), the 125th Street fault strikes N35°W and dips 55° to 75° SW and cuts across both the tunnel line and the steeply dipping foliation in the schist. Within the fault zone, in the overhead roof of the tunnel, many 3- to 15-m-scale blocks of the Manhattan had been rotated at least 90° about a vertical axis. The blocks remained internally coherent within an otherwise broad zone of cataclastic rock. Clearly, this observation indicates that along the 125th Street fault, much of the motion has been strike slip. Indeed, slickensides 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 in one area (Eileen Schnock, personal communication). Cross-fault offset of the prominent Manhattan Ridge indicates more than 200 m of composite right-lateral slip along the 125th Street fault valley, a valley greatly enlarged by Pleistocene glaciers II, III, and V flowing from the NW.

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 on the 125th Street fault. We consider them, along with the Dobbs Ferry fault in Westchester, to be seismically capable NW-trending faults with a demonstrable protracted history of offset of geological features. We have not been able to demonstrate that earthquakes have occurred along the faults in New York City in historic times, but offer circumstantial evidence from the Bronx River, that fault-localized neotectonic surface deformation may have occurred and that it occurred in post-glacial times.

We cannot prove that the surface displacement of the bedrock of the East 204th Street bulge accompanied an earthquake generated by sudden slippage along the reactivated Mosholu fault nor can we prove that surface rupture took place. However, in many seismically active zones, surface displacement, such as the bulging mentioned, typically accompanies energetic earthquakes. No surface breakage of crustal rocks has been previously reported in connection with any of NYC's magnitude ~5.0 earthquakes of 1737, 1783, and 1884. In fact, no historic earthquake has caused recognizable surface rupture of a fault anywhere along the east coast seismic zone.

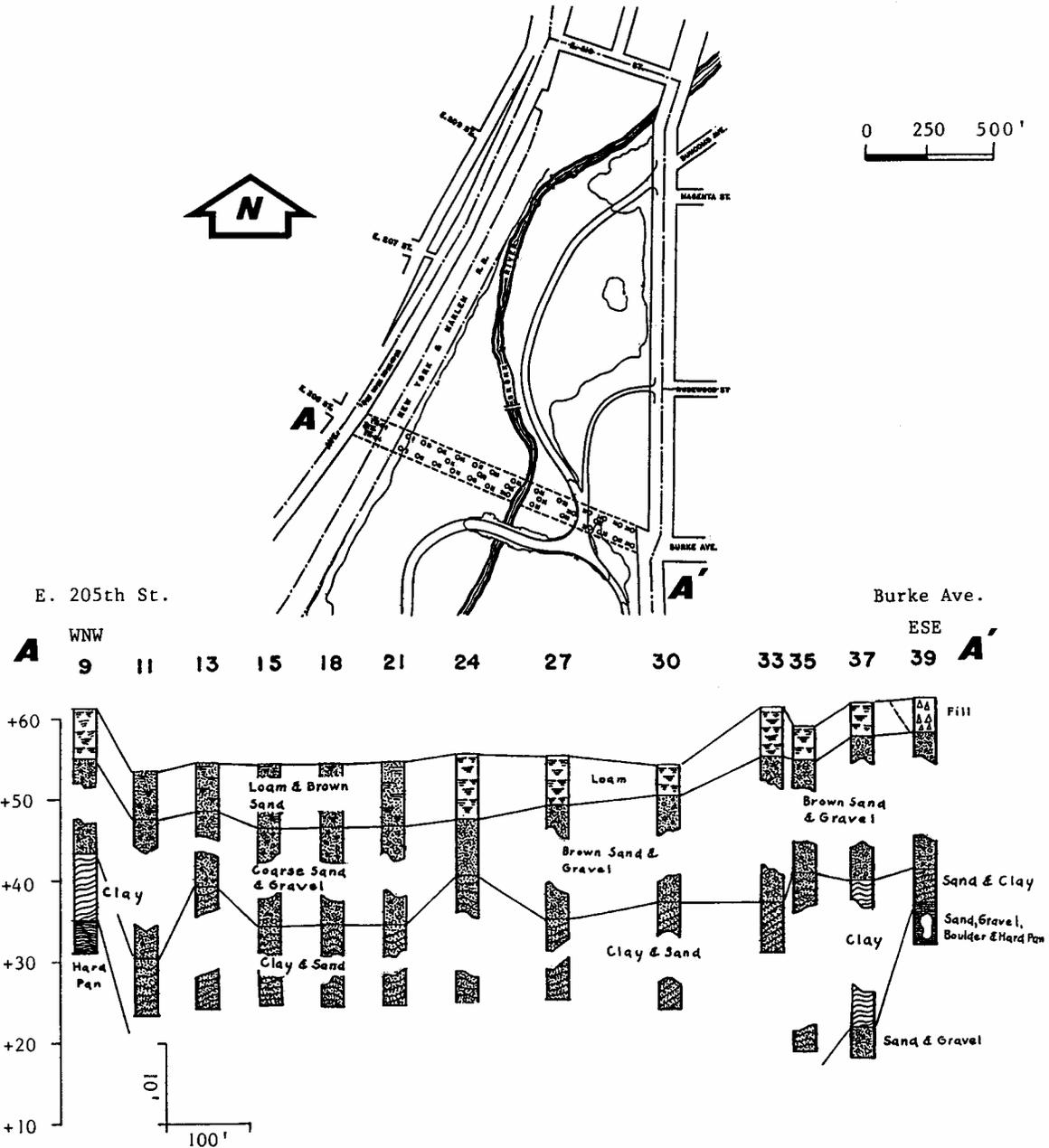


Figure 4. Index map and subsurface stratigraphy from E. 205th Street east-south-eastward to Burke Avenue in the Bronx, upstream of point of diversion of Bronx River based on records of borings assembled in the 1930s by the WPA rock-line map of the Bronx. Line of section shown on Figure 3. Index map shows 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.

Indeed, if our interpretation of the neotectonic diversion of the Bronx River is correct, it would be the first example that earthquake-generated fault motion affected the land surface in New York City. Given the known history of time-separated 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.

CONCLUSIONS

The anomalous course of the Bronx River through the narrow, N-S-trending, schist-walled Snuff Mill gorge (as contrasted with a course to the SW via the broad Webster Avenue lowland underlain by the Inwood Marble) resulted from blockage of the Webster Avenue lowland. We infer that this blockage resulted from neotectonic uplift of a block of bedrock (the East 204th Street bulge) along the NE side of Mosholu fault, which ended the former flow of the Bronx River to the SW along the Webster Avenue lowland.

We reject both Schubert's (1968) inference of a Miocene age (15 million years ago) and his view that the Snuff Mill gorge follows a weak zone in the schist along a N-S-trending fault. We concur with Kemp's (1897) assignment of a postglacial age (possibly 13,000 years ago) for this diversion but disagree with Kemp that as part of the diversion, the Bronx River "surmounted" a "bedrock reef." Precisely because the Bronx River could not "surmount" the newly elevated East 204th Street bulge, it formed a lake. Subsurface data (borings for the E. 205th Street-Burke Avenue sewer-line section NE of the bedrock barrier), indicate that a unit of clay, an inferred lake deposit formed when the bedrock dam blocked the Bronx River (See Figures 3 and 4.), overlies a probable till. Eventually, the outflow from this lake eroded the Snuff Mill gorge. A postglacial age of diversion is further demonstrated by the absence on the jagged walls of the Snuff Mill gorge of evidence of glacial erosion (for example, smoothed-, polished- and striated rock surfaces). We have presented evidence from the region where the Bronx River crosses the Mosholu fault, that localized surface deformation may have occurred and that it occurred in post-glacial times.

ACKNOWLEDGEMENTS

We are indebted to **Lawrence Ebbitt** and **Michael Greenman** of the Subsurface Exploration Section, Bureau of Building Design, Department of General Services of the City of New York for their timely help in tracking down archival subsurface information. The continued willingness to share subsurface information and assistance of **Eileen Schnock** and **Scott Chesman** of the NYC Department of Environmental Protection (Geology Section) are gratefully acknowledged. **Dr. J Bret Bennington** of Hofstra University assisted in the computer formatting and labeling of Figures 1 and 3 and **Jessica Levine**, also of Hofstra University, assisted in figure preparation.

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