

Tunnel Vision: Subterranean Paradise or “Name That Quake”

Hofstra University Distinguished Faculty Lecture Series
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Introduction

Since late May of 1998 I have been engaged in an absolutely thrilling research project mapping the structural geology of rocks exposed in the Third New York City Water Tunnel in western Queens. Varying in depth from 690' to 760' below the surface and extending in a curved path from Maspeth northeastward to Woodside thence westward to Long Island City, the tunnel has been excavated by a 300' long tunnel boring machine or TBM (Figure 1). Beginning in October 1996, the TBM has bored a cylindrical 23' diameter, 5 mile long transect through metamorphic rocks of the Appalachian mountain chain in an area where no natural surface bedrock exposures exist. The new tunnel, which will be lined with concrete starting in April 2000, has exposed a treasure trove of new information on the subsurface bedrock geology of New York City. I have had the opportunity to explore and verify the existence of many geologic features and contacts formerly mapped in adjacent areas and have discovered many new geologically important features. Perhaps the most important of these is the corroborative proof that offset along NW-trending faults is the youngest geological event to affect the region. A hypothesis I have promoted from surface mapping in The Bronx, this new supporting data forces a new evaluation of the earthquake potential of New York City.



Figure 1 - The front cutterhead and thrust assembly (business-end = 84' length and 23' diameter) of the Tunnel Boring Machine that formerly operated beneath western Queens. With a total length of nearly 300', the complete machine excavates, processes, and removes the rock chipped by the cutters. The cutterhead rotates against the raw rock face with thrust applied hydraulically by mechanical contact from behind against the sides of the bored tunnel. The TBM holed through beneath Long Island City in October 1999 after three years of nearly continuous subsurface mining.

The purpose of this paper and associated slide-illustrated lecture is to share some of the specialized techniques of TBM tunnel mapping I have developed over the past 22 months and to discuss the seismic implications of the well-displayed fault history of the region. Unfortunately, some of the subsurface geological information is proprietary until some issues between the City of New York and the tunneling contractor are settled. Suffice to say that mapping has documented the presence of thousands of faults in the subsurface and has shown that the youngest set of these correlates to geologically young, post-glacial NW-trending faults I have previously mapped in the Bronx that offset the course of the post-glacial Bronx River. The presence of NW-trending brittle faults is well-known in NYC and over the years I have not only documented their existence but have championed their potential as seismic failure zones. History records at least three notable seismic events in the New York City area since 1737. As such, future seismicity in the New York City area can not, and certainly should not be ruled out as we face a potentially serious human disaster and multi-billion dollar economic debacle.

The Queens Tunnel

The Queens Tunnel is a 23' 2" diameter circular tunnel that has been mined 655' to 763' below sea level in west-central Queens (Figure 2) by the world's most powerful, high-performance tunnel boring machine (TBM). Upon completion to yield a five-mile long, 20'-wide concrete-lined pressure tunnel, the Queens Tunnel will serve as a crucial link in completing Stage 2 of New York City Water Tunnel #3 (CT3), by connecting the already constructed Stage 2 Brooklyn Tunnel in Maspeth, Queens (Shaft 19B; base at -655') with CT3, Stage 1 beneath Long Island City, Queens (Shaft 16B; base at -763'). A significant increase in water pressure and delivery capability and the ability to shut down and maintain components of the two existing distribution tunnels are the two main goals of this huge construction project.

Work on the Queens Tunnel began in September 1995 with site mobilization and excavation of starter- and tail tunnels beneath Shaft 19B utilizing traditional drill-and-shoot technology. Underground fabrication of the TBM commenced by September 1996, after a year of on-site utility and equipment installation. The TBM, which had been shipped from Chesterfield, England in June 1996 and delivered in 28 truckloads of assemblies and parts, was designed and engineered by the Robbins-Atlas-Copco Company. Since the inception of mining northeastward from the Maspeth (Shaft 19B) in late October 1996 and completion in October 1999, five miles of tunnel have been excavated, producing a 23' 2"-wide, subhorizontal fresh bore hole through this deeply eroded crystalline portion of the Appalachian Mountain chain. After the completion of mining, the TBM was disassembled and hoisted out from the Maspeth Shaft (19B), which, by the end of the tunneling excavation, was nearly five miles away from where the TBM was located. Preparations for the installation of forms for a pressure-injected concrete lining are already underway.

Since late May 1998, I have had the unique opportunity to map the structural geology of the Queens Tunnel at a scale of 1"=10' providing a detailed record of the subsurface geology of Queens, a region not particularly well known in the Michelin travel guides for its rock outcrops. The dog-leg shape of the tunnel (a NE-trending leg of 10,000' and a NW-trending leg of 15,989' - See Figure 2.) offers a deep cross-sectional view of the region. Between May 1998 and

February 2000, I have mapped more than 25,000' of the exposed tunnel (roughly 1.9 million feet²). I have employed some new techniques that I can share in this paper and will present some of the cartographic results and digital imagery from underground. Having spent the last 20+ years mapping metamorphic rocks at the surface throughout the Appalachians and specifically in and around New York City allowed me to examine the geology with an "experienced" eye but could not have prepared me for the geological three-dimensionality experienced in the tunnel.

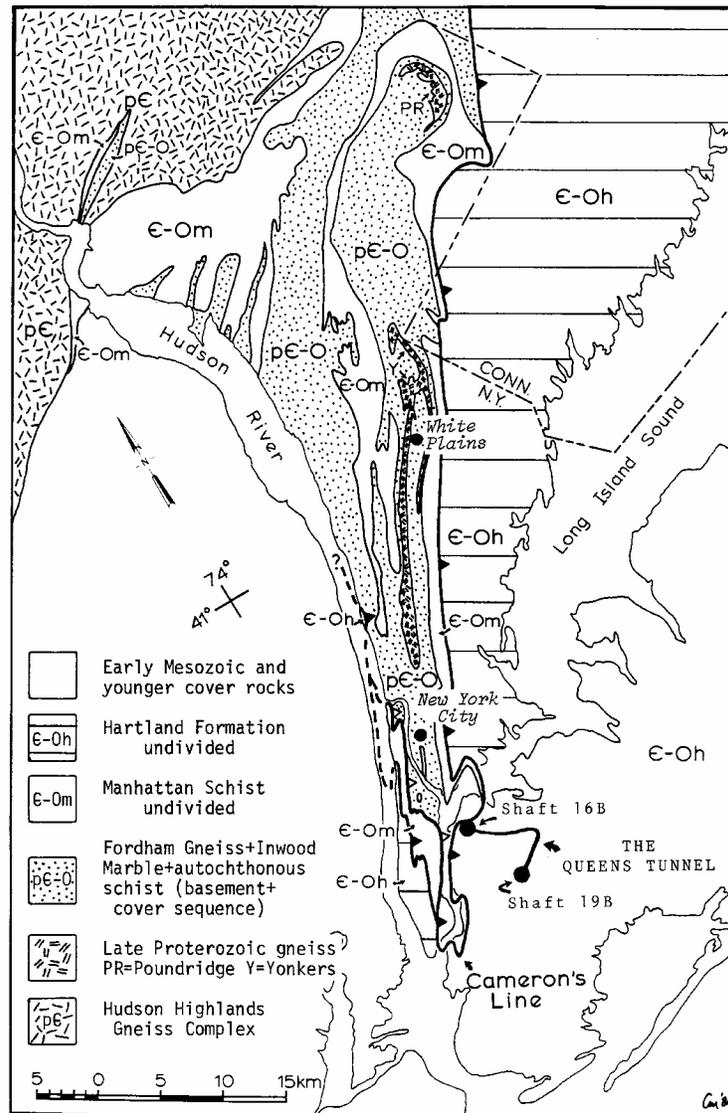


Figure 2 - Simplified geological map of the Manhattan Prong showing the distribution of metamorphic sequences in the vicinity of New York City. The Queens Tunnel (Stage 2, NYC Water Tunnel #3) is rooted in Fordham Gneiss and extends for nearly five miles northeastward from Shaft 19B in Maspeth to Woodside where a 116° curve modifies the tunnel trend to northwesterly. When completed, the Queens Tunnel will terminate at existing Shaft 16B (already constructed during Stage 1) in the subsurface of Long Island City.

Regional Geology

New York City is situated at the extreme southern terminus of the Manhattan Prong (See Figure 2.), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terranes of New England. The Queens Tunnel is nestled within the Fordham Gneiss, a zone of highly sheared metaplutonic rocks of Proterozoic age that were already part of North America during the Taconic orogeny when a former deep-seated ductile shear zone known as Cameron's Line formed.

Field Mapping in a Cylinder

In late May 1998 I began a geologic survey of the Queens Tunnel, mapping the structural geology, including the development of a detailed database on orientation and characteristics of specific faults and fault zones. Mapping has delineated an amazingly complex structural history for the rocks of the Queens Tunnel. The presence of superposed folds and the multitude of faults (both ductile- and brittle varieties) serve to complicate the geology beyond simple understanding. After a steep learning curve, structures can be visualized in three-dimensions and mapped accurately as described below. Great pains were taken to map and document the lithology, folds, fault- and joint patterns, paying particular attention to structural sequence and to note any geological controls on the integrity of the tunnel perimeter.

Phase One - The Field Map

Never fully realizing the scope and dimension of the project, I first began by slicing up paper cylinders to see how planar and curved surfaces of different orientation (then folds and irregular masses) would look with the cylinder unwrapped. After calculating the circumference of the tunnel, I constructed a template for mapping that unwrapped the cylindrical tunnel section onto flat graph paper (10 boxes/inch) measuring 10" by 7". Recognizing that a few feet in the crown were simply not available for view (because of a tunnel-length 50" diameter ventilation duct), the 72.75' circumference of the tunnel was reduced to the observable 70' on the mapping template. Thus, the template for each individual map sheet covered 100' of exposed tunnel, as measured parallel to the centerline, or 7,000 square feet of cylindrical area. Pre-cut 8.5" x 11" frosted mylar was used for the archival field maps because the overall humid to wet environment precluded the use of paper-based maps underground. Surveyed station numbers, which were painted every five feet on the left wall along the springline, were relied upon for location and the field maps were carefully drafted underground with ink and scale-constant mylar in 100' sections at a scale of 1" = 10'. A full #00 Rapidograph and Magic-Rub eraser were the preferred "tools of the trade" for this phase of the mapping, where interpretation and accurate drawing of the structural features were conducted.

Mapping was complicated at times by visual obscurity in the form of "variations of darkness", walls and inverts covered by muck (ground up rock and TBM fluids), dust, leaking water, support, and in some cases grout (a chemical substance injected into leaking geologic features to retard water flow). A tunnel-length 24"-wide belted muck conveyor system was

installed on the left wall which, although of an open design, managed to obscure some of the geology. The invert area was largely obscured because of the locomotive trackway and muck thrown from the conveyor. A clear view was further hindered by a 50" air duct suspended from the crown, four sets of pipes along the length of the tunnel right wall, and various large-scale mechanical installations for pumping, power, and muck handling. Power washing the tunnel walls proved to be the single greatest help in overcoming these related problems. A diver's halogen flashlight proved an essential tool.

Given the time constraints and the enormous scope of the tunnel mapping, on average 1.5 hours were allocated for each 100' section of tunnel mapped underground. After the mapping of each 100' section was completed, digital images of important geological relationships were taken (roughly 2,500 total to date) and later keyed with descriptions to the maps in a searchable database. Beginning in May 1998, raw digital images at 1280 x 960 resolution and 16.7 million colors were imaged in SHQ (super-high quality) mode and saved in numerous formats (Zip, Jaz, CD-R) for archival protection. Images were processed using Adobe Photoshop 5.0. Almost all images needed to be brightened and increased in contrast because of the generally poor lighting conditions but excellent results, including the ability to annotate features, were obtained using this non-film imaging method. The ability of the digital camera to auto-focus in dim light and compensate for exposure was of great utility in this unique field environment. Kodachromes were also taken but needed severe bracketing (up to 2 stops beyond normal aperture settings) because of variable lighting conditions. Accurate focusing was especially difficult in the low-light conditions.

Phase Two - Field Checking and Fault Data

Field checking of contacts and measurement and analysis of faults and joints took place during subsequent field checks. The field maps were first checked when the faults and joints were individually surveyed to determine their characteristics (orientation, width, filling type and consistency, roughness, seepage, displacement, and mineral coatings) for a fault- and joint database. A secondary field check was made when the University of Trondheim Fracture Class system was applied to the entire tunnel over a seven-day period, and finally checked again when additional support and water leakage patterns were measured over a five-day period.

The presence of iron in the train tracks, piping, ductwork, and the conveyor system precluded the use of a Brunton (magnetic) compass for standard strike-and-dip measurements of planar and linear features. I constructed a laser-pointer leveling device that was able to accurately measure the orientation of features with respect to the tunnel trend. By climbing up on the piping of the right tunnel wall and having a clear view of the left wall, features such as faults, foliation, and dikes were relatively easy to view and trace across the crown. Great care was taken to properly calibrate the device to the centerline trend in the various curves (four) of the tunnel. Dips were measured using a Brunton compass and checked by trigonometric calculation from the field maps. Strikes were checked from the field maps, as well. By the end of this phase an upgraded and annotated mylar-and-ink field map was produced for each 100' section of the tunnel.

Phase Three - Final Map Preparation

Final drafting of the integrated field maps took place after the field checks had been completed. Mylar and ink were deemed the best media choice for this phase. Final maps were redrawn at scale (1"=10') from the archival base map which incorporated any new information surveyed during Phase Two. During the final-drafting stage, digital images from that 100' section were carefully examined for added accuracy. The final maps were checked for errors and then scanned at 400 dpi resolution as *.gif files and ported to Photoshop where color enhancement was added. As a side project, with the assistance of my students, we were able to "pick" the true 24-bit colors of distinctive units from the digital images and "colorize" them on the map units and explanation. Once in this digital format, variable scaling and piecing together of maps into longer sections is facilitated. Naturally, the final Queens Tunnel Map Portfolio is a work in progress whose preliminary version includes all basic geologic data on 8.5" x 11" digitally scanned map sheets that each show 100' of the tunnel. With mapping complete, 250 map sheets cover the entire Queens Tunnel. A thorough sampling was completed in March 2000 and a petrographic study is planned for 2000/2001 (Phase Four). Plans are underway to publish the Queens Tunnel in DVD format as a virtual tunnel, with a continuous mapping stream rerolled in real time into cylindrical format. Researchers will embark on an on-line virtual journey or walk-through of the tunnel with digital image "outcrops" to examine along the way. Petrographic imaging, geochemical data, and fault data will also be presented via "hot spots" in the virtual tunnel. Thus, traditional- and computer-based mapping techniques were of great utility in accurately recording the geology of the Queens Tunnel.

Geology of the Bronx River Channel

In a joint study two years ago, Merguerian and Sanders (1997) documented the neotectonic effects of seismicity on offset of the Bronx River along the NW-trending Mosholu fault in the Bronx, New York (Figure 3). My studies have continued and now include our undergraduate geology students interested in pursuing field research at Hofstra University. Together, these studies have helped outline the basic structural geologic framework of the NYC area, the focus of my professional research efforts over the past twenty years, and have provided a geologic framework that has now been refined by recent work in the Queens Tunnel. As described below, these new insights corroborate data from the Bronx River.

North of the New York Botanical Garden, near the Mosholu Parkway in the Bronx, the NW-SE-trending Mosholu fault offsets the Bronx River valley (a NNE-SSW-trending strike-valley lowland underlain by the Inwood Marble) from the Webster Avenue lowland (another NNE-SSW valley also underlain by the Inwood Marble). The Amtrak-Metro North railway follows these two lowlands. Just at the point of offset of the marble lowland, the Bronx River leaves its former wide NNE-SSW-trending strike-valley lowland and occupies a narrow N-S-trending gorge, here named the Snuff Mill gorge, cut across the more-resistant Hartland Terrane.

The geologic literature contains two concepts about the origin of the Snuff Mill gorge, which is a first-order drainage anomaly. According to Schuberth (1968, p. 88), the Bronx River formerly followed the marble lowland, but about 20 million years to 30 million years ago, was

diverted into its N-S-trending course following a N-S-trending fault along which Schubert contends the schist has been deeply decomposed.

By contrast, Kemp (1897) proposed four hypotheses of diversion, all but one of them connected with Pleistocene glaciation. Although he preferred the concept of ice blockage of the Webster Avenue lowland as the mechanism for causing the Bronx River to cut the Snuff Mill gorge, Kemp admitted that the duration of the ice-blocking episode was embarrassingly short in comparison to the time required to erode the gorge. Kemp mentioned an outcrop of gneiss just E of the RR culvert over what he took to be an abandoned channel and suggested that here the river had "surmounted" a bedrock "reef."

In this paper, I present new evidence about the tectonic features in the bedrock, based on my field observations and from subsurface information in the two valleys obtained from the archives of the City of New York. These new data refute Schubert's concept that the Snuff Mill gorge coincides with a weak zone in the schist along a N-S-trending fault. The data further substantiates Kemp's assignment of a post-glacial age to the Snuff Mill gorge. The Bronx River did not "surmount" a bedrock "reef," but rather was blocked by postglacial elevation of a bedrock barrier formed adjacent to the NW-trending Mosholu fault. Significantly, I here offer the first evidence for surface changes in response to neotectonics in the New York City area. This has been a "bone of contention" for years between seismologists and geologists as no observed or historic ground-breaking has ever been associated with known faults.

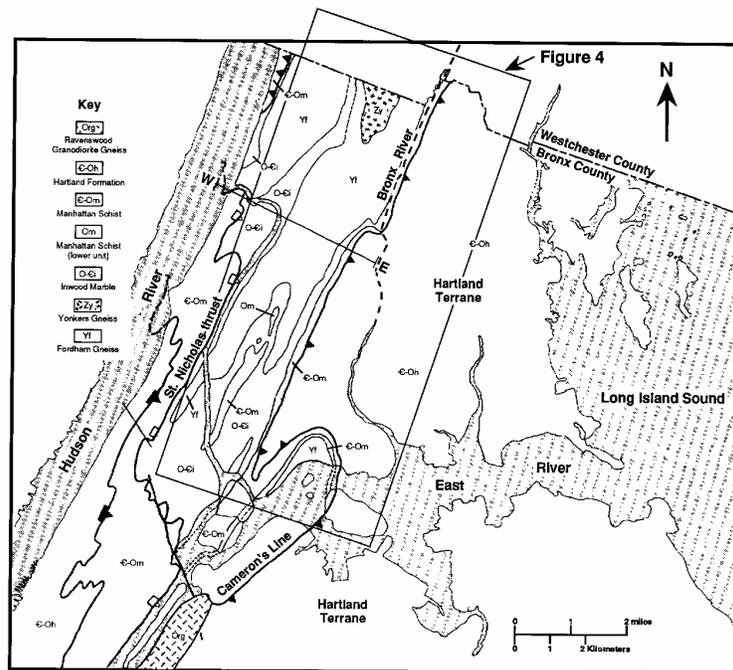


Figure 3. Geologic map of south end of Manhattan Prong showing Cameron's Line, the St. Nicholas thrust, the Hartland Terrane (as previously mapped), and the Ravenswood Granodiorite (Org). Rectangle shows location of Figure 4. (Adapted from Merguerian and Baskerville, 1987, fig. 3, p. 139.)

Geologic Factors Bearing on Diversion of the Bronx River

Several geologic consequences would be associated with any diversion of the Bronx River out of the presumably ready-made course underlain by the Inwood Marble along the wide Webster Avenue strike-valley lowland (Figure 4). If the river did indeed follow the marble lowland SW of the Mosholu Parkway, 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 sediments would have been deposited. After a new course to the south through the Snuff Mill gorge had been established, water from the lake would have been locked into this new course across the Hartland Terrane, so that even if the blocked Webster Avenue lowland became available, the river would not re-occupy it.

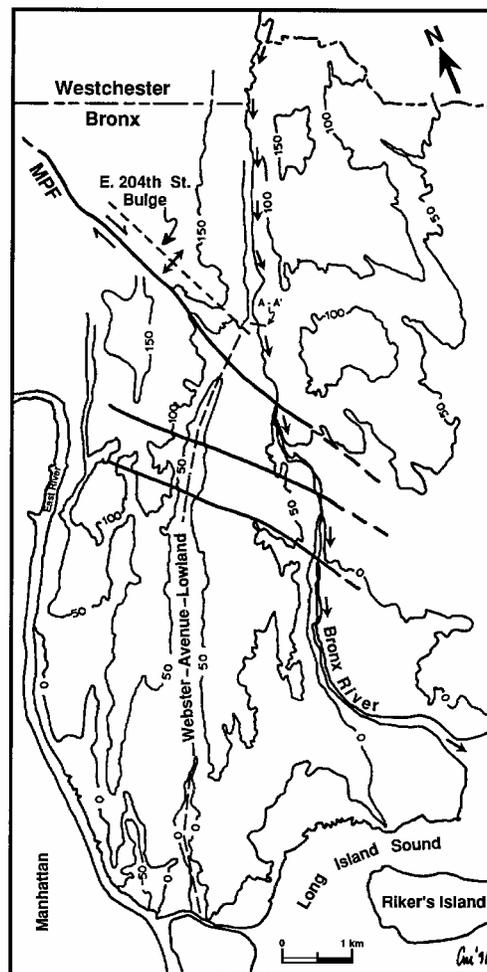


Figure 4. Index- and bedrock-contour map showing the present course of Bronx River, its V-shaped gorge, major NW-trending strike-slip faults including the Mosholu fault (MF), the 204th Street Bulge, and section A-A' of Figure 5. The Webster Avenue Lowland marks the previous course of the Bronx River. Subsurface- and fault data from Baskerville (1992) and engineering records of the New York City Subsurface Exploration Section.

Subsurface Relationships

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 5 is a stratigraphic profile section culled from borings taken across the Bronx River valley from E. 205th Street to Burke Avenue, at a point upstream from the proposed blockage/diversion. Several noteworthy features of these boring records stand out. First of all, 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 a thick clay. Merguerian and Sanders (1997) inferred that this post-glacial clay was deposited from a lake that formed in connection with the blockage/diversion.

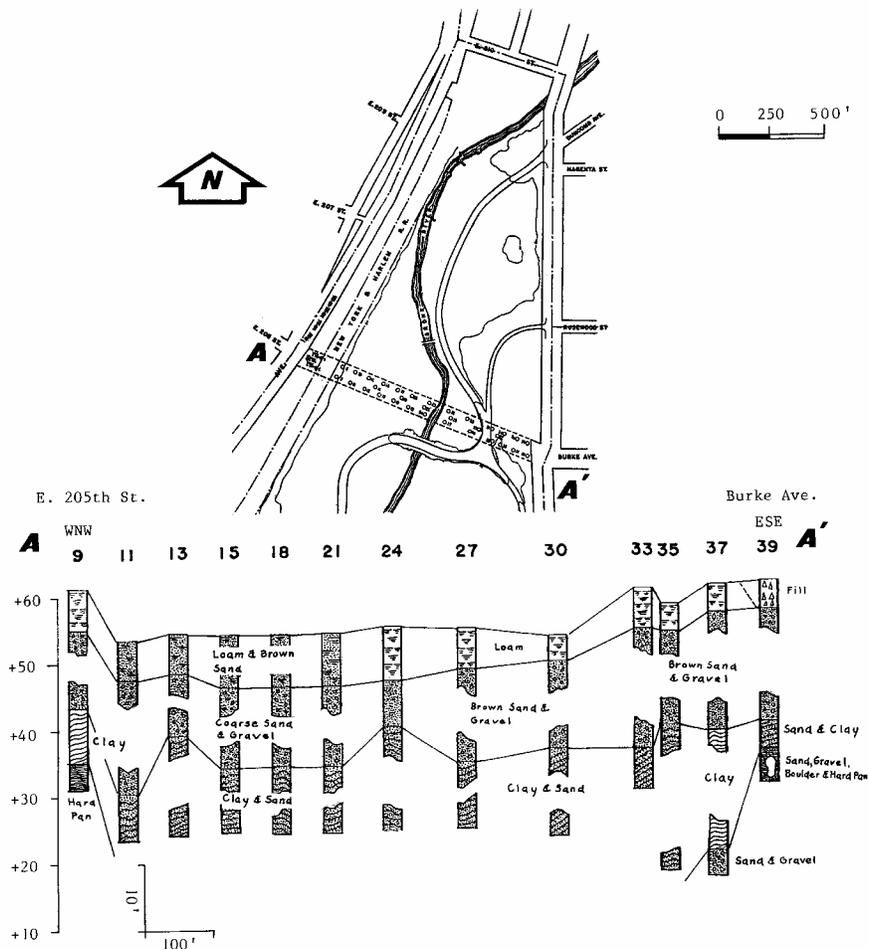


Figure 5. Index map and subsurface stratigraphy from E. 205th Street east-south-eastward to Burke Avenue in the Bronx, upstream of point of diversion of Bronx River based on records of borings assembled in the 1930s by the WPA rock-line map of the Bronx. Line of section shown on Figure 4. (Adopted from Merguerian and Sanders, 1997, fig. 4, p. 8.)

A. Index map showing locations of borings and section A-A'.

B. Stratigraphic correlation diagram using original WPA lithologic symbols for individual boring logs. Drawn at 10X vertical exaggeration. Elevations are Bronx Highway Datum.

Hypotheses Bearing on the Origin of the Snuff Mill Gorge

Kemp (1897) entertained four hypotheses as possible causes of the Bronx River's diversion. These are: (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). Because he could not find any remnants of a valley-blocking sediment deposit, he rejected hypothesis (1). Likewise, he cited several large, fresh potholes as evidence against hypothesis (2). He cited as his basis for discarding the related hypothesis (4) the small size of the stream flowing in the western valley (the Webster Avenue lowland) compared with the size of this valley. Even though he favored hypothesis (3), he emphasized that: "A lobe of entirely stagnant ice in the old channel as a diverting cause is regarded as an almost too temporary (*sic*) affair" (Kemp, 1897, p. 22) Kemp concluded that the age of diversion was postglacial.

I fully accept Kemp's postglacial age assignment. However, I 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 4.) to a broader U shape and would have polished and striated its bedrock walls. Therefore, the narrow V-shaped 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. As to when the diversion of the Bronx River took place, this would mean no older than about 12,000 years ago, just "yesterday" in terms of geological time.

Merguerian and Sanders (1997), added a fifth hypothesis to Kemp's list of four, namely that postglacial local uplift of a bedrock high (E. 204th Street Bulge of Figure 4.) along the NW-SE-trending Mosholu fault blocked the 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, rapidly cut and eroded the N-S-trending Snuff Mill gorge in the New York Botanical Garden, where the Bronx River crosses the Hartland Terrane.

Diversion of the Bronx River as a Byproduct of Motion Along the Mosholu Fault

According to Baskerville (1992), the Mosholu fault (= Van Cortlandt fault of Lobeck [1939] as originally mapped by Merrill and others [1902]) trends NW-SE parallel to the Mosholu Parkway. Baskerville has mapped this fault as being roughly 5.5 km long; his map shows it cutting across the Fordham ridge toward Van Cortlandt Park. The map symbols indicate that Baskerville regards the Mosholu fault as a right-lateral strike-slip fault with the north side up.

Studies of subsurface boring records and my recent field examinations indicate that the Mosholu fault is indeed a NW-trending right-lateral oblique-slip fault that projects across the Bronx River channel immediately below the area (near Webster Avenue and E. 203rd Street in the Bronx) where the Bronx River departs from its previous NNE-SSW-oriented channel and N-S-directed flow begins. (See Figures 3, 4.) A NW-trending bedrock high exists at this point as shown by depth-to-bedrock profiles, topographic maps, and surface exposures. The axis of this basement high (E. 204th Street Bulge) parallels the Mosholu fault and may, in fact, have been caused by motion along the footwall (northern segment) of the fault. I propose that the northern segment may have moved upward in response to normal oblique-slip motion. Such motion would be identical in orientation and magnitude to offset noted for the subparallel 125th Street fault found southward in Manhattan, which I also examined in a deep tunnel constructed during Stage 1 of City Tunnel #3 in 1983.

Conclusions

Geologists and seismologists generally agree that earthquakes produce dislocations known as faults and that preexisting faults 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 brittle faults which belong to two contrasting sets oriented NE and NW. These faults dissect the New York City area into large fault-bounded blocks. A “bone of contention” among seismologists and geologists revolves around a perceived lack of evidence that surface ground breaks have accompanied historic bedrock faulting. Many seismologists argue that the faults that structural geologists map in the field experienced offset at great depth with **no** surface connection and that uplift and erosion have unroofed these structures to the surface. New research from the Queens Tunnel and the Bronx provides the first demonstration of surface deformation in response to faulting in geologically recent (postglacial) time.

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 Webster Avenue lowland underlain by the Inwood Marble) resulted from postglacial blockage of the Webster Avenue lowland. A postglacial age is demonstrated by the absence of glacial polishing and -striae on the jagged walls of the Snuff Mill gorge and by a subsurface unit of clay that overlies a probable till in the E. 205th Street-Burke Avenue section. Neotectonic uplift of a block of bedrock adjacent to the Mosholu fault is thought to be the explanation for the diversion of the Bronx River out of a former course down the Webster Avenue lowland.

Mapping in the Queens Tunnel has documented a complicated structural sequence for the bedrock of NYC. The youngest geological event discovered in the tunnel is strike-slip offset along steep NW-trending faults, identical in orientation to the Mosholu fault. If the explanation for Bronx River diversion is correct, I here provide the first evidence for surface deformation in response to faulting in NYC suggesting that ground-breaking rupture and seismic activity can not and certainly should not be ruled out for this region. Because large magnitude earthquakes have struck NYC in 1737, 1783, and 1884, this new data identifies a potential failure surface along which earthquake energy could be released. Given the population, cultural development, infrastructure, and financial investment concentrated in New York City, the specter of a massive earthquake must be considered in revising existing building code designs and emergency preparedness procedures. Unfortunately, despite the scientific community's pleas for action, severely limited emergency planning exists at the present time. Clearly, this should be changed, as pre-emptive urban seismic planning is an absolute necessity in New York City.

Acknowledgements

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