

# **Brittle Faults of the Queens Tunnel Complex, NYC Water Tunnel #3**

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## **Introduction**

Mapping indicates that five generations of superposed brittle faults cut highly sheared granulite facies orthogneiss and associated rocks of the Queens Tunnel Complex. Faults in the Queens Tunnel vary from early ductile faults and related structures, to intermediate age steep to low angle normal and reverse ductile/brittle faults (often found injected by syntectonic granitoids) and subhorizontal brittle fractures, to steep, late-stage brittle faults with thick clay- and zeolite-rich gouge zones and quartz veins.

The two youngest brittle fault sets cross cut all metamorphic structures and late Paleozoic rhyodacite dikes. The dikes are offset by NNE-trending faults that are associated with thick zones of fault breccia and clayey gouge. The NNE-faults are cut by NNW-trending faults of the 125<sup>th</sup> Street “Manhattanville” type. Recent seismicity in the southern Manhattan Prong (NYC in 2001; Dobbs Ferry in 1985) was localized along faults of this young set and post-glacial offset of drainages along NW-trending faults may have occurred in the Bronx. The need to evaluate the seismic potential of these neotectonic features is evident.

## **Geology of the Queens Tunnel**

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 (Figure 1). Taking almost twice as long as expected, low TBM penetration rates resulted from unusual rock mass conditions attributable to the high-grade metamorphic history of the rocks and disturbed ground conditions resulting from the amplification effect of superposed brittle faults. Indeed, evidence from field mapping at 1"=10' and from petrographic, geochemical, and geochronologic studies conclusively demonstrate that the TBM penetrated weakly foliated granulites containing broad zones of garnet enrichment (Merguerian 1999a, b, and c; 2000). Granulite facies metamorphism of predominately mesocratic intrusive rocks resulted in coarse granoblastic textures consisting of interlocking plagioclase, pyroxenes (opx+cpx), and garnet (Brock, Brock, and Merguerian, 2000; Merguerian, Brock, and Brock, 2001). Based on these studies, Proterozoic Fordham orthogneiss is now recognized to underlie western Queens and Brooklyn, a covered region where mixed Paleozoic metasedimentary and metaigneous rocks of the Hartland formation were formerly anticipated.

A complex ductile and brittle geological history has emerged from study of the Queens Tunnel. This paper focuses on the brittle fault history, a protracted episode of fracturing that is superimposed on older ductile structures. A brief discussion of the ductile structures is a necessary prelude to describing the brittle fault history of the Queens Tunnel.



**Figure 1** – Index map showing the plan view of City Water Tunnel #3, Stage 2. The positions of Brooklyn Tunnel (Shafts 23B to 19B) and the Queens Tunnel (Shafts 19B through 16B) are shown. North is toward the lower left.

### Ductile Structures of the Queens Tunnel

In the Queens Tunnel, ductile shear zones and long-limbed isoclinal- to shear folds are associated with early deformational episodes of Proterozoic age ( $D_1$  and  $D_2$ ). These events were separated by the 1.0 Ga intrusion of a vast sequence of dioritic, tonalitic, and gabbroic magma. Granulite facies metamorphic conditions prevailed throughout the early ductile history of the Queens Tunnel Complex, producing massive to layered orthogneiss from the pre- $D_2$  plutons. Although coarse granoblastic textures predominate in the tunnel, deformation and shearing has produced gneissic layering ( $S_2$ ) that can be traced to the axial surface of gently plunging  $F_2$  reclined and recumbent folds.

Presumed to be the result of the Taconian orogeny, later  $D_3$  deformation produced tight to isoclinal  $\sim N35^\circ E$ -trending  $F_3$  folds with localized development of a penetrative foliation and  $D_3$  ductile shear zones. Upper amphibolite facies metamorphism caused slight to moderate retrograde amphibolitization of the older granulites in areas away from the shearing. During  $D_3$ , major ductile thrusts formed that imbricated Proterozoic (Fordham) and Paleozoic (Walloomsac) rocks, based on comparative studies conducted along the Queens and Brooklyn tunnels.

Later stage,  $D_4$  post-peak metamorphic ductile shears and associated foliated granitoid intrusives are found to cut the family of penetrative  $D_1$ ,  $D_2$ , and  $D_3$  ductile-fault structures as well as less sheared areas of the Queens Tunnel Complex. The  $D_4$  ductile faults are commonly injected by cm- to m-thick foliated granitoids and pegmatite masses and veins. These intrusives typically outline the faults and also form dikes, sills, veins, and irregular masses within the hanging wall and footwall blocks.

The D<sub>4</sub> ductile shear zones are identified based on their unique retrograde ductile fault fabrics consisting of aligned biotite and offset of geological contacts. These faults are predominately gently dipping to subhorizontal in orientation, show offset from centimeters to 6 m, and commonly include foliated syntectonic granitoid masses up to 1.5 m thick. Invariably the late D<sub>4</sub> shearing and related syntectonic intrusives resulted in granitization and the production of broad zones of biotitization and feldspar metasomatism. In the Queens Tunnel, protracted shearing has produced mylonitic rock textures, tectonic intercalation of rock units, and broad zones of highly strained rock. Indeed, most mapped formational contacts are sheared lithologic boundaries, shear zones, or modified former intrusive contacts.

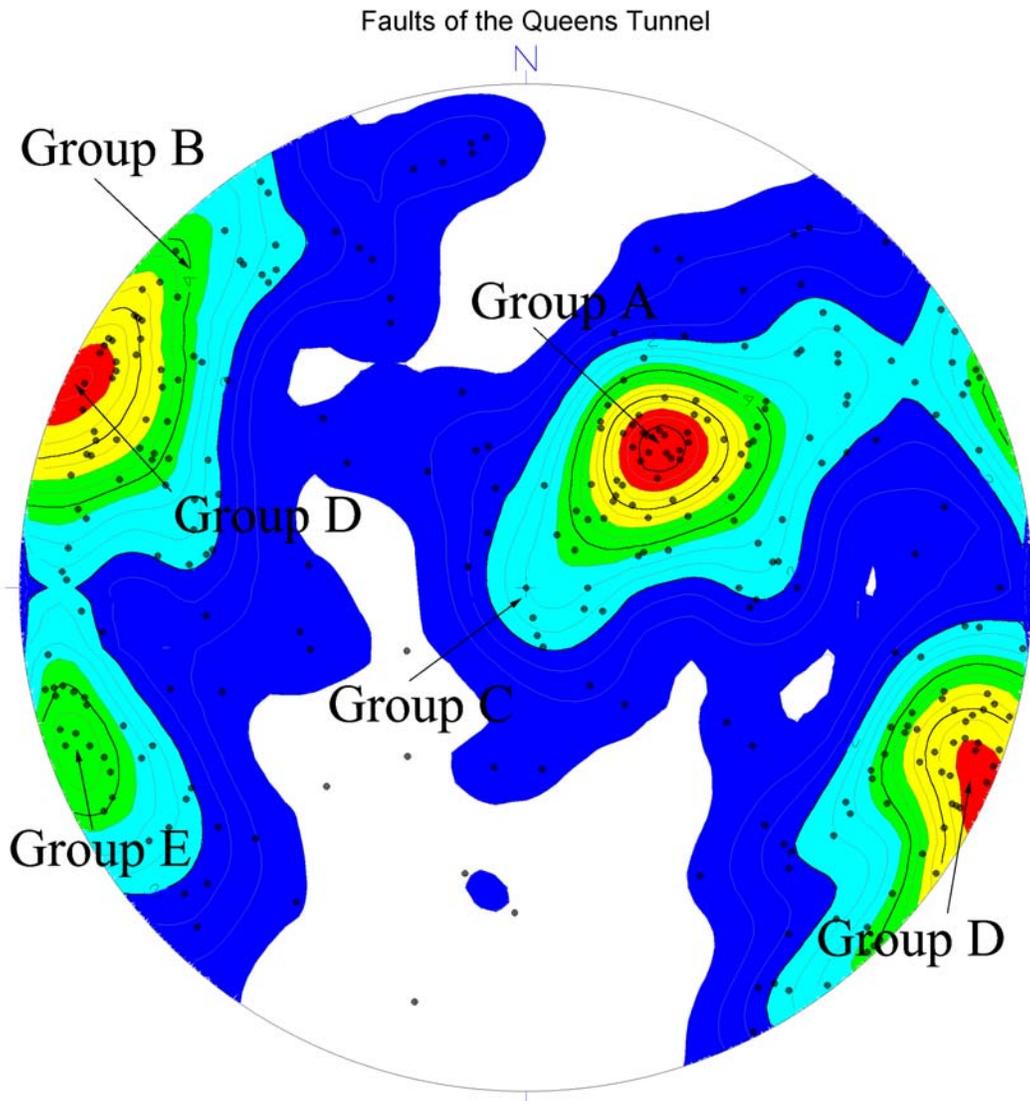
### **Brittle Faults of the Queens Tunnel**

Five generations of brittle faults are superimposed on polydeformed bedrock units of the Queens Tunnel often causing brittle reactivation of ductile faults and pre-existing brittle faults. Brittle faults are outlined by zones of fault breccia, clay-rich gouge, zeolite+calcite+pyrite mineralization, and quartz veins. They have created extended areas of high strain prone to stress relief in the form of joints, invert heave, and rock popping. In areas of fault convergence, the brittle faults and sub-parallel regional joints are a persistent cause of geological disturbance and related detrimental effects on tunneling, including a persistent collapsing face, rib and crown fallout, stress relief phenomenon, and voluminous water inflow.

A stereonet plot (Figure 2) shows that the brittle faults cluster into five groups corresponding to reactivated old NW-trending gently SW-dipping faults (**Group A**), younger ENE-trending faults with moderate to steep dips (**Group B**), subhorizontal faults, reactivated low-angle faults, and fractures (**Group C**), a younger steep NNE-trending fault system (**Group D**), and by the youngest NNW-trending strike-slip faults of the “Manhattanville” fault system (**Group E**). Reactivation of older faults is quite common, especially obvious in the Group D response to Group E faulting.

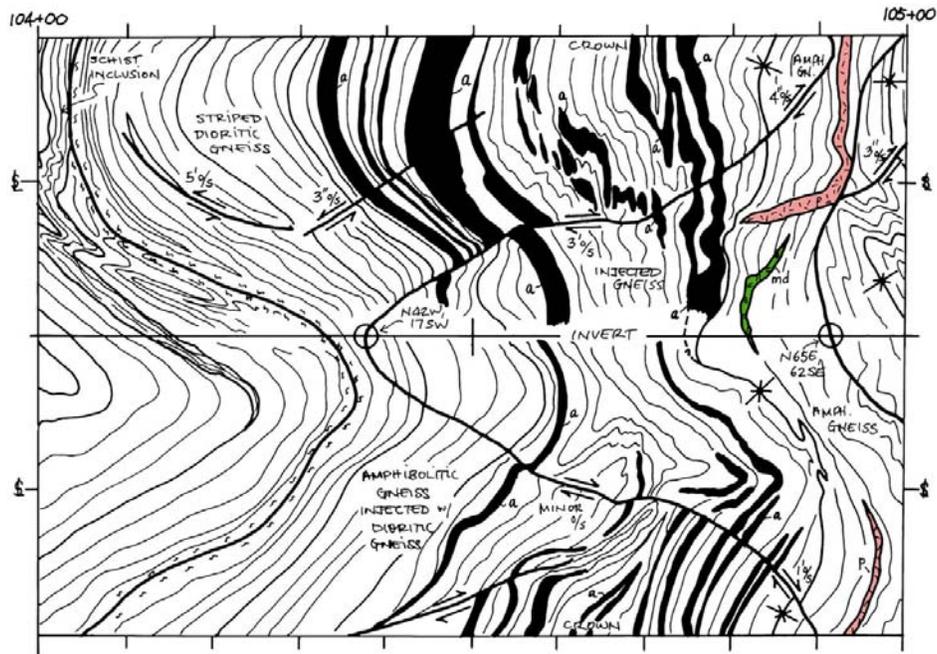
#### **Group A – Gentle to Moderate NW Faults**

The NW-trending faults of **Group A** both reactivate the NW-trending (D<sub>4</sub>) ductile faults and also occur throughout the tunnel in the absence of these faults. In composite zones, brittle reactivation has produced anastomosing seams of breccia and has cut the related felsic intrusives producing local contact dislocations. The Group A faults show an average trend of N46°W and exhibit both normal and reverse offset senses (Figure 3). The 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.



**Figure 2** – Schmidt equal-area stereogram showing the poles to 366 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 subhorizontal 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.

The faults are laterally continuous undulating features that persist over 100 m in some tunnel reaches (Figure 4). The faults vary from tight splays to open features outlined by gouge and crush breccia up to 0.5 m thick. 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. Coplanar joints developed parallel to the Group A faults have produced a dominant NW-trending regional joint pattern that has controlled the parallel emplacement of younger rhyodacite dikes (Merguerian, 2001).



**Figure 3** – 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".)

### Group B – NE Faults

The Group B 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<sub>3</sub> ductile fabrics. 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<sub>4</sub> 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 (Figure 5).

### Group C – Subhorizontal Minor Faults and Fractures

The features of Group C are subhorizontal, minor brittle faults and fractures that extend for great distances in the Queens Tunnel. They typically show little or no offset and tend to cut or reactivate subhorizontal portions of Group A faults. A number of coincident poles at the center and those clustered near the center of the stereonet (See Figure 2) mark the Group C features found throughout the tunnel.

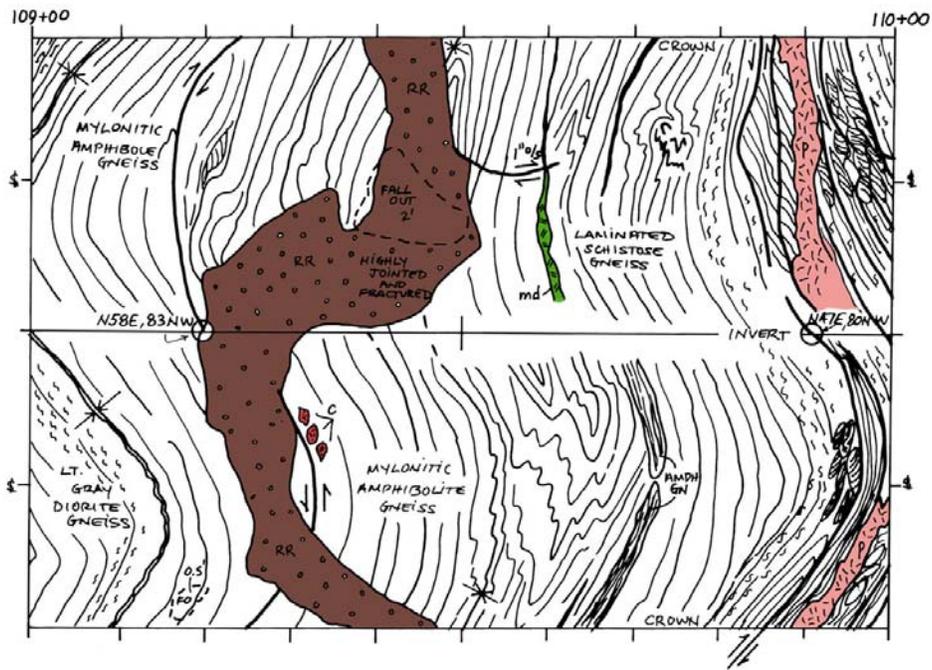


**Figure 4** – View of migmatitic amphibolite, dioritic gneiss, and minor biotite schist highly fractured because of composite movement along a SW-dipping shear zone. The shear zone is a continuous gently dipping feature for 107 m that originates at Station 195+25 and continues on both tunnel walls to 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 0.4m thick in areas of fault splay intersection near the central reach of the zone to a hairline fracture at the end. [Image by C. Merguerian, 18 November 1999.]

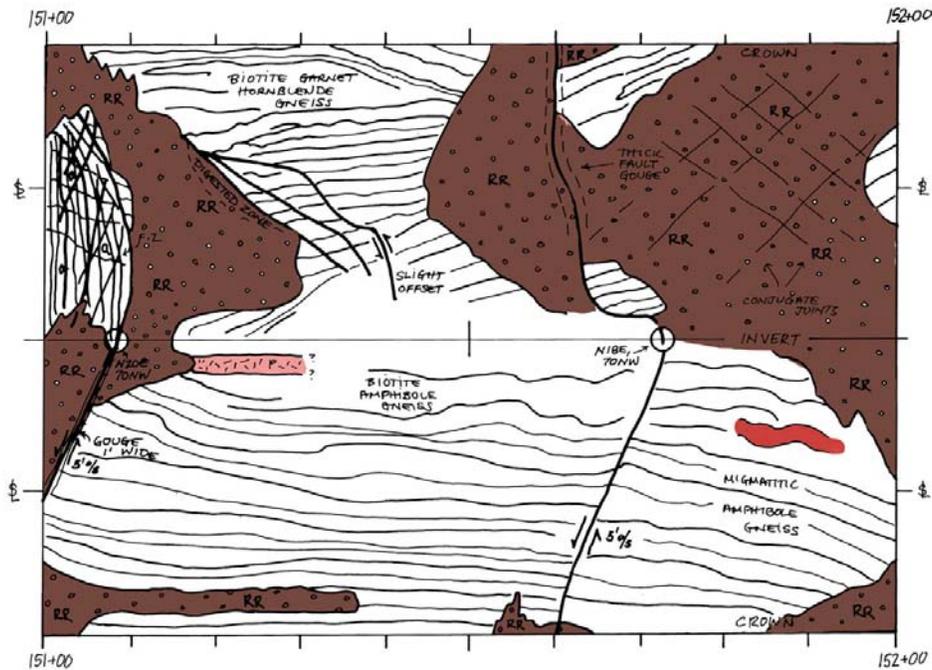
### **Group D – NNE Faults**

A hitherto unknown, steeply dipping, major NNE-trending fault set cuts the Queens Tunnel from beginning to end but most are strongly concentrated along the NW tunnel leg just beyond the major curve in the tunnel. Here, the NNE faults crosscut the tunnel at a high angle and greatly contributed to tunnel perimeter instabilities encountered during mining, especially when found in combination with other weak structural features. They cut the rhyodacite dike swarm (Figure 6) and most other geologic features of the tunnel (Figure 7).

Group D constitutes a third (~100) of all mapped brittle faults (~300) in the tunnel. They form a system of geologically young dip-slip faults and related joints with an average N21°E trend and steep dips. (See Figure 2.) In the fault surface, dip-slip slickensides show reactivation by oblique-slip mechanisms, the result of younger (Group E) faulting. The Group D faults are characterized by thick clay, breccia, and clayey gouge that vary in thickness from 1 cm up to 5 m. Minerals found healing the NNE-trending faults show a clear paragenesis of apophyllite and/or heulandite followed by stilbite of two generations (yellow to orange followed by translucent). The stilbite is overgrown with spheres and interpenetrant cubes of pyrite, calcite, and clear crystals of chabazite.



**Figure 5** – 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".)



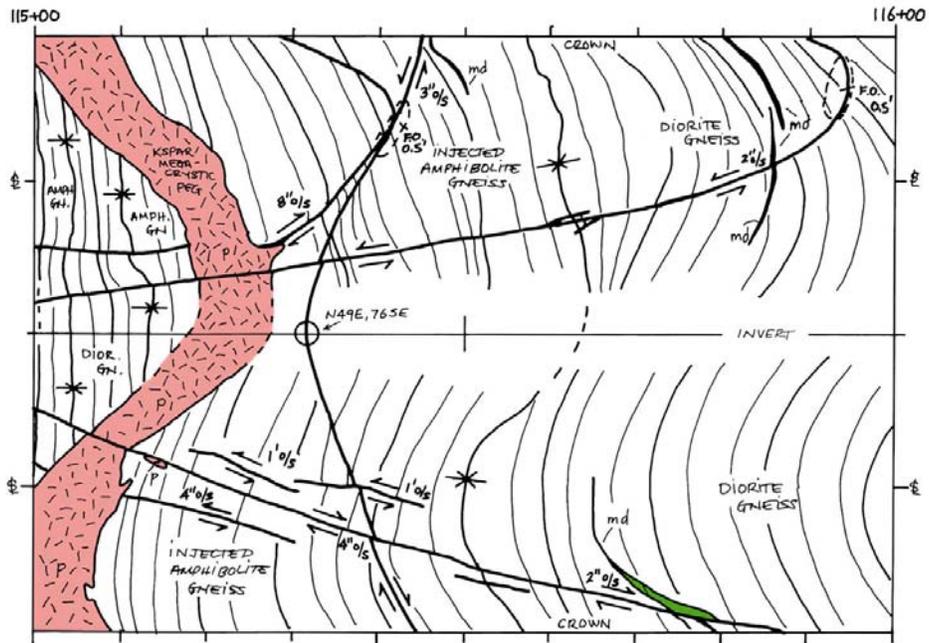
**Figure 6** – Map of migmatitic biotite garnet amphibole gneiss cut by two rhyodacite dikes. The dikes are cut by NNE-trending faults of Group D. (Tunnel bearing is N71°W; Original map scale 1"=10'; tunnel diameter 23' 2".)



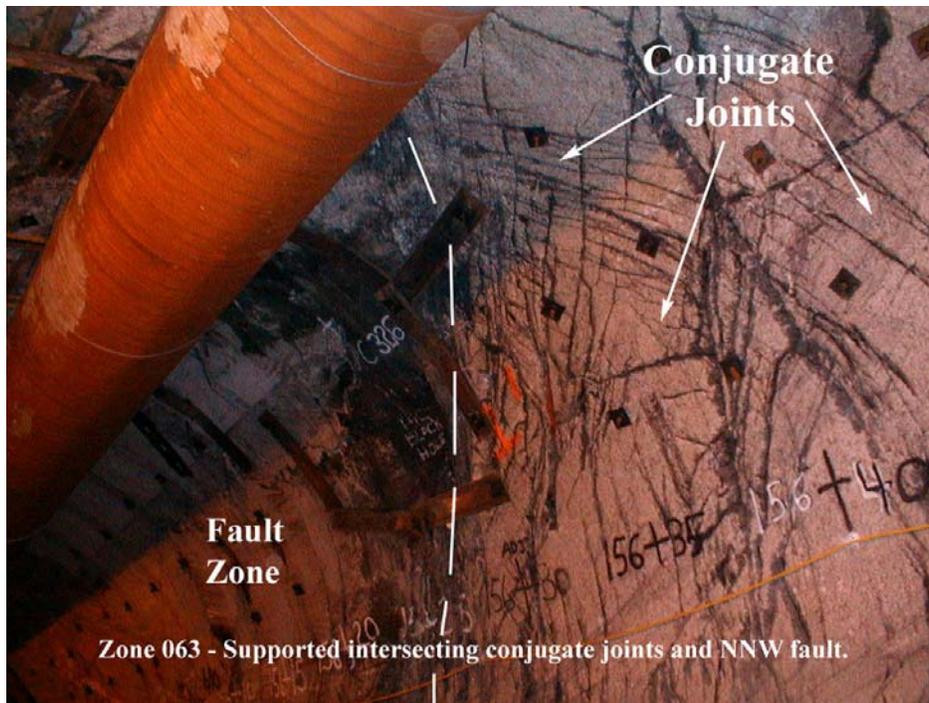
**Figure 7** – The geology of this disturbed interval (Station 214+30, left wall) is dominated by a major NNE-trending SE-dipping normal fault exposing a 3m thickness of clay-rich crush breccia. The NNE fault of Group D displaces older low-angle reverse faults (Group A) in both the footwall and hanging wall blocks of the fault. Fault splays of various orientation and offset sense are found adjacent to the NNE-fault. [Image by C. Merguerian, 18 November 1999.]

### **Group E – NNW “Manhattanville” Faults**

The youngest group of brittle faults trend  $\sim N20^{\circ}W$  (See Figure 2), exhibit steep dips and show predominately strike-slip offset (Figures 8 and 9). They crosscut every geological feature in the tunnel and mark the youngest structural event to be recorded. These faults are steeply inclined with subhorizontal 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. The NNW-trending faults are best developed near the western 1.5 km of the tunnel where these overstress phenomenon are concentrated. An extension of the famous "125<sup>th</sup> Street [Manhattanville] Fault" of New York City and parallel to many similar faults in the NYC area, the Group E faults of the Queens Tunnel are a part of a regional fracture set along which recent earthquakes have been localized.



**Figure 8** – 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. (Tunnel bearing is N41°W; Original map scale 1"=10'; tunnel diameter 23' 2".)



**Figure 9** – 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). [Image by C. Merguerian, 30 December 1998.]

## Discussion

Protracted brittle faulting in the NYC area has developed a regional pattern consisting of three major, mutually intersecting fracture orientations (NW, NNW, and NNE) that together provide a nearly orthogonal pattern of crustal weakness. The brittle NNW-trending faults (Group E in this abstract) have proven to be the youngest geological episode recorded in the Queens Tunnel. Slip along NNW-trending faults has produced recent seismicity in the Manhattan Prong.

The epicenter of a small earthquake (~2.4 Richter) localized in NYC on 17 January 2001 plots adjacent to the trace of the 125<sup>th</sup> Street fault near 102<sup>nd</sup> Street and Park Avenue in Manhattan. Later that year (27 October 2001) another similar earthquake (~2.6 Richter) struck NYC with an epicenter near 55<sup>th</sup> Street and Eighth Avenue. Seismic activity along the NW-trending Dobbs Ferry fault in late October 1985 produced two small (~4.0 Richter) tremors and many aftershocks. Larger, earthquakes in and around the vicinity of NYC were recorded in 1884 (~5.0-5.5), 1783 (~4.9), and 1737 (~5.2). In the Bronx, field evidence suggests that right-lateral offset along the NW-trending Mosholu fault was a post-glacial phenomenon with demonstrable offset of surface drainage (Merguerian 1996a, b; Merguerian and Sanders 1997, 1996). Clearly, a pattern of seismic slip along NNW- and NW-trending faults is beginning to establish itself in the NYC area.

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