YOUNG RHYODACITE DIKES FOUND IN THE QUEENS TUNNEL BENEATH WOODSIDE, QUEENS

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Introduction

One of the most scientifically startling and unforeseen discoveries made during detailed mapping of the subsurface geology of the Queens Tunnel has been the identification of a suite of red-colored, rhyodacite dikes ~800' beneath Woodside, Queens. The dikes are found to crosscut Proterozoic granulite facies rocks of the Queens Tunnel Complex with which they are genetically and temporally unrelated. Field, geochemical, and petrographic studies all support the conclusion that the rocks are rhyodacitic in composition and exhibit textures and contact relationships typical of hypabyssal volcanic rocks. The shallow-level rhyodacite dikes are found to intrude a high-grade bedrock series that was exhumed from depths of roughly 40 km. The dikes cut gneissic layering, folds, and most faults in the tunnel but are cut by a relatively young NNE-trending fault system. The presence of relatively young rhyodacitic dikes proximate to their initial injection site adds a hitherto unknown volcanic formation the developmental geology of the NYC region.

Geology of Western Queens, New York

Studied by geologists for over 200 years, the durable crystalline rocks of New York City form the substrate for many civil and municipal engineering construction projects. Situated at the extreme southern end of the Manhattan Prong physiographic province of the New England Appalachians, New York City exposes a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rock. Although no natural bedrock is exposed along the Queens Tunnel alignment, borings indicate that the crystalline rocks of western Queens underlie a gentle SE-sloping nonconformity surface that projects upward to the location of Long Island Sound. Cretaceous and Pleistocene sediment overlie the nonconformity. As such, the depth to bedrock along the Queens Tunnel alignment varies from between 70' (-49.3' MSL) near Shaft 16B to depths of 248' (-233.5' MSL) near Shaft 19B in Maspeth (Figure 1).

Because of the depth of bedrock, contract borings and previous construction experience supplied the only available evidence about the subsurface geology of western Queens. The area encompassed by the Queens Tunnel was previously believed to be part of the Hartland Formation, a Paleozoic metamorphic and igneous rock complex found to the east of Cameron's Line. However, recent geochemical, geochronologic, and petrographic analyses by Brock, Brock, and Merguerian (2001, this volume) indicate that most of the rocks of the Queens Tunnel Complex are correlative with the 1.0 Ga Fordham Gneiss and are **not** part of the Hartland Formation. Thus, our allied studies require that the position of Cameron's Line be shifted to the east of the Queens Tunnel alignment.

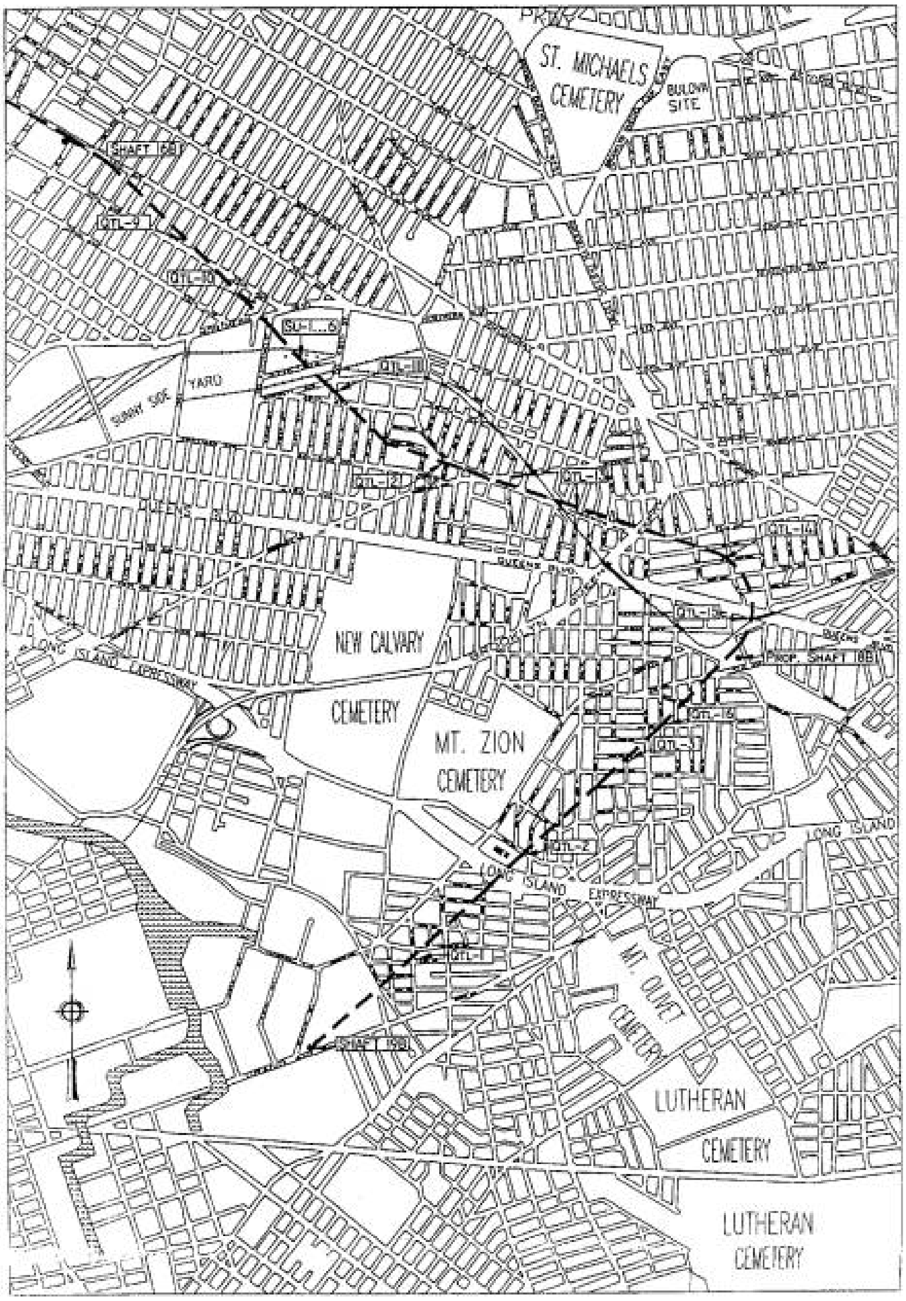


Figure 1 - Street map of a portion of the Third NYC Water Tunnel in Queens showing the Queens Tunnel alignment and the positions of shafts and borings. This segment of the tunnel (Contract 542) begins at Shaft 19B in Maspeth and continues 10,000' in a NE direction to Shaft 18B. After the 116° curve to the left near Shaft 18B, the tunnel changes trend to a NW direction, ending near existing Shaft 16B. Dikes were found in the tunnel between the position of boring QTL-15 beyond boring QTL-13.

Bedrock Geology of the Queens Tunnel Complex

Between May 1998 and February 2000, I mapped the bedrock geology of the Queens Tunnel providing a detailed record of the subsurface geology of the Queens Tunnel. A tangible result of my efforts includes a portfolio of field maps (scale 1”=10’) consisting of 250 map sheets, each covering 100 feet of the tunnel (Merguerian, 1999). The 4.8 mile long Queens Tunnel is interrupted by one major 116.7° curve and three smaller curves (1.8°, 13.7°, and 26.5°; See Figure 1). The dog-leg plan view of the tunnel (a NE-trending leg of 10,000’ and a NW-trending leg of 15,522’) offers a broad cross-section of the geology of the region. The rhyodacite dikes described in this report crop out near the middle of the tunnel beneath Woodside. They extend between Stations 109+20 and 152+40. (Between the position of boring QTL-15 to just beyond boring QTL-13 in Figure 1.)

Geology of the Rhyodacite Dike Suite

Distribution

A suite of five sub-parallel dikes, all displaying non-metamorphosed igneous textures, crops out in nine separate locations in the tunnel (Table 1). Many of the nine locations were undoubtedly connected before mining and the tunnel boring machine (TBM) may have removed dikes no longer exposed in the tunnel walls. The dike rocks are exposed for a minimum of 667’ between Stations 109+20 and 152+40 and compose 15.4% of the tunnel perimeter rocks within that 4,320' tunnel reach. They occur as tabular, discordant bodies roughly oriented N53°W and average just under 10' in thickness. The larger dikes vary from 16' down to 3' and taper off to thin dikelets. During excavation of the Queens Tunnel this volcanic formation, with its distinctive cooling fractures and contact effects, produced zones of geological disturbance including working-face collapse and perimeter fallout.

Table 1 – Rhyodacite Dikes of the Queens Tunnel

Dike	Stations	Orientation	Exposed Length	Thick-ness	Brief Comments
1	109+20 - 109+52	N65°W, 57°NE	32'	12'	cuts N58°E, 83°NW normal fault
2	117+58 - 118+24	? - RW Only	66'	>8'	cuts N52°E, 76°NW normal fault and shear zone
3	128+70 - 129+21	? - LW Only	51'	7'	cuts D_3 shear zone
	129+53 - 130+41	N48°W, 78°SW	88'	11'	cuts N20°E, 10°NW thrusts and older F_3 fold
4	131+70 - 132+42	? - LW Only	72'	6'	cuts N30°W, 23°SW thrust fault
	132+40 - 132+56	? - RW Only	16'	3'	thin selvage cuts thrust fault and shear zone
	132+58 - 133+62	N61°W, 81°NE	104'	5'-10'	cuts N44°E, 83°SE reverse shear zone; fractured
5	149+93 - 151+36	N52°W, 90°	143'	16'	cut by N20°E, 70°NW normal fault; clay-rich gouge
	151+45 - 152+40	N40°W, 83°SW	95'	14'	cut by N18°E, 70°NW normal fault; clay-rich gouge

Intrusive Forms

The five dikes and their extensions and offshoots (See Table 1.) produce a broad zone of injection that crosscuts the Proterozoic granulite facies orthogneisses and associated rocks of the Queens Tunnel Complex and younger Paleozoic metamorphic rocks. The rhyodacite dike rocks are predominately thin tabular bodies oriented approximately parallel to a ~N50°W regional fault and fracture pattern but local offshoots of the rhyodacites are sill-like, occurring as small masses that intrude parallel to the existing foliation in the deformed host rocks.

The dikes truncate all major lithologic units of the Queens Tunnel Complex, gneissic layering, folds, mafic dikes, and most faults found in the tunnel. They are themselves cut by a generation of steep, NNE-trending faults. In the tunnel and elsewhere in NYC, NNE-trending faults are cut by steep NW-trending faults (Merguerian and Sanders, 1996, 1997). These have exhibited post-glacial neotectonic activity as indicated by the 17 January 2001 magnitude 2.4 tremor on the Manhattanville (125th Street) fault in NYC. As such, the injection of the rhyodacite dike suite occurred relatively late in the overall Queens Tunnel structural sequence.

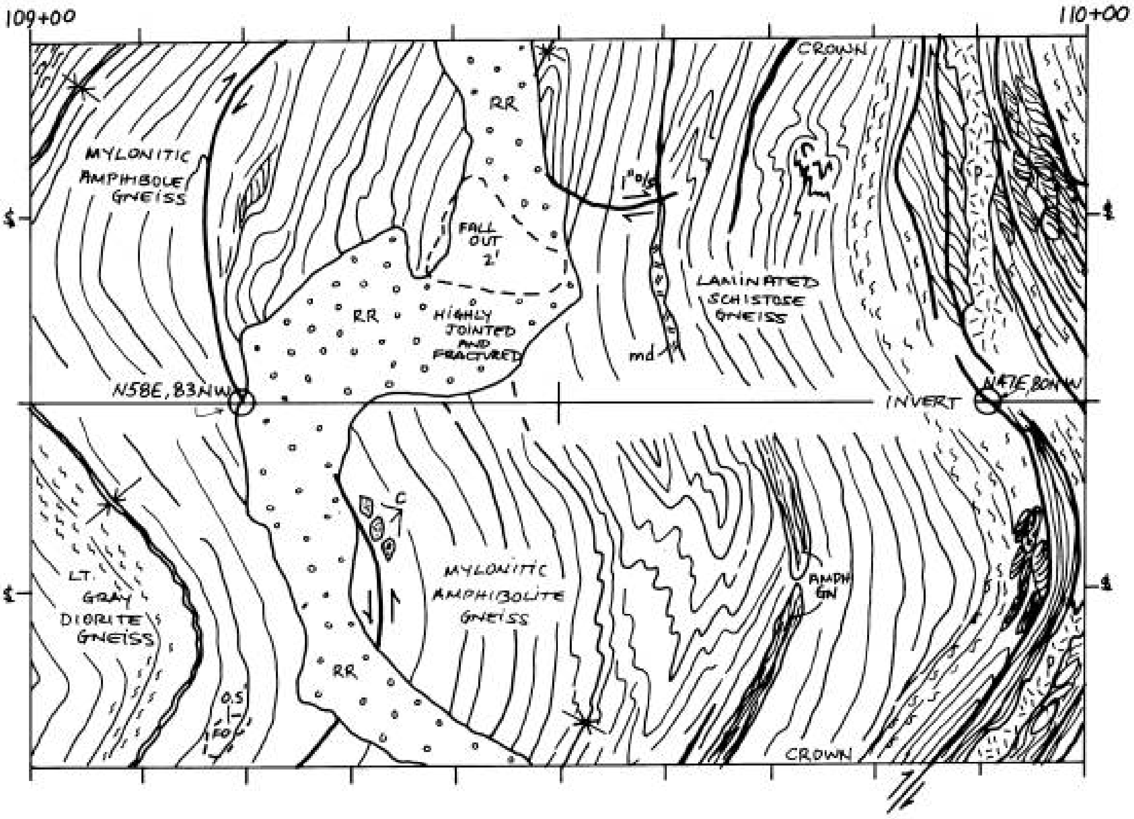


Figure 2 – Geologic map of the Queens Tunnel showing rhyodacite dike #1 (RR), found between Stations 109+20 and 109+52 (tunnel bearing is N4°W). The dike truncates mylonitic amphibolitic gneiss and a N58°E-trending brittle fault. The tunnel invert is shown along the center of the map and the tunnel walls curl upward into a cylinder to join at crown. 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".)

Dikes #1 and #2 are found in the 116° curve of the tunnel just beyond Shaft 18B. (See Figure 1.) Figure 2 is a map of dike #1 showing the sinuous profile of a tabular dike cutting the tunnel axis at a high angle. Dikes #3, 4, and 5 and their extensions are found in the N71°W-leg of the tunnel. Because the regional dike trend and the NW-leg of the tunnel are roughly parallel, these unusual rocks may be more extensive than the tunnel exposures reveal. They could extend alongside the tunnel for great distances, based on the presence of thin selvages of dike material exposed at the tunnel springline positions at stations 117+58 to 118+24, 128+70 to 129+21, 131+70 to 132+42, and 132+40 to 132+56; See Table 1).

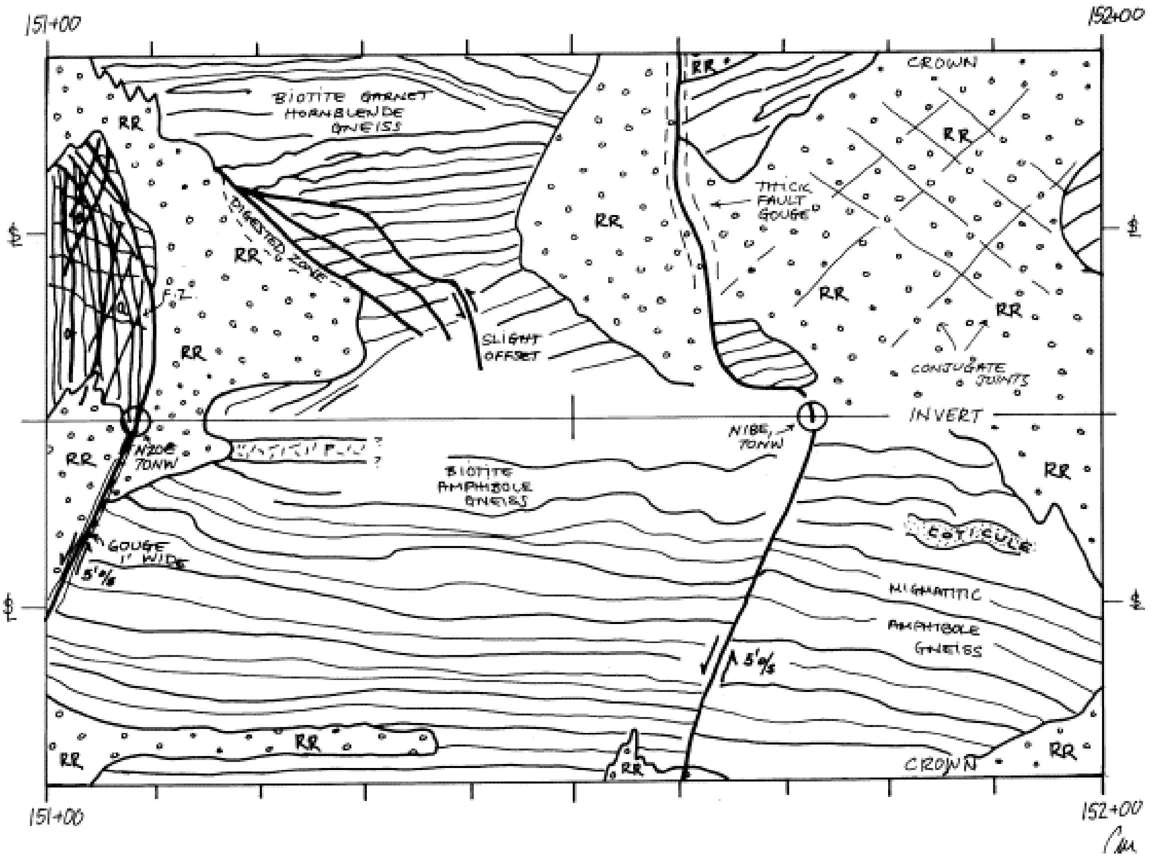


Figure 3 – Geologic map showing a portion of rhyodacite dike #5 (RR) exposed between Stations 149+93 and 152+40 (tunnel trend N71°W; west of boring QTL-13 in Figure 1). The dike truncates gently SE-dipping biotitized migmatitic garnet amphibole gneiss and is offset by a N18°E–trending brittle fault, part of a young NNE-trending fault system. This map covers 100 linear feet of the Queens Tunnel. (Original map scale 1"=10'; tunnel diameter 23' 2".)

Many of the dikes deform and reorient the foliation in the bounding gneiss complex into parallelism with the dike margin indicating forceful intrusion. Local syn-intrusive deformation has resulted in local fold patterns not found elsewhere in the tunnel. At least one dike (#3) is phacolithic in form following the shape of an existing antiformal fold. The most extensive dike (#5) is cut by young NNE-trending faults and related gouge (Figure 3). Thus, the dikes are cut by one of the youngest episodes of brittle fault activation mapped in the tunnel.

Lithologic and Petrographic Descriptions

Based on field, mesoscopic, and petrographic examination, the rhyodacites are reddish, glassy to aphanitic igneous rocks with no metamorphic fabric and low average density (~2.58 g/cm^3). Hand samples are hard and flinty in aspect and fresh in appearance with a multitude of curviplanar cooling joints whose intersection produce cobble- to boulder-sized multifaceted blocks and slabs. Many of the planar fracture surfaces are coated with combinations of chlorite, calcite, stilbite, serpentine, other zeolite minerals (apophyllite?), and pyrite but some of the joint surfaces are non-mineralized. Some of the mineralized joint surfaces show evidence of slip in the form of slickensides. The joint surfaces (found both parallel and perpendicular to the contact margins) are interpreted to be cooling joints. Together with the omnipresent regional joint sets found throughout the tunnel and in the presence of fault zones (along which the rhyodacitic melts were initially emplaced and quenched), the areas of the Queens Tunnel underlain by the dike are typically intensely fractured.

The rhyodacites are highly porphyritic. Suspended in the red, siliceous groundmass are non-aligned 1 mm to 6 mm euhedral phenocrysts of hornblende, clinopyroxene, biotite, plagioclase, and subordinate K-feldspar. The groundmass is enriched in quartz and K-feldspar and dusted with fibrous aggregates of iron oxide - the probable result of quenching and devitrification of initial felsitic volcanic glass. Numerous rounded and irregularly shaped ~1 mm vesicles indicate former high vapor content. Many of the voids are rounded in outline indicating that they were the products of outgassing during cooling of a melt. Yet, some of the voids are sub-angular with remnant phenocrysts and corroded replacement crusts of calcite and zeolite minerals, indicative of in-situ alteration of primary mineral phases by late-stage igneous processes.

The unique devitrified texture of the groundmass and the presence of vesicles unequivocally identify the rhyodacite as a hypabyssal rock. The pervasive reddish color of the dikes is not an indication of near-surface weathering and chemical alteration because the color is evenly found throughout the rock mass. Rather, the unique coloration is produced by iron oxide minerals found within the groundmass, the result of devitrification of quenched glass during late-stage igneous processes. The iron may have been introduced by assimilation of the host rocks based on the abundance of gneissic inclusions in the dike rocks.

Contact Relationships

Contacts with the surrounding gneisses are typically lobate indicating that melting and assimilation of the country rock took place to some degree. Some dikes contain large numbers of bedrock xenoliths and display grayish green chilled margins where assimilation of the bedrock host has resulted in hybrid “mixed” rock. Local retrograde metamorphism has been noted in the vicinity of the dikes with the production of mica-rich zones in high-grade gneissic rocks that are typically poor in micaceous minerals. The introduction of hydrothermal fluids, easily derived and introduced from a felsic melt, is the likely candidate for such alteration.

Forceful emplacement of igneous melts often results in shouldering the country rocks aside and synintrusive deformation because of the space invaded and replaced by the intruded melt. Country rocks adjacent to the rhyodacites show the effects of localized folding and reorientation of the gneissic layering as a result of dike intrusion. Annealing of the bounding metamorphic rocks has induced a flinty aspect to these gneisses. Stress relief has been observed adjacent to some dikes in the form of thin, spalled slabs of rock in the tunnel invert and ribs. In addition, contact zones with the bedrock have been mineralized with thin veins of pyrite and fine-grained chloritization, the result of high heat flow and a penetrating vapor phase from the parental liquid. Such veining has induced additional weakness and fracturing in the host rocks. Mesocratic to mafic garnet gneiss rock fragments are common xenoliths, although these are typically totally or partly assimilated.

Cooling Fractures

Cooling hypabyssal rocks lose heat to the country rock rapidly because of the temperature gradient between the melt and the surrounding host rock. Isothermal surfaces within cooling igneous masses are produced parallel to their contacts and contact-parallel cooling joints result. In addition, tensional strain during cooling and contraction produces polygonized columnar joints, both colonnade and entablature, perpendicular to such contacts. Thus, rapid cooling promotes the development of a multitude of planar to curviplanar joints that intersect to produce multifaceted blocky breakage patterns (Figure 4).

Figure 4 - Discordant intrusive contact of highly jointed rhyodacite (Dike # 3) that truncates metamorphic layering in the adjacent biotitized gneiss at a high angle. Note the multidirectional cooling joints both parallel to and crosscutting the contact with the gneiss and the thin, altered zone of contact metamorphism.

The joints in the Queens Tunnel rhyodacite dikes, are generally tight to hairline in width and parting takes place along the joints rather than through the dense, hard rock mass. By contrast to the generally massive surrounding gneisses, the rhyodacite rocks formed loose, noncohesive, cobble-sized blocks that exhibited little resistance to sliding on joint surfaces and thus collapsed freely. Moreover, in the contact areas with the surrounding gneisses, the external propagation of cooling joints has induced additional fracturing within the country rocks. In some instances, cooling joints extended over 10 feet from the contact into the surrounding gneiss (Figure 5).

Figure 5 - Cooling joints in rhyodacite formed perpendicular to the dike margin (dike # 1) and extend over 10 feet (parallel to hammer handle) into surrounding amphibole gneiss.

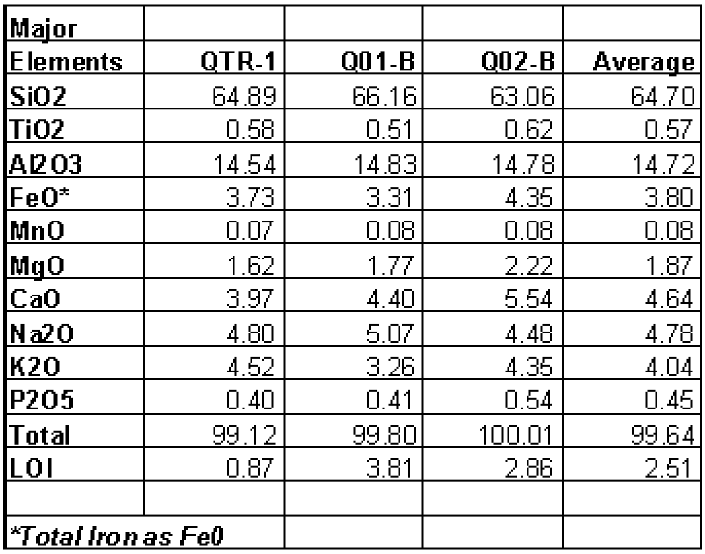
Relative Age Relationships of Dikes to Faults

As indicated above (See Table 1), emplacement of the dikes took place along preexisting faults, fault zones, fold axial surfaces, shear zones, and joints in the host rocks. The average trend of the dike suite is ~N53°W, essentially parallel to both the N50°W regional joint direction and orientation of a major pre-dike injection fault set in the New York City area (Merguerian, 1996). Thus, the rhyodacite dikes are cut by most fault systems and related fault zones mapped in the tunnel. (See Figures 2 and 3.) The dikes show no evidence of post-intrusive folding or deformation and none of them are metamorphosed. Dike #5 shows internal fractures and dislocations of the rhyodacite-gneiss contacts along steep, relatively young ~N20°E, 70°NW normal faults with their characteristic greenish, 1' to 2' thick clay-rich gouge zones. (See Figure 3.)

Geochemistry

Preliminary major and trace element geochemical analyses of one dike sample was performed in April 1999 by Dennis Radcliffe and Crystal Pearl at Hofstra University. During the summer of 2000, two additional geochemical analyses were performed at Washington State University Analytical Labs and support the preliminary findings (Table 2). The "average" Queens Tunnel rhyodacite is closely comparable to the average of 115 rhyodacite analyses of Nockolds (1954; p. 1014). They are slightly less siliceous (~1.5%) and are enriched (~1%) in CaO, Na_2O, and K_2O, but are otherwise nearly identical to this long-standing reference standard. As such, the geochemical data supports the lithologic- and petrographic character of the Queens Tunnel rhyodacites.

Table 2 – Geochemical Analyses of the Queens Tunnel Rhyodacites



Major Elements	QTR-1	Q01-B	Q02-B	Average
SiO2	64.89	66.16	63.06	64.70
TiO2	0.58	0.51	0.62	0.57
Al2O3	14.54	14.83	14.78	14.72
FeO*	3.73	3.31	4.35	3.80
MnO	0.07	0.08	0.08	0.08
MgO	1.62	1.77	2.22	1.87
CaO	3.97	4.40	5.54	4.64
Na2O	4.80	5.07	4.48	4.78
K2O	4.52	3.26	4.35	4.04
P2O5	0.40	0.41	0.54	0.45
Total	99.12	99.80	100.01	99.64
LOI	0.87	3.81	2.86	2.51
**Total Iron as FeO*				

Note: Sample QTR-1 is a from the interior of dike #5 (Hofstra University analysis). Samples Q01-B and Q02-B from dike # 1 and #2 interiors, respectively (Washington State University analyses).

Probable Age and Significance of the Rhyodacite Dikes

After the Queens Tunnel TBM penetrated through zones of rhyodacite in early 1998, the geological staff of the City of New York indicated that rhyodacite was indeed encountered in a single boring but not at the level of the bored tunnel. Recognizing that the boring logs had incorrectly described the dike rock as "weathered gneiss", on 03 June 1998, I examined the core from boring QTL-13 and examined the adjacent core (QTL-14, QTL-15, and QTL-16; See

Figure 1). Rhyodacite was indeed found in the upper part of boring QTL-13 but not in any of the other borings from the tunnel alignment. About 22 feet of moderately jointed continuous core of the rhyodacite was found in boring QTL-13 between depths 349' and 371' (corresponding to -262' and -284', MSL). This occurrence in boring QTL-13 was positioned well above the actual bored tunnel (depth range 783' to 806') beneath QTL-13. Thus, a minimum of 435 vertical feet exists between the red-colored rhyodacite observed in the QTL-13 boring versus the rhyodacite mapped in the bored tunnel below.

The volcanic rock in the upper part of QTL-13 was identical in color, texture, bulk mineralogy, and mineralization of joints, to the rhyodacite dikes of the tunnel except for two very important details. The QTL-13 rock was much more highly vesiculated, by a factor of 3 to 4 times, than the rhyodacite encountered in the Queens Tunnel. Furthermore, the QTL-13 cores exhibited a relative paucity of intersecting joints.

Vesicle production in an igneous rock is controlled both by volatile content and ambient lithostatic pressure. As such, greater vapor phase expulsion and production of vesicles typically occurs nearer the surface during the ascent of lava. Thus, in comparing the QTL-13 core with the rhyodacite from the Queens Tunnel, the marked difference in the number of vesicles may have been controlled by former pressure differences sensitive to changes in lithostatic load over a depth range of only 435 feet. It follows then, that the observed increase in vesicles over a vertical distance of only 435 feet, together with devitrification textures in the groundmass support an interpretation that the rhyodacite parental liquid was injected very near the surface of the earth.

With certainty, the lithology and petrography of these singular and unusual rocks are clearly inconsistent with their metamorphosed bedrock host. The granulite grade assemblage of the Queens Tunnel Complex indicates that the rocks attained their initial metamorphism at depths of ~40 km. Based on their texture and by comparison to similar rocks I have mapped in California and elsewhere in the western Cordillera, I would be surprised if the former intrusive depth of the Queens Tunnel rhyodacite dikes was any more than ~1-2 km. In the absence of geochronologic dating, the absolute age of the rhyodacite dikes is unknown. Based on their unique texture and former shallow intrusive depths, I would hypothesize that they are Mesozoic or perhaps Cenozoic in age. In terms of relative age dating of critical field relationships, they are the youngest event to affect the region with the exception of the NNE-trending fault system and the younger NW-trending faults.

Age dating will be performed on these rocks at some future time. To my knowledge, such shallow-level felsic rocks have never been described from the NYC area. That the rhyodacite dikes are much younger than and geologically unrelated to the surrounding rock is borne out by cross cutting relationships and their glassy and vesiculated textures by contrast to the coarse-grained texture found in adjacent rocks of the Queens Tunnel Complex. Hitherto unknown, the rhyodacite dikes may mark the feeders to volcanic constructs and possible flows in Woodside, Queens - an important new view into the geological evolution of the area. Clearly, the suite of rhyodacite dikes, which are chemically, texturally, and temporally unrelated to their predominately mesocratic to mafic bedrock hosts, represent an anomalous geological formation that forever changes our view of the post-Paleozoic geological evolution of the New York City area.