Geological Controls on Effective Hard-rock TBM Tunneling in Crystalline Terrains

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ABSTRACT

Rock does not equal rock when it comes to cost-efficient tunneling. Vast global experience gained from over 50 years of TBM tunneling indicate that proactive geological investigations in the pre-bid and as-built periods can mitigate losses encountered during hard-rock tunneling. Changed rock condition scenarios can commonly be avoided by professional geological study.

The compilation of published bedrock data are an essential prelude to bidding subsurface work. At the pre-bid stage, core analysis to establish lithologic and mineralogic trends and targeted petrographic and geotechnical investigations are essential to fully characterize rock mass properties. In particular, cores should be examined at the tunnel depth to establish the weighted percentage of different rock types and for noting any anomalous rock types or horizons for further study. For example, fine-textured (aphanitic or vesiculated) dike rocks have proven to create collapsed ground as a result of intersecting cooling fractures yet coarse-grained dike rocks (pegmatites) are easily mined through by comparison. Allied studies on rock mass composition (felsic, intermediate, and mafic categories), texture, density, and metamorphic grade are also important. Here, petrographic analysis can offer profound insights into the degree of interlocking texture vs. foliated texture in metamorphic and igneous terrains. Rock mass texture and mineralogy, easily determined by petrographic study, are paramount in predicting TBM penetration destiny in igneous and metamorphic terrains.

Brittle fault and -joint systems of numerous orientations typically cut bedrock creating fractured and disturbed ground often with high water inflows. From cores extracted at and surrounding the tunnel horizon, comparative statistical studies on fracture index, RQD, and rock fabric orientation offer an effective means of categorizing the rock mass. During the as-built stage, geological mapping, structural analysis, fracture class mapping, and machine performance data together provide the ability to adjust to changed conditions. A clear understanding of the geology of any tunnel line is the simplest and most cost-effective method to mitigate losses encountered during TBM tunneling in crystalline terrains.

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INTRODUCTION

This paper is arranged under two major headings (Pre-bid Investigations and As-built Stage) to best summarize the important geological controls on tunneling that can and should be established long before subsurface construction is bid. As borings provide the most important information on the nature of the rock, a considerable research effort should be directed toward accurately categorizing rock mass conditions.

PRE-BID INVESTIGATIONS

Compilation of Published Maps and Reports

Effective tunneling is aided greatly by a thorough literature search to identify prevailing research on the region to be mined. In addition to the usual governmental sources, on-line search engines and local University resources can best fulfill the mission of compiling and digesting the state of the art knowledge on the bedrock of the proposed alignment. Not to be overlooked, research in the form of Masters and Ph.D. theses are harder to track down but good libraries can tap into that important resource. Naturally, any legacy engineering data from adjacent construction is an essential data resource for new construction.

Boring Analysis

Typical core logs include information on fracture density, recovery, lithology, and sometimes the nature of fracture surfaces. Statistical studies on the borings should include recording detailed lithologic, mineralogic, and petrographic characteristics by a trained professional geologist. One with local geotechnical research experience would be a preferred choice for such investigations. Integrated research on the actual core should be targeted at the depth of the tunnel horizon but comparative analysis outside the tunnel horizon should better identify possible changes that could result in surprises during actual tunneling. All of the core should be examined by the same geologist to establish consistency and core logging by drillers without professional degrees in geology of geological engineering should not be relied upon without careful checking. In particular, anomalous lithologies are the common cause of changed condition losses in underground work. Professional geologists are more likely to accurately identify different lithologies – many examples of misidentified rock types have resulted in tunneling inefficiencies related to changed conditions.

Fractures. Detailed boring analysis in the pre-bid interval allows for compilation of RQD, % recovery, and fracture index – all useful tools in outlining the major parameters for geotechnical predictions in tunneling. Yet, the nature of the fractures is often overlooked. Fracture width, filling type (broken rock, quartz, pegmatite, clay, zeolite, calcite, pyrite), consistency (healed, fissile, soft, firm, hard), roughness (planar, undulating, stepped, slickensided, smooth, and rough) are the parameters that allow for application of the Q-system as developed by Barton et al. (1977) and Bieniawski (1989). Q-system quantitative analysis has been proven to be an effective way to predict support requirements in TBM tunnels. Downhole geophysical imaging techniques allow for accurate mapping of fracture density and orientation.

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Regional fracture patterns can commonly be identified by literature searches but local fracture patterns can best be identified by careful pre-bid core study and by as-built mapping. Joints sets are commonly parallel to regional fault trends but can also be superimposed on the regional fault orientations as conjugate sets. Single faults or joints seldom lead to tunneling difficulties but zones of sub parallel fault dislocations and areas of intersecting faults often result in blocky ground that can slow penetration, induce TBM cutter and machine damage, or require installation of additional support (Merguerian, 2002). Some forms of fractures are unique to certain rock types. For example, fine-grained or glassy igneous dike rocks bear cooling joints both parallel and perpendicular to the dike margins (Merguerian, 2001). Depending upon the orientation and thickness of such dikes, intersecting cooling fractures can result in profound crown and sidewall instability (Figure 1). Highly folded metamorphic terrains also possess fractures unique to the rock mass. In particular fractures formed parallel to the axial surfaces of folds (A-B joints) and those formed perpendicular to fold axes and lineations (A-C joints) can compromise tunnel integrity depending upon structural orientations vs. tunnel alignment. In polydeformed terrains, late stage folds can induce fractures related to axial surface slip cleavage that together with joints related to earlier folds can produce an internally weakened rock mass. Late brittle faults typically reactivate older surfaces of structural weakness.


Figure 1 – View of crown and sidewall instability and support in the Queens Water Tunnel, NYC in an area of red-colored rhyodacite dike rocks, unique to the NYC area. The crown failure resulted from internal cooling joints and intersecting NNE-trending faults. Note that the cooling joints cut not only the dike rocks but project into the surrounding gneisses, further extending the area of disturbed ground. The lack of roughness along joint surfaces enabled the blocks to fall freely from the working face, crown, and sidewalls resulting in considerable cutter damage and downtime for repairs and support installation in excess of the patterned rockbolts used throughout the tunnel. (Queens Tunnel station 152+25. Digital image by C. Merguerian taken 27 May 1998.)

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Foliation. The nature and orientation of foliation (or the lack thereof) is a second order control on effective TBM tunneling. Most foliated rocks are rich in mica, a soft mineral that tends to provide internal weakness in the form of a basal cleavage. Highly flattened and foliated rocks (slate, phyllite, and schist tend to split readily on the foliation and as long as the foliation is not horizontal or vertical, allows for, and in fact fosters rapid excavation. Thus, favorable orientations occur when the foliation dips away from or toward the TBM cutterhead with the strike more or less connecting opposing tunnel springlines. All other things being equal, when the foliation dips toward the heading, crown fallout in the heading may be a problem but when the foliation dips toward the TBM head, stable headings and maximum penetration rates can be anticipated. Excessive fines can result when the TBM cuts across the foliation (horizontal or vertical orientation), especially in hard, recrystallized gneissic terrains. Regional mapping and oriented core study will alert contractors to the prevailing orientation allowing potential adjustments in TBM drive direction that may enhance penetration. Stereonet analysis is the most effective method of understanding the variation and prevailing orientation of foliation or gneissic layering in a given terrain.

The mineralogy of the foliation is of importance here as well. Although mica is the most common foliation-producing mineral, not all foliated rocks are micaceous. Hornblende and other linear minerals can also produce a foliation in rocks in much the same way that spilled box of pencils can flatten out into a planar orientation on the floor. Metamorphic terrains that are highly lineated are isotropic in that penetration parallel to the lineation is typically less than across the lineation although this will depend on the mineral and its individual lattice properties. Deformation can produce planar and linear anisotropies in rocks in the form of grain-shape flattening (lenticular quartz), strain hardened mylonitic textures, and crystallographic lineations (aligned c-axes of quartz and amphiboles). All of these can be identified by careful pre-bid core sample and petrographic analysis (as discussed below).

Lithology. The overall composition of the rock mass holds a first order control on TBM penetration. Stated simply, the more mafic (iron- and magnesium-rich) the rock mass the lower the penetration rate. Careful core analysis and tabulation should discriminate between felsic, intermediate, and mafic lithotypes at the tunnel horizon. Weighted bar- or pie-graphs display such information in an easy to understand graphical format (Figure 2). In this way, a clear quantification and understanding of the anticipated lithologic abundances can be established during the planning stages of TBM engineering, construction, and utilization.

Special rock types (such as fine grained or glassy dike rocks, amphibolite, pegmatite, intrusives, garnetiferous zones, quartz veins) have important bearings on TBM penetration and these should be identified and categorized accurately. Metamorphic grade has a controlling influence on penetration owing to the decrease of hydrous minerals phases during progressive metamorphism. As explained below, unique igneous and metamorphic textures can make or break a tunneling contract. These can often be identified early in the process by targeted, careful geological examination.

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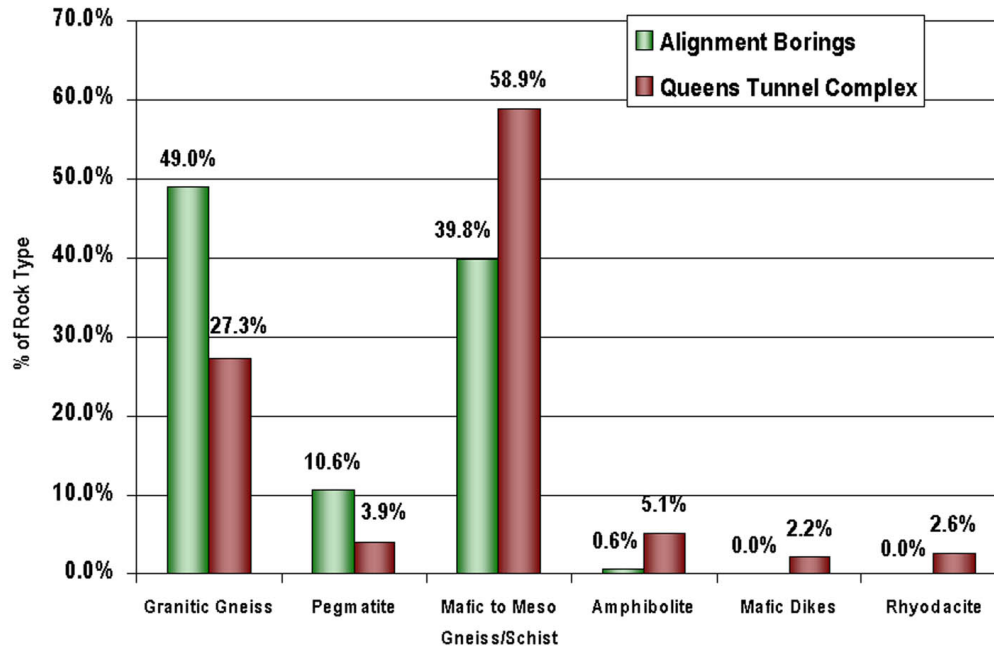
Figure 2 – Comparative bar graph showing the disparity between lithotypes identified by examining borings (green) vs. those found to occur in a tunnel horizon by as-built mapping (red). Note the difference in the relative proportion of granitic and pegmatitic (felsic) rocks vs. the mafic, amphibolitic, and mesocratic (mafic and intermediate) rocks and the presence of unanticipated rocks of rhyodacite affinity. This compositional variation from pre-bid anticipation proved an impediment to efficient mining. (Adapted from Merguerian and Ozdemir, 2003.)

Density. The density or specific gravity of rocks is a simple and useful litmus test for predicting TBM penetration. Higher density rocks are less penetrable simply because they tend to contain dense and/or hard minerals such as garnet, pyroxene, and aluminosilicate minerals such as sillimanite and kyanite. Density is readily measured using simple, inexpensive apparatus. A density profile along the tunnel alignment can help predict variation in density over a planned TBM expedition and can help identify anomalous zones or trends in rock mass properties (Figure 3).

Petrographic Mineralogy. Perhaps the most useful but underutilized piece of scientific equipment by the tunneling industry is the petrographic (polarized light) microscope. The details of the mineralogy and texture of any rock mass are simply established using standard petrographic techniques. In this method a thin slice of sample is mounted on a glass slide and ground to a specific optical thickness of 30 microns by any number of firms specializing in such work. Careful petrographic analysis by a trained specialist can establish the actual percentage of common minerals such as feldspar, quartz, mica, amphibole, and pyroxene and also identify the existence and volume percentage of garnet, sillimanite, kyanite, and other abrasive minerals. Establishing an abrasivity index is paramount in predicting penetration rates and whether the production of excessive fines will occur during TBM mining. Adjustments in the metallurgy of cutters, cutter spacing, and head configuration can thus be made in advance of mining.
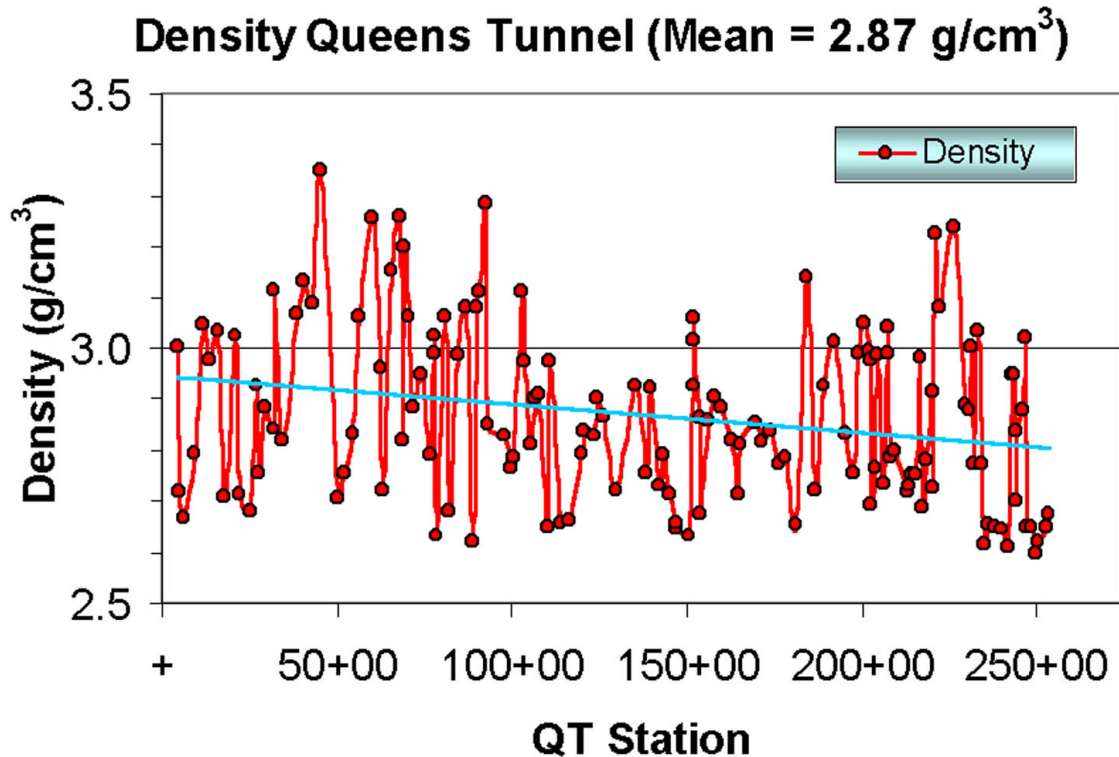
Figure 3 – Rock mass density variation as compiled from sawn slabs from 161 samples collected during as-built mapping of the Queens Tunnel, NYC. The graph indicates that the bulk density of the tunnel varied from 2.62 to 3.35 gm/cm^{3} and that density decreased toward the higher stations (sloping dark line). The mean density (2.87 g/cm^{3}) was in keeping with the lithotype analysis (See Figure 2.) that indicated that more intermediate- to mafic lithologies were penetrated in the tunnel by comparison to what core study suggested. (Adapted from Merguerian and Ozdemir, 2003.)

Textures in crystalline rocks vary greatly depending upon whether they are igneous, metamorphic, or hybrid. For the igneous rocks, aphanitic (fine-textured = 0.05 mm to 1 mm) and glassy textures (no crystals) have proven to be an impediment to efficient mining because such rocks do not produce TBM chips as readily as coarse-textured or foliated rocks. Instead they tend to produce sharp, angular blocks that clog grizzlies and damage cutters and belted conveyance systems. Glassy textures, as found in hypabyssal dike rocks, are highly injurious to cutters but they can be quickly and easily identified utilizing standard petrographic techniques. On the positive side, very coarse-textured rocks (pegmatitic rocks have individual crystals > 10 mm in size) and break readily as the large crystals tend to fail along their internal cleavage surfaces or along boundaries with adjacent crystals. Moderate textured rocks with phaneritic texture (= 1 mm to 10 mm) break with moderate ease unless the rocks have been annealed by metamorphic reheating. Indeed, annealing (Merguerian, 1988) produces granoblastic textures that can decrease penetration rates. As described below, metamorphic recrystallization can produce annealed, granoblastic textures in igneous or metamorphic rocks of appropriate composition and transform foliated rock masses into massive gneiss. Such changes inhibit the production of TBM chips because of the lack of internal surfaces of weakness to act as loci for crack propagation.

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Metamorphism. Metamorphism is a dehydration reaction that tends to drive off water from minerals. Progressive metamorphism is quite common in crystalline terrains. Those exhibiting evidence for polydeformation and syntectonic intrusion also display rapid changes in rock mass properties over short distances. Relatively consistent rock conditions have been recorded from low- to medium grade terrains with slaty-, phyllitic-, and foliated textures predominating (Figure 4a). At higher metamorphic grades (upper amphibolite or granulite facies) the destruction of mica and amphibole and the replacement of these foliation-producing minerals by anhydrous phases that include quartz, feldspar, orthopyroxene, clinopyroxene, garnet, cordierite, corundum, and aluminosilicate minerals produce gneissic rocks that tend to lack a penetrative foliation. Such rocks exhibit equigranular mineral textures displaying no preferred orientation as indicated by stable 120° crystal boundary configurations (Figure 4b; compare to 4a). At the highest metamorphic grades (granulite or high pressure granulite facies) thorough recrystallization results in a tough, anisotropic rock mass. Such textures, easily identified by the microscope, produce rock masses that are legendary for their poor TBM penetration rates and by the extremes of blocky ground and excessive fines (Merguerian and Ozdemir, 2003).

Other Types of Geological Testing. In areas of complex geology, geochemical and geochronologic analysis can often be employed to correlate rock types with those of known properties in adjacent areas (Brock, Brock, and Merguerian, 2001). Minor-, trace-, and rare-earth element analysis and geochronologic testing have been effectively employed for precise regional correlation. Though not by any means a standard test at the pre-bid stage, in complex areas where the stratigraphy of the rock mass is up for question, such techniques, although somewhat expensive compared to those described above, can be unequivocal.

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AS-BUILT STAGE

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In order to better mitigate changed conditions, careful monitoring of TBM data loggers during mining should be integrated with an active geological mapping program. Probe drilling should be required in all subsurface contracts.

Machine Performance Data

On-board TBM data loggers allow for instantaneous data from an operating TBM by recording such useful parameters as stroke, amperage, and thrust. When graphically coupled with pre-bid geological investigations and integrated laboratory testing (including punch, point load, tensile strength, Cerchar abrasivity, linear cutting tests, and as-built mapping), such data together can help predict TBM penetration for the length of the contract, allow for efficient cutter change programs, and allow the potential for machine modification in advance of TBM insertion.

Geological Mapping Program

A well–planned geological mapping program should be required of all underground construction. This undertaking not only provides a way to quickly identify and adjust to changed conditions
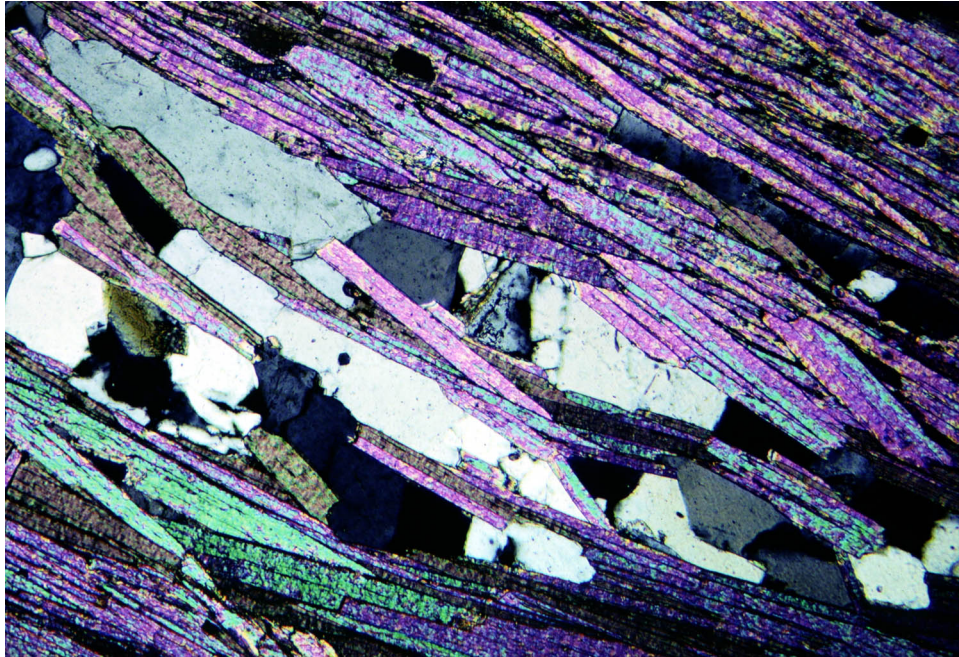
Figure 4a – Photomicrograph in crossed nicols of aluminous Hartland schist (N403-1; World Financial Center site, lower Manhattan). The section shows fine-grained lenticular quartz and minor plagioclase separated by aligned muscovite and minor biotite (highly colored crystals). Such directional mineral growth results in a penetrative micaceous foliation.
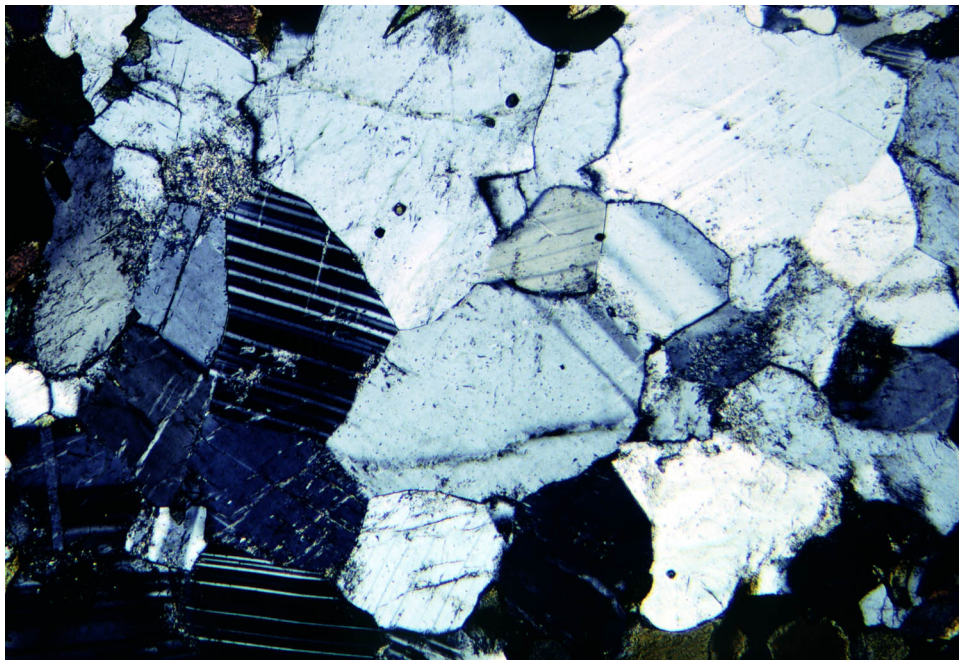
Figure 4b – Photomicrograph in crossed nicols of Queens Tunnel gneiss (Q085; Station 159+80) showing granoblastic intergrowth of plagioclase and minor quartz. Note the medium-grained granular texture, the stable 120° grain boundaries of the interlocking plagioclase, and the lack of any penetrative foliation. Both photomicrographs are 2 mm across.

but ultimately provides a data resource for future construction in adjacent or similar terrains. Circumferential mapping at the scale of 1" = 10' allows for enough detail to truly categorize the rock mass conditions during the as-built stage (Figure 5). Fracture class mapping (Sandberg et al., 1994) and detailed mapping of brittle features (faults and joints) will supplement the data collected by other means and provide an important predictive comparison for the life of the TBM mining endeavor. Luckily the tunneling industry has seen the importance of such compilations and many jobs require these services on an on-going basis.
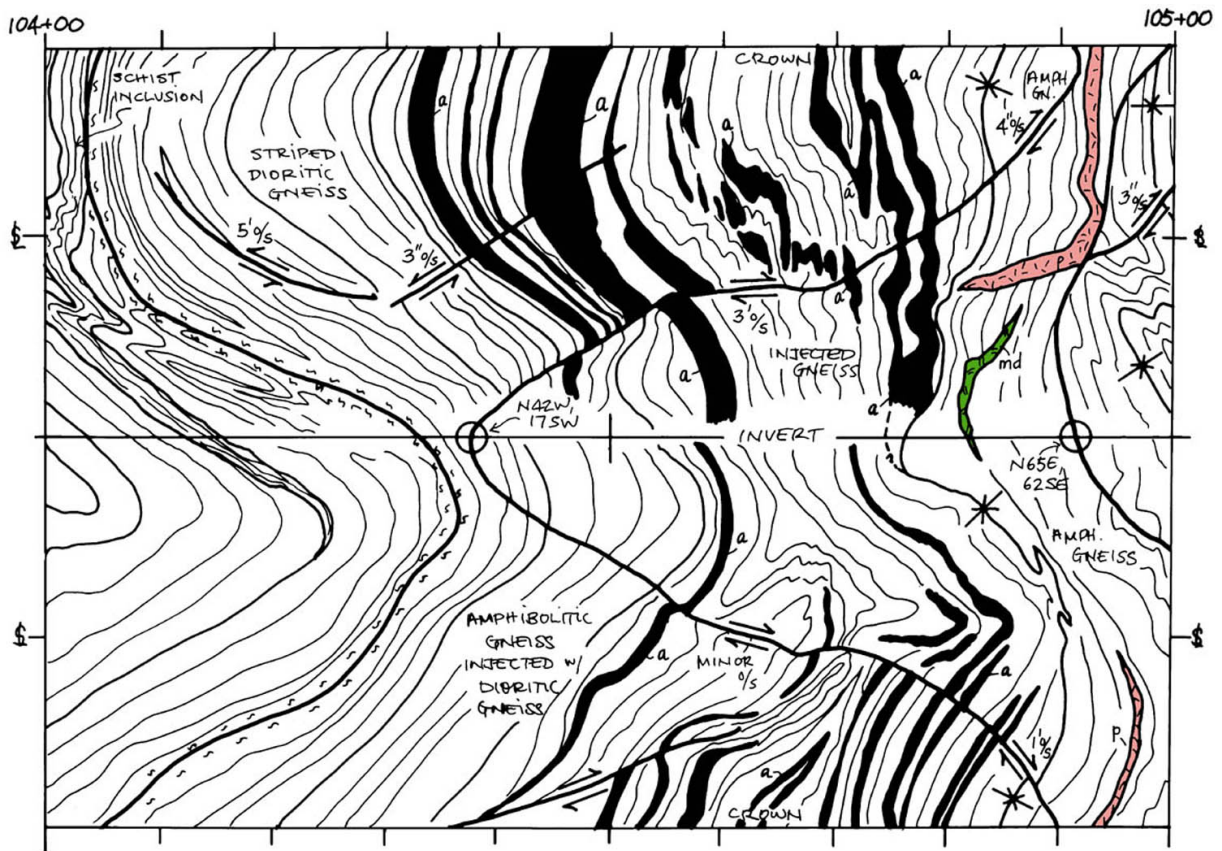
Figure 5 – Geological map of the Queens Tunnel Complex shows granulite-facies amphibolite gneiss and younger dioritic orthogneiss cut by pegmatite (p) and a mafic dike (md). The amphibolitic gneiss is locally sheared but clearly occurs as inclusions in the dioritic gneiss. A low-angle reverse fault oriented N42°W, 17° SW cuts the invert at Station 104+38 (tunnel bearing is N22°E). A younger N65°E, 62°NE brittle fault cuts the invert at Station 104+91.

   Note: 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. The position of the tunnel springline is shown at the map edge. This map, one of 250 in the Queens Tunnel Map Portfolio, covers 100 running feet of the tunnel. Original map scale 1"=10'; tunnel diameter 23' 2". (From Merguerian, 2000.)

Probe Drilling

Probe drilling in advance of TBM excavation during tunneling is a cost-effective way to mitigate loss as a result of excessive water inflows and to identify potential environmental hazards.

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Urban areas that have developed during the industrialization of the twentieth century are particularly prone to subsurface build-ups of hydrocarbon pools that can be gravity injected into tunnels during construction as a result of breaching of faults and fractures that intersect pools of contaminants in the unconsolidated drift above the tunnel horizon. Such inflows result in excessive downtime as means and methods of filtering out contaminants are devised and implemented. Regular probe drilling in advance of TBM mining can identify such hazards and localize the source for effective removal or grouting before the entire tunnel becomes contaminated or flooded.

CONCLUSIONS

As a result of internal variability, crystalline terrains provide an unforgiving medium for effective TBM utilization and penetration. A clear understanding of the geology of any tunnel line is the simplest and most cost-effective method of mitigating potential losses encountered during TBM tunneling. During the as-built stage, geological mapping, structural analysis, fracture class mapping, and machine performance data together provide the ability to adjust to changed conditions.

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