ASCE Metropolitan Section Geological Constraints on TBM Penetration for Hard Rock Tunneling, New York City, NY

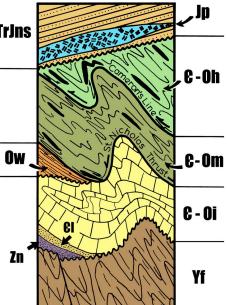
Charles Merguerian







NYC Rocks



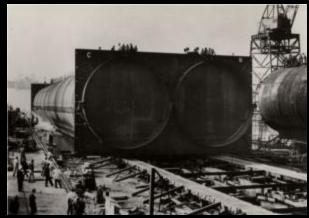


NYC TBM Projects (1964-2010)

Richmond Water Supply Tunnel West Side Interceptor 63rd Street Tunnel Brooklyn Water Tunnel Queens Water Tunnel Con Edison Steam Tunnel Manhattan Water Tunnel East Side Access Project Croton Water Tunnel/Plant No. 7 Line IRT **Second Avenue Subway**

Richmond Water Supply Tunnel (1964)

- First TBM Job NYC (Perini-Morrison-Knudsen JV)
- Tunnel planned from Staten Island to Brooklyn
- German TBM Failure After Only 400'
- Indurated Pegmatitic Schist Too Hard For TBM
- Cutters (Diamond Grinding Heads) and Bearings Failed
- Granite, Serpentinite, Schist = Hartland Formation
- Main Shaft in Tompkinsville, Staten Island



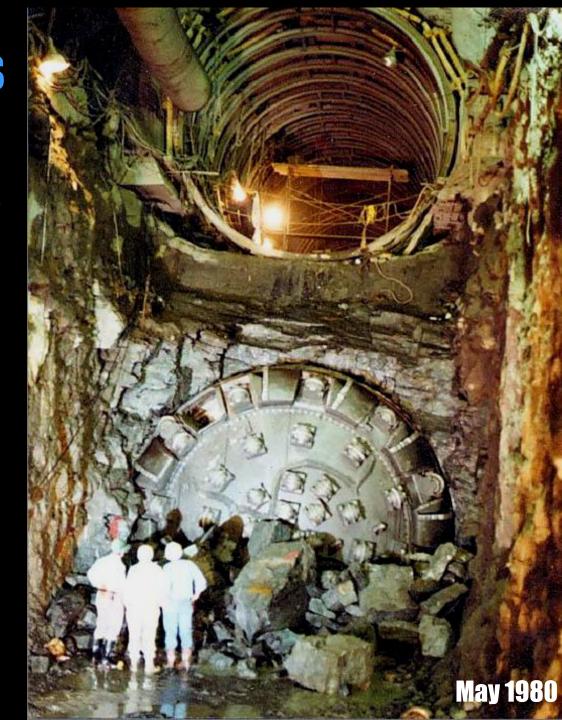
West Side Interceptor

- Second TBM Tunnel in NYC
- Two 9,000 Tunnels
- S=11' / N=8.5' Diameter
- ~Jul 1971 Jul 1973
- Jarva Mark 12-1200
- Last 1,100' D&B Mined in Inwood Marble
- Hartland Formation (S) and Manhattan Schist (N)
- 488 Button Cutters in 8955'
- Penetration = 4.5'/Hr in 11'



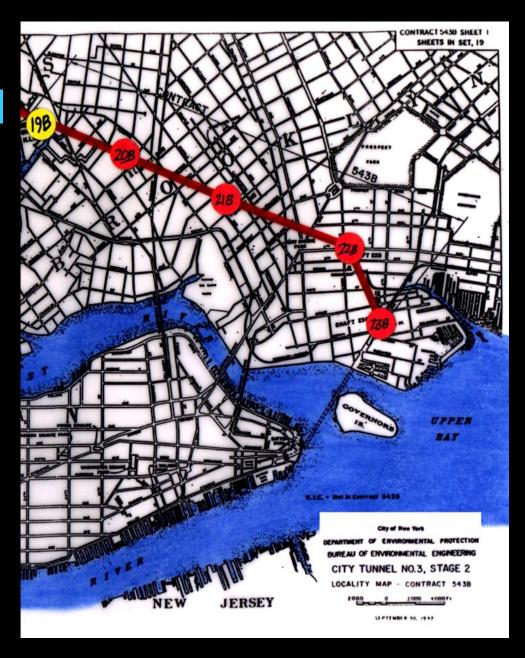
63rd Street Tunnels

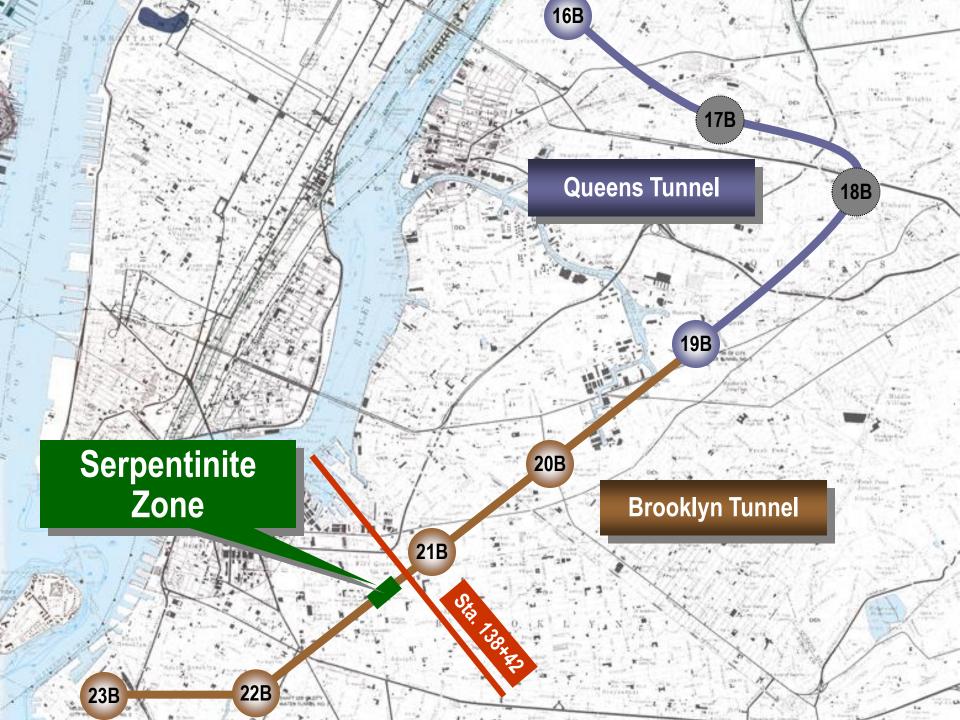
- Twin Tunnels 4 Tracks
- Robbins 203-205 TBM
- Diameters 20.17'/22'
- Feb 1980 May 1980
- Immersed Tube First
- Lower Level for LIRR
- Fordham Gneiss and Hartland Formation
- Penetration = 4.31'/Hr



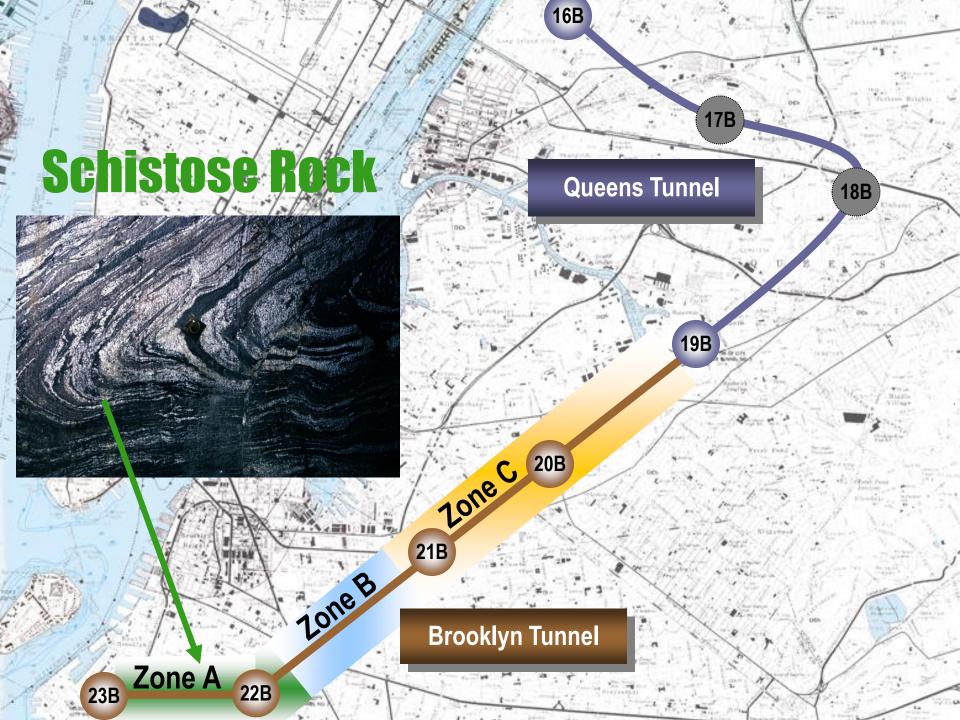
Brooklyn Water Tunnel

- Open Beam TBM from 63rd Street Tunnel Job
- July 1994 Jan 1997
- 19' Diameter; 5.5 Mi
- Variable Penetration Through Zones A, B, C
- Fordham Gneiss and Walloomsac Schist
- Penetration = ~10'/Hour



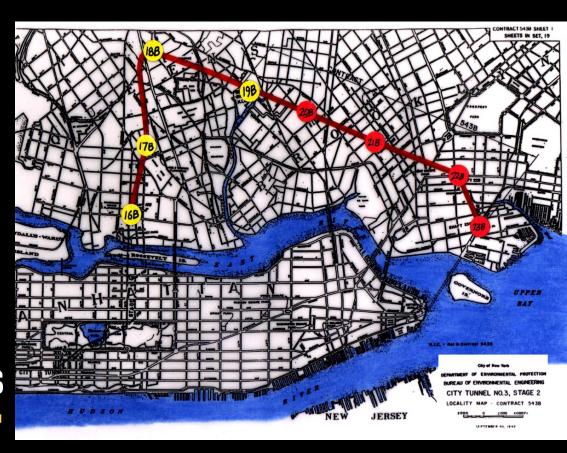






Queens Water Tunnel

- Open Beam HP TBM
- Oct 1996 Oct 1999
- 19" Cutters; 4.76 Mi
- Garnet Zones (10%)
- Dike Swarm
- NNE Fault System
- Intersecting Faults
- Subhorizontal Fabrics
- QTC = Fordham Gneiss
- Penetration = 5.82'/Hr

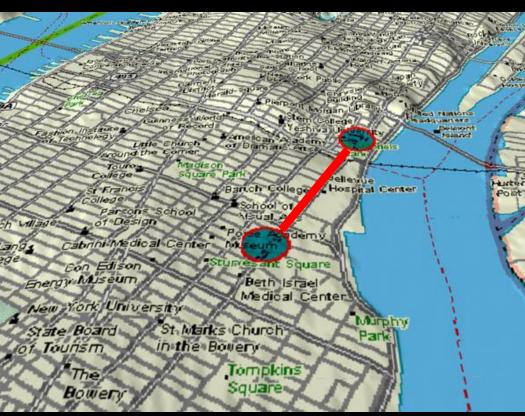


Con Edison Steam Tunnel

- 12.5' Open Beam HP 215-257 TBM
- 17" Cutters; Length 0.76 Mi
- Oct 2002 Feb 2003
- Hartland Formation
- Penetration = ~9'/Hr











Manhattan Water Tunnel

- Retrofitted Con Ed Steam TBM
- Separate Drives (N, S, E-W)
- Length 9.04 Mi
- Diam 12.5'; 17" Cutters
- Hartland Formation
- Penetration = 13.6'/Hr





East Side Access Project

- Diam = 22'; 7.7 Mi; 19" Cutters
- Gently Inclined Hartland
- Seli Double Shield (7'/Hr)
 Robbins Open Beam (10'/Hr)
- Penetration Max = 15'/Hr







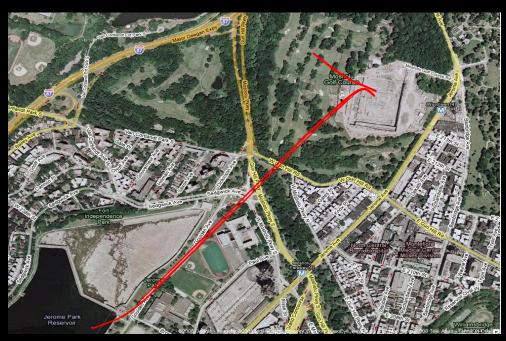




Croton Water Tunnel/Plant

- Retro Manhattan TBM
- 17" Cutters (27 Total)
- Low 3,650'; Hi 3,150'; Raw 865'
- Diam = 13.5'; Length 1.29 Mi
- Bid as D&B; ~250 Mining Days Saved w/ TBM
- Fordham, Yonkers Gneiss
- Penetration = ~10'/Hr



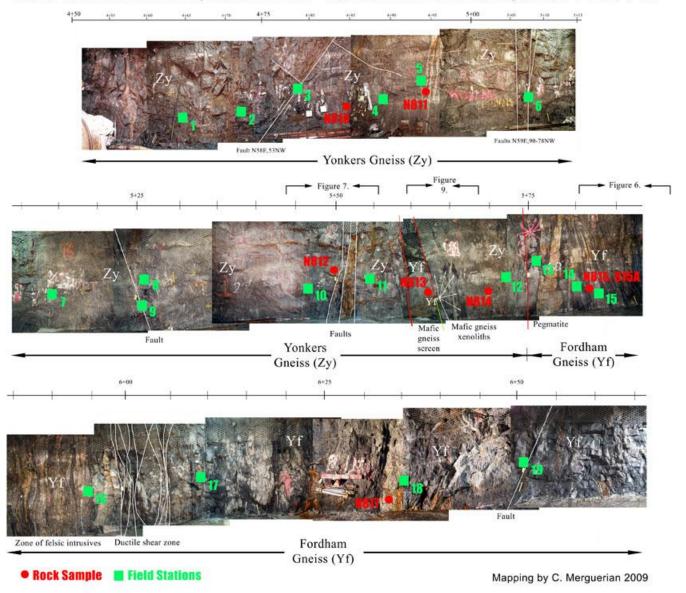








Croton Water Treatment Plant, Bronx New York - North Wall Raw Water Tunnel, Stations 4+50 to 6+65



No. 7 Line IRT Extension

- Double Shielded TBMs
- 34th Street Cavern D&B
- Diam = 22.5'; Length 1.78 Mi
- Hartland Formation
- 4,700' One Year (~16'/Day) with Installed Segments









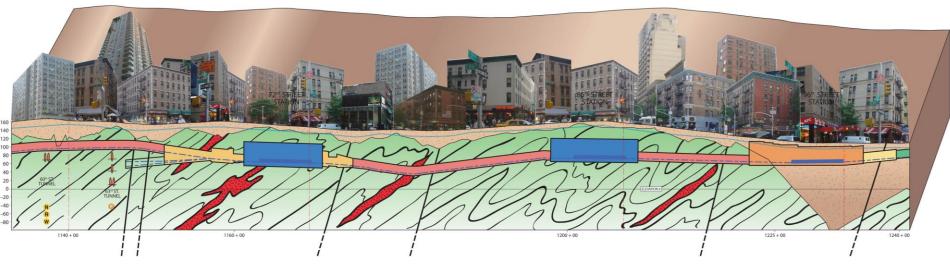
Second Avenue Subway

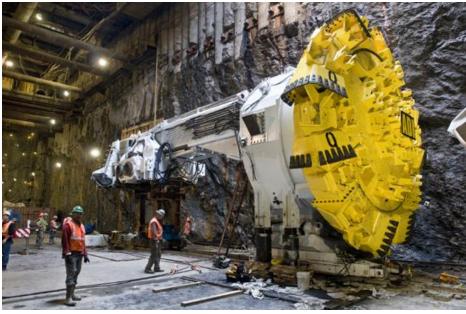




1929 - NYC BOT Proposes
Second Avenue Subway
1931 - Plans Postponed
Depression Era
\$86M → \$249M → \$500M
By 1948 - Abandonment

Threading The Needle









Factors: TBM Penetration Destiny

Intrinsic Factors (Penetration Rate)

- · UCS
- Fracture Density RQD/Recovery
- Faults/Joints
- Mineralogy
- Hardness/Density
- Rock Type
- Texture/Metamorphic Grade
- Fabric Orientation/Development

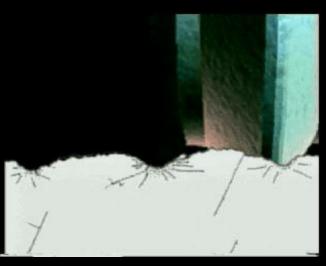
Episodic Factors (Utilization)

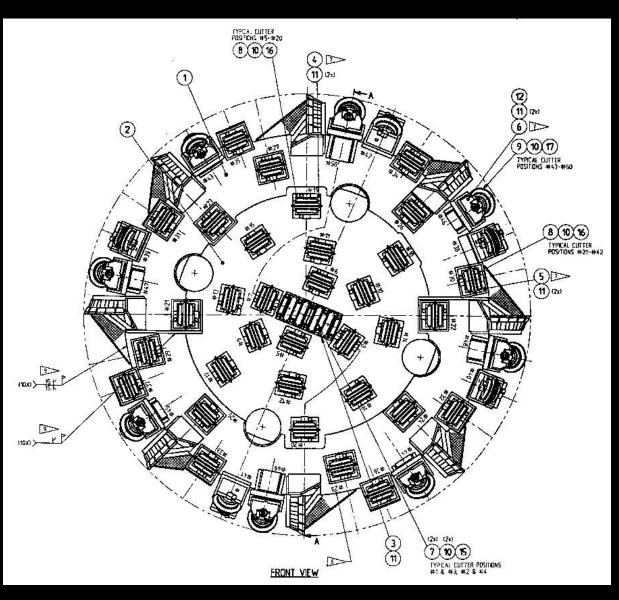
- Convergent Fault Zones
- Unusual Rock Types/Structures
- Stress Popping/Heave
- Water Inflows



TBM Chip Production

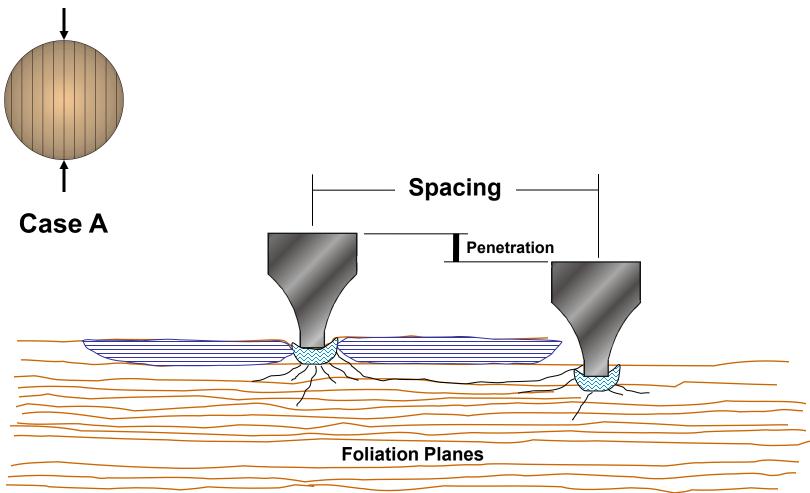






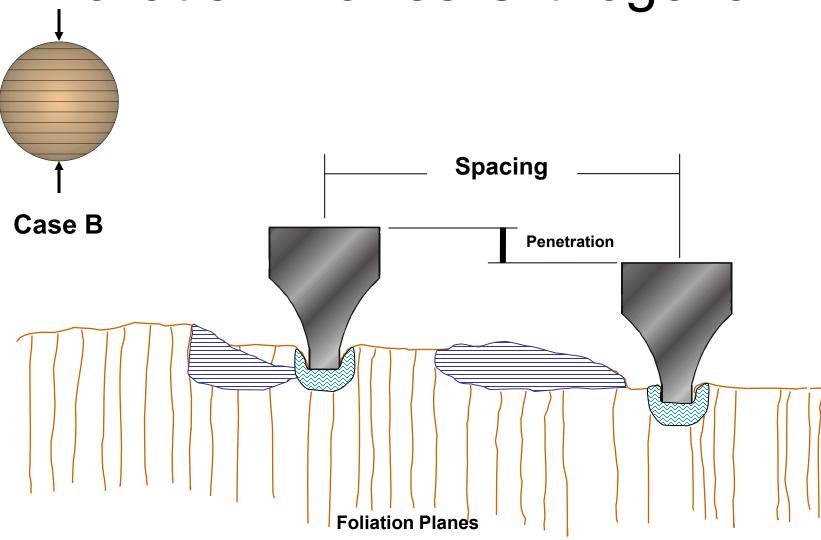


Foliation Planes Parallel

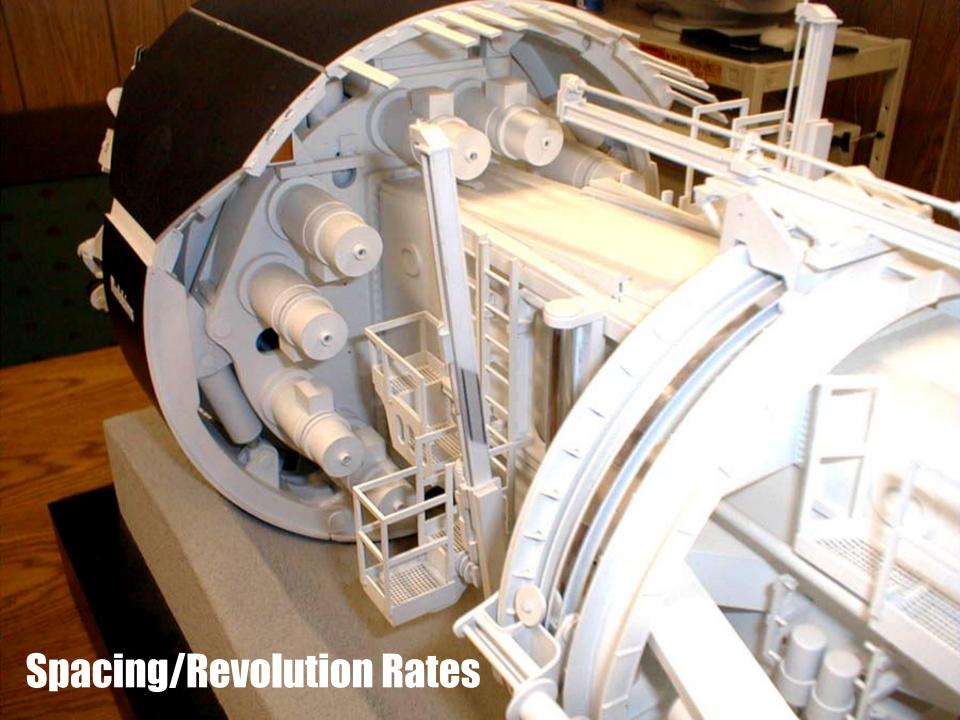


Chipping mechanism when TBM advancing perpendicular to foliation (Case A)

Foliation Planes Orthogonal



Chipping mechanism when TBM advancing parallel to foliation (Case B)





Queens Tunnel TBM 422 HP Electric Water Cooled, Three Phase Motors

10 Motors Total
Usually 8 Online
Rotated Cutterhead
at 8.3 Rev/Min



New Research TBM Cutter Head Torque Dynamics

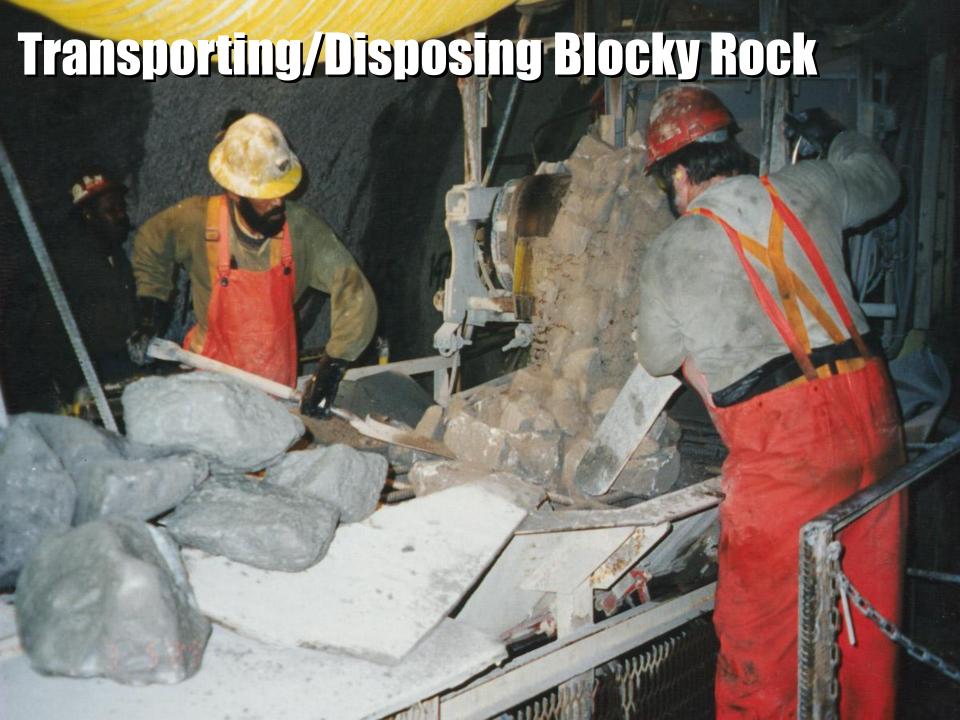


What Are the Geological Causes of Intrinsic and Episodic Hard Rock TBM Effects in Crystalline Terrains?

Excessive Fines Blocky Ground Unstable Headings and Sidewalls Stress Popping Water Inflows Cutter Damage/ Cutter Wear = Poor Penetration/Utilization

















Unforseen Tunneling Problems



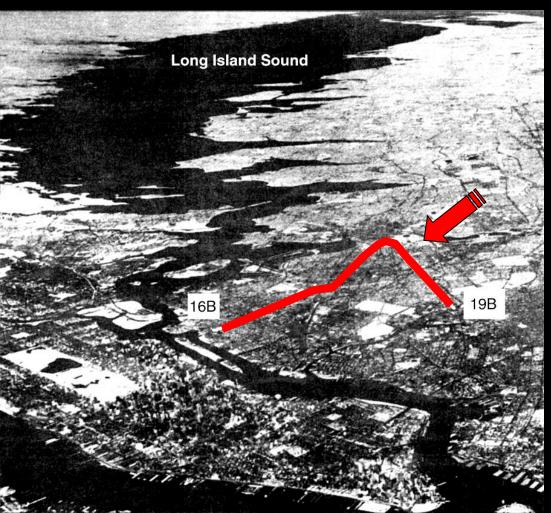






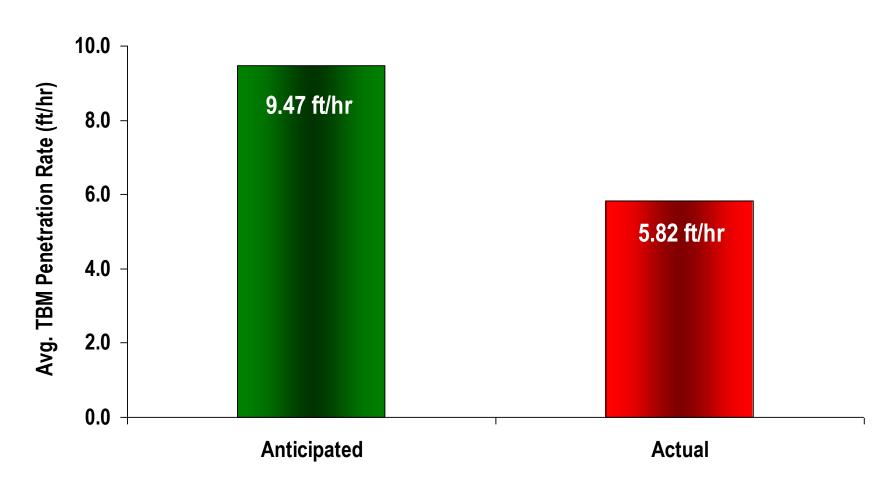


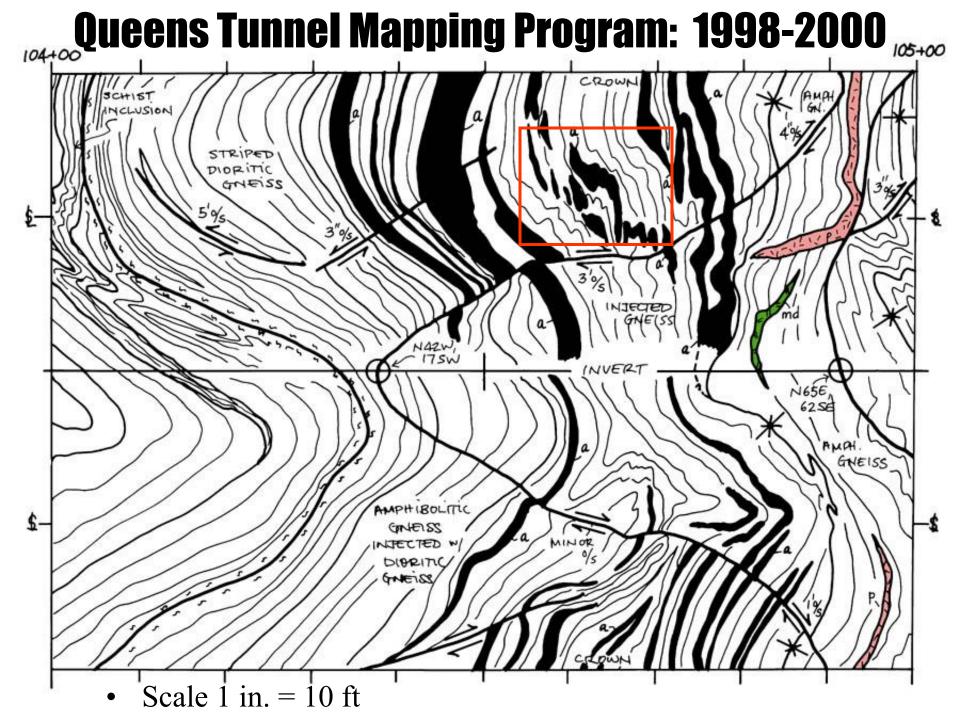
Construction of the Queens Tunnel NYC Water Tunnel #3 Oct 1996 – Oct 1999





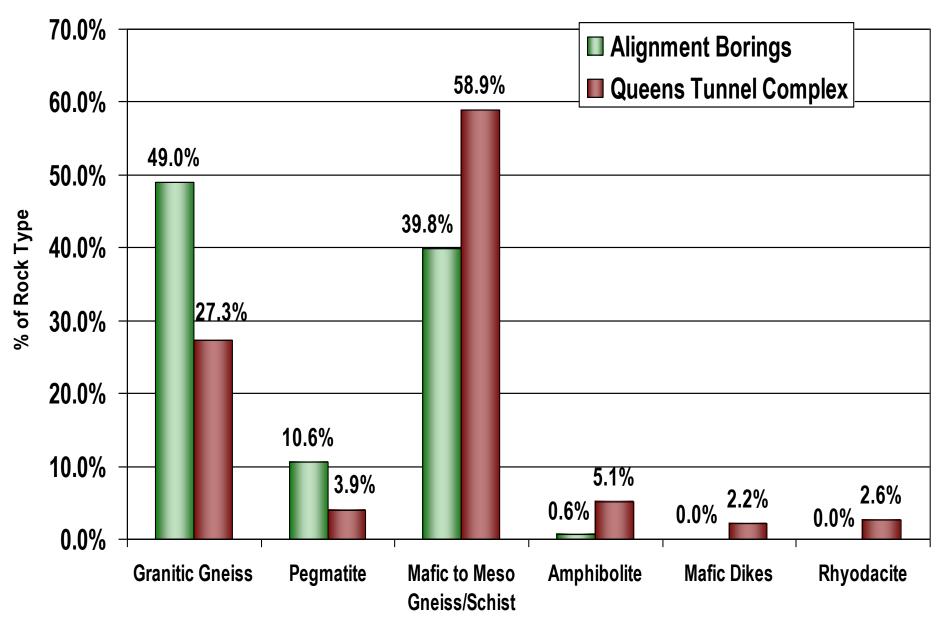
QT Anticipated vs. Actual Penetration Rate





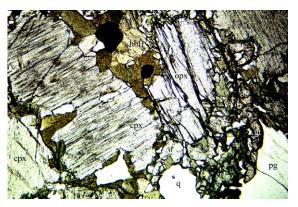


Comparative Lithologic Analysis



Petrographic Analysis (92 Samples)

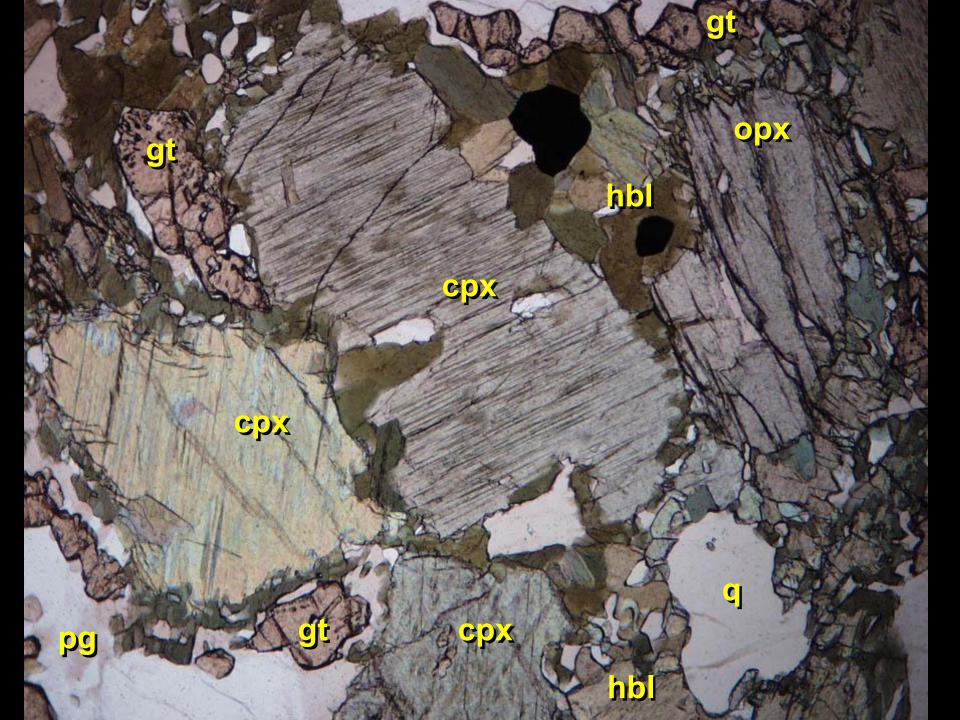
- Texture
- Mineralogy
- Internal Structure
- Metamorphism

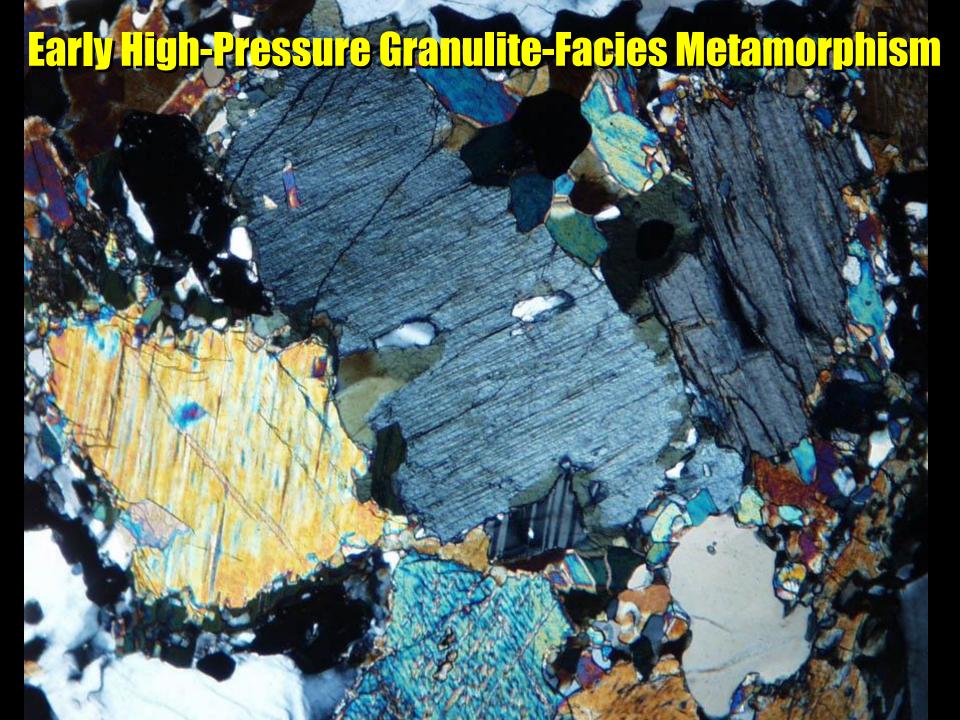


Thin section photomicrograph

Number	Location	Color	Densi	yQtz	Kspar	Plagio/	An	Орх	Срх	Hbld	Bio	Garnet	Opaque
Q109	004+80					М	35	M		M			
Q109	004+80	25	2.72	М		М	35			m	m	m	
Q110	006+42	10	2.66	М	tr+AP	М					m gnbk	tr	tr
Q111	009+25	25	2.79	М		М		m		tr	m	M py encl Q	tr
Q112	011+60	35	3.05	m		М	51		M exsol	m gnkh		М ру	
Q114	015+90	45	3.03	m		М	53-39r	n Mns omeEx	o l s∕loExsol	mgnkh		m necklace	tr
Q115	017+70	10	2.71	М	tr AP	М				m bugn sieve	m rbn	m porange	tr
Q117a	022+25	15	2.72	М	tr	m	27			m dgygn	m rbn	m porange siev	etr
Q119	026+65	45	2.93	m 10	De 1 15	М	27			M khgn	tr rdbn	m	m
Q123	032+15	60	3.11	m		m	44	m		m gnHB	m rbn	M sieve	tr
Q127	042+67	60	3.09	m		М		tr	М	M gnkh	m red	М	m
Q129	049+95	25	2.71	М	M	М	low				M kh	M	
Q130	051+83	15	2.76	40	tr	М					m obn	M.vermic/sieve	trims
Q133	059+95	55	3.26	m		М	38-29		М	Mkhtan	m	M	m
Q134	062+45	60	3.17	m		М	28-40F	Rev Zoning	М	M bugn some	vermic w i Qtz	M fine sieve/ve	m1n0cverm
068+10	068+10	5:50		М		M	55	m	М	m gn		m vermic with p	lang
070+60	070+60	45		М		М	45+	?	core?	m. Gn	m	M	m
Q141	071+80	30	2.9	5		M sieve	•	M sieve		tr gn	M okh	M sieve	2

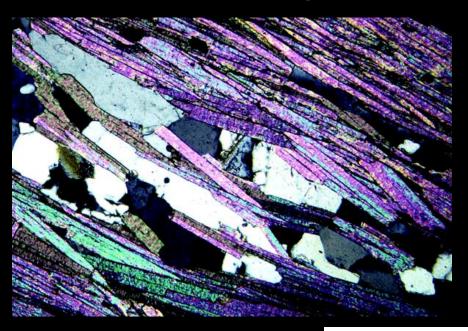
Petrographic Data Sheet

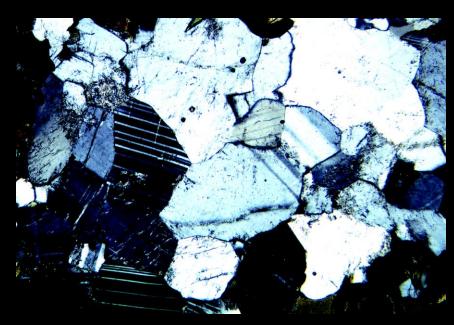




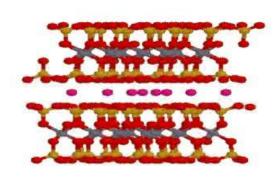
Mica Content of Rock Fabric

Micaceous (+/- hornblende) penetrative foliation vs. non-foliated "granoblastic" rock mass

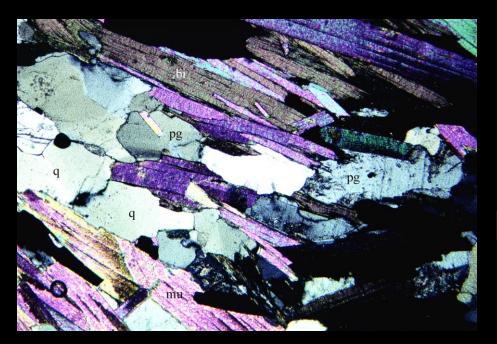




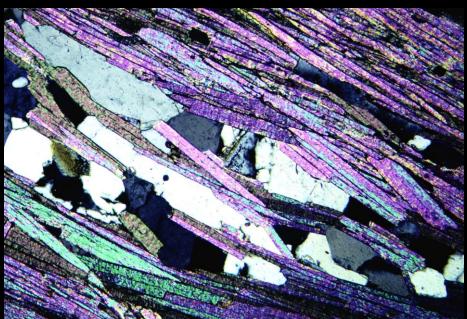
Foliated



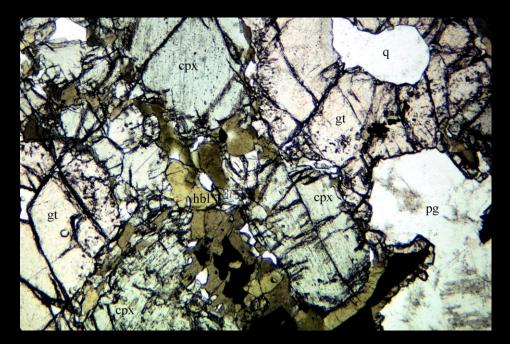
Non-Foliated



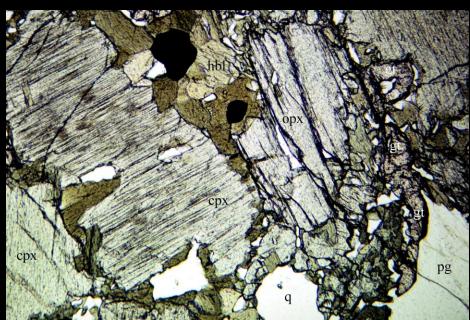
In Western and Central Manhattan: Amphibolite Facies Schists Well-layered Hartland Fm. Penetrative Foliated Textures Great Rocks for Tunneling and Excavation!

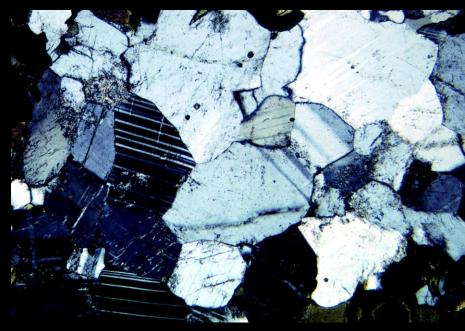






Granulite Facies Gneisses
Found in the Queens Tunnel
and Elsewhere =
Granoblastic Textures
Tough Rocks for Excavation





Foliation Index

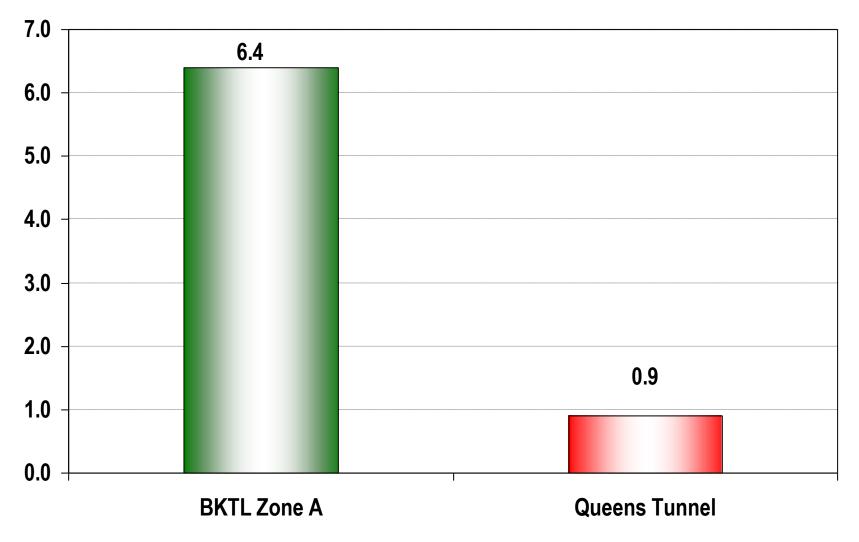
Foliation Index = % biotite

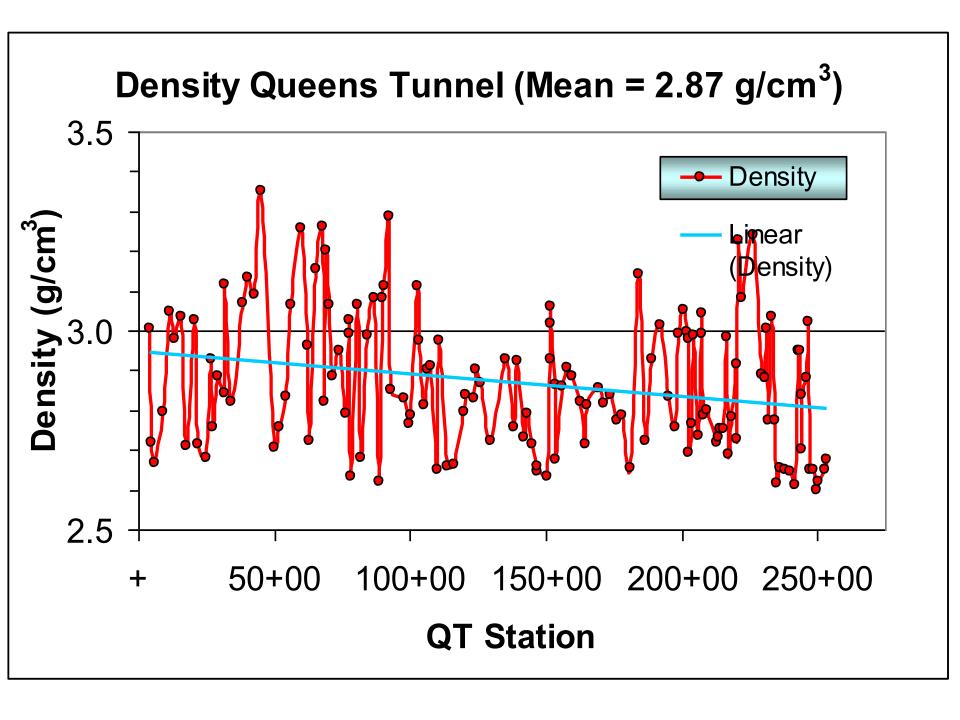
% hornblende + % pyroxene

- Indicates relative degree of regeneration of weak mica during retrograde metamorphism
- Foliated rocks fail more readily because of the continuous nature of the mica crystals, a soft mineral with perfect basal cleavage
- Aligned biotite produces a penetrative metamorphic foliation in Zone A of the Brooklyn Tunnel, not found in the Queens Tunnel

Foliation Index

Ratio of % biotite to % [hornblende + pyroxene]



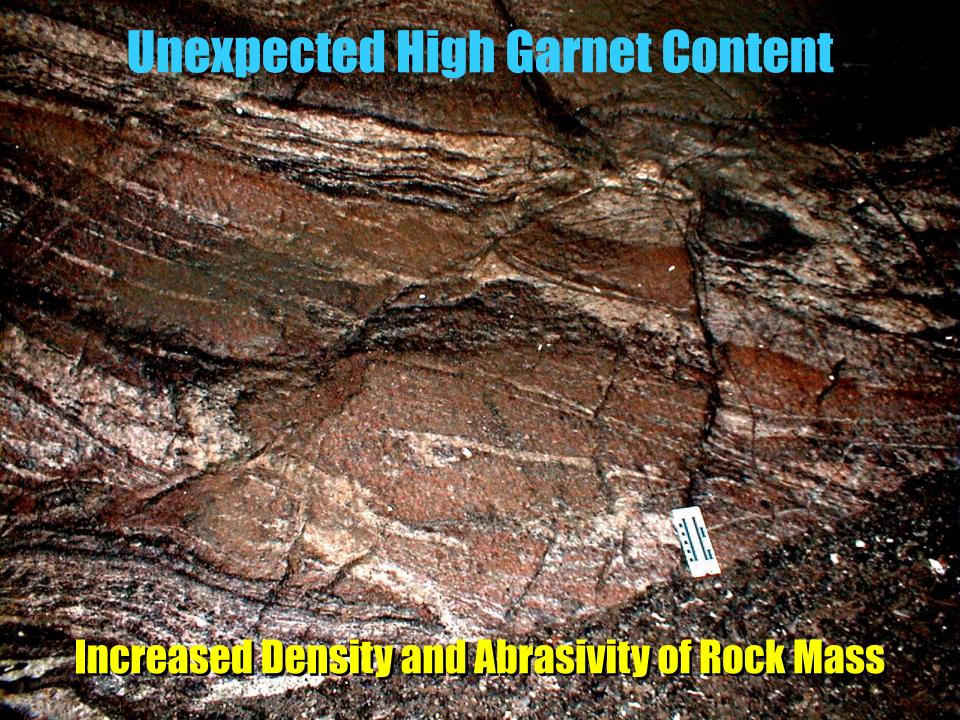


Density Analysis

			Mean
	Low	High	Density
Granite	2.516	2.809	2.667
Diorite	2.721	2.960	2.839
Gabbro	2.850	3.120	2.976

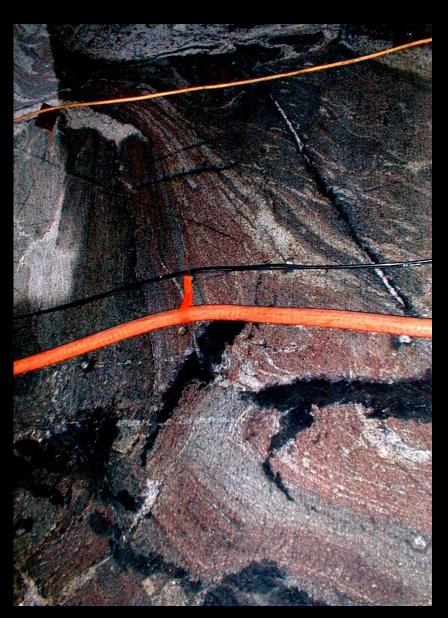
QT Mean = 2.87 (Dioritic Rock Mass)

From: Clark (1966, p. 20)



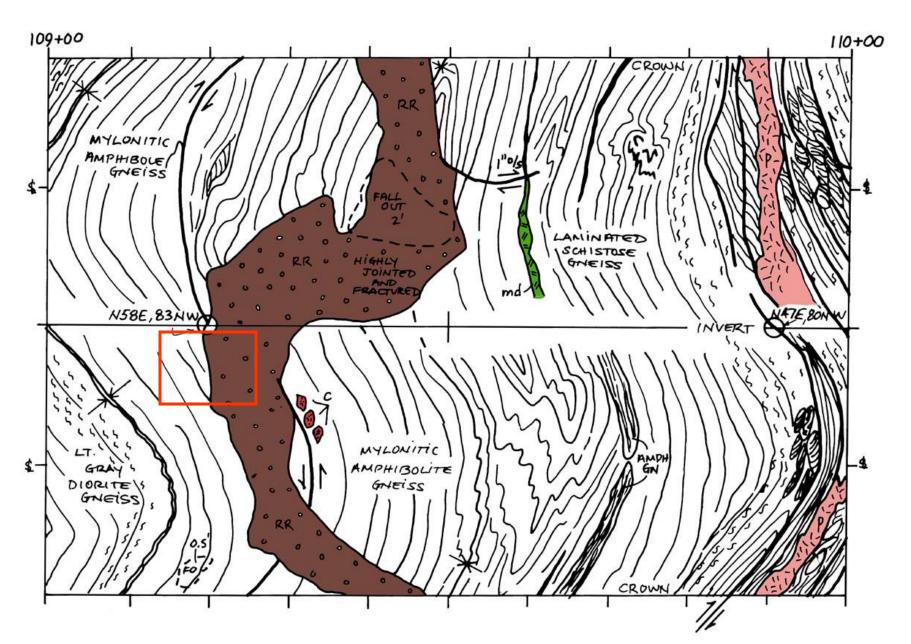
Unexpected High Garnet Content

- Boring logs cite garnetiferous.
- Most geologists, "garnetiferous" rocks contain a few % garnet
- Queens Tunnel rocks contain up to 50% garnet
- Thirty-two QT Garnet Zones underlie 2,663' or 10.64% of tunnel.
- QT Garnet Zones "ore deposits".
- Results in abrasivity to cutters and production of excessive fines

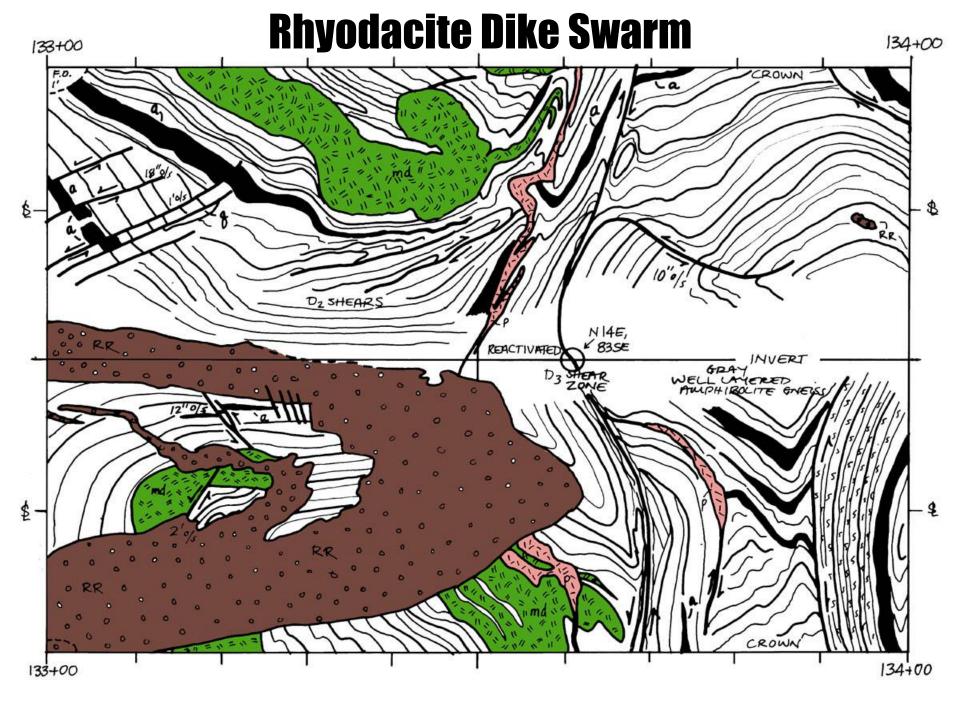




Dike 1











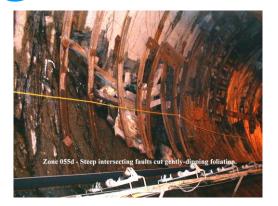




Orientation of Rock Layering

NE strike and moderate 57° dip anticipated

IBased on borings, Chesman, Tarkoyl



Highly variable trends found

Extended reaches of tunnel exhibited gentle dips

Only one boring (QTL-12) exhibited gentle dips at tunnel horizon

	NE Leg		NW Leg	
Gentle Dips	17/93	18%	44/139	32%
Moderate Dips	34/93	37%	28/139	20%
Steep Dips	42/93	45%	67/139	48%

QT Brittle Faults

> 300 faults mapped in five major groups From oldest to youngest:

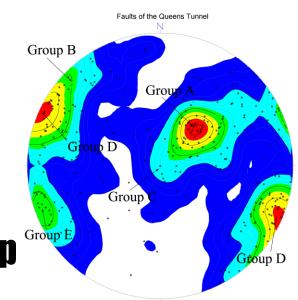
Group A = NW strike and gentle SW dip

Group B = ENE strike and steep dips

Group C = Subhorizontal fractures, faults, and shears

Group D = NNE-trending fault system (hitherto unknown)

Group E = NNW-trending "Manhattanville" fault system





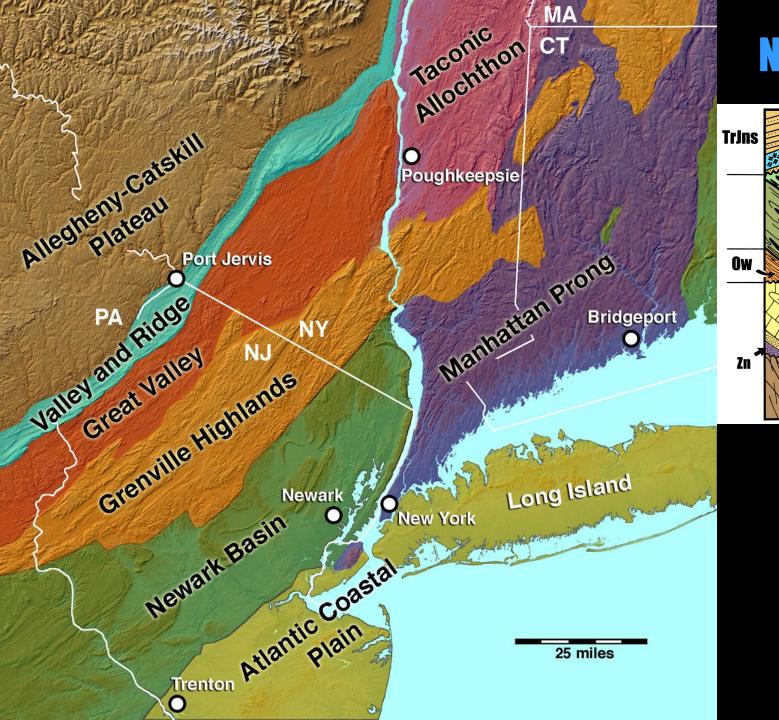
<u>Summary – QT \$110M Penetration Claim</u>

Intrinsic Queens Tunnel: Fordham, not Hartland

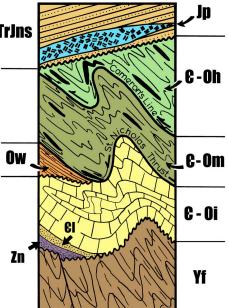
- Tougher, much older deep-seated granulite terrane
- More highly metamorphosed and structurally complex than the Hartland
- Weakly foliated near-isotropic orthogneiss rock mass
- Decreased TBM penetration rate the result of tougher Fordham rock

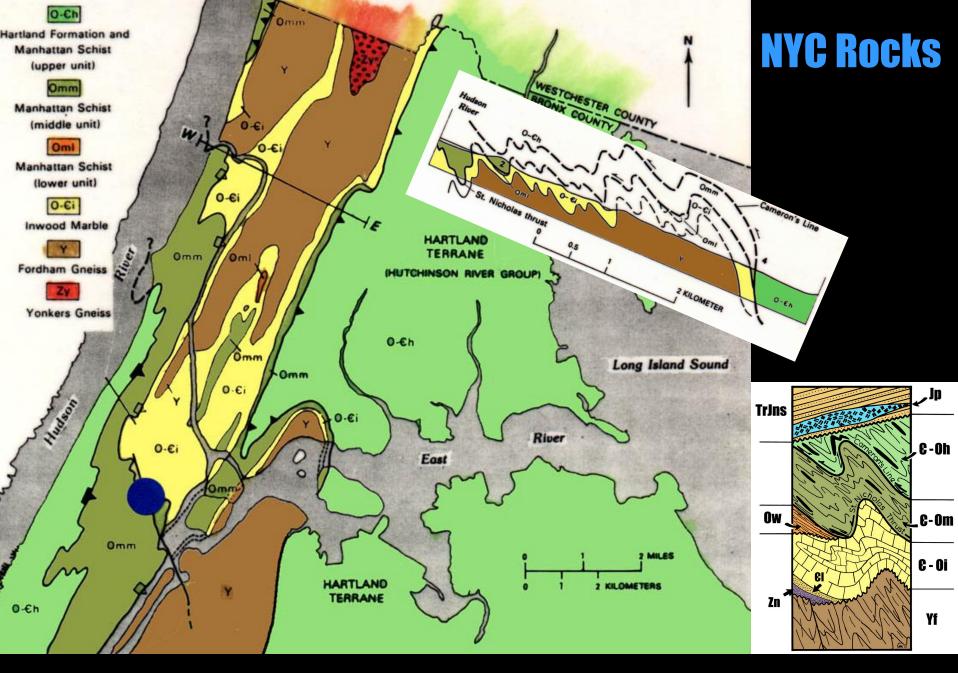
Episodic collapsing face, crown, and sidewalls forced additional support installation caused by:

- Massive ground cut by >300 intersecting fracture zones
- Rhyodacite cooling fracture pattern and contact effects
- Broad zones of subhorizontal fabrics and shear zones



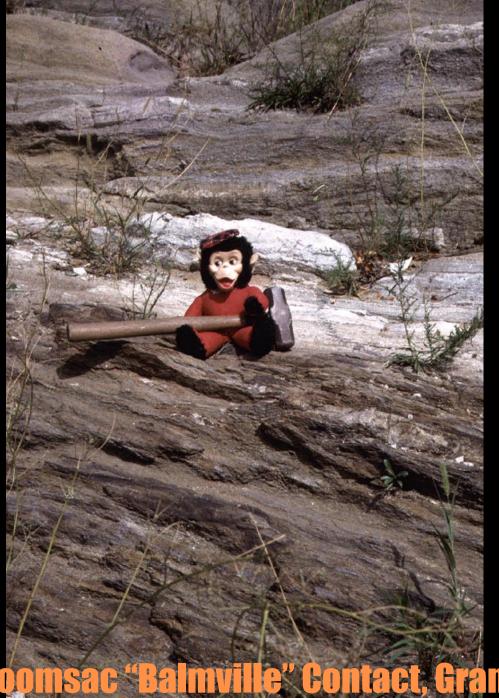
NYC Rocks

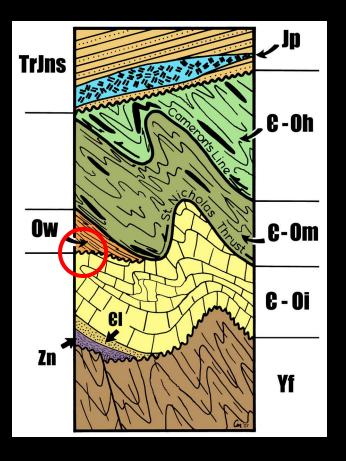




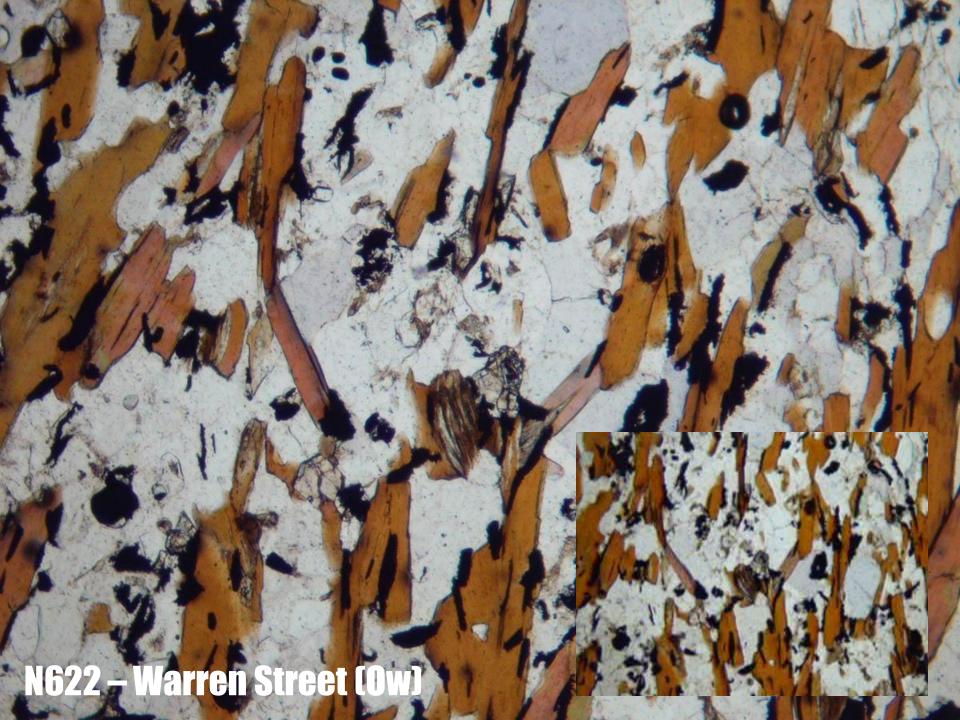


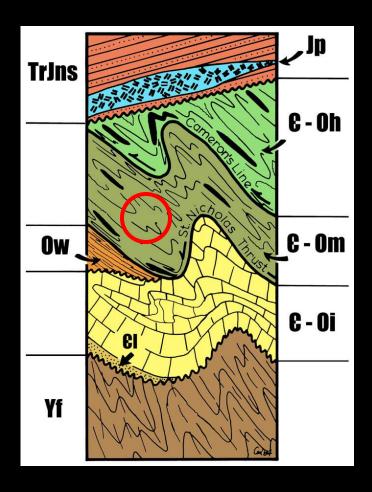






Nalloomsac "Balmville" Contact, Grand Concourse, Bronx, Ny

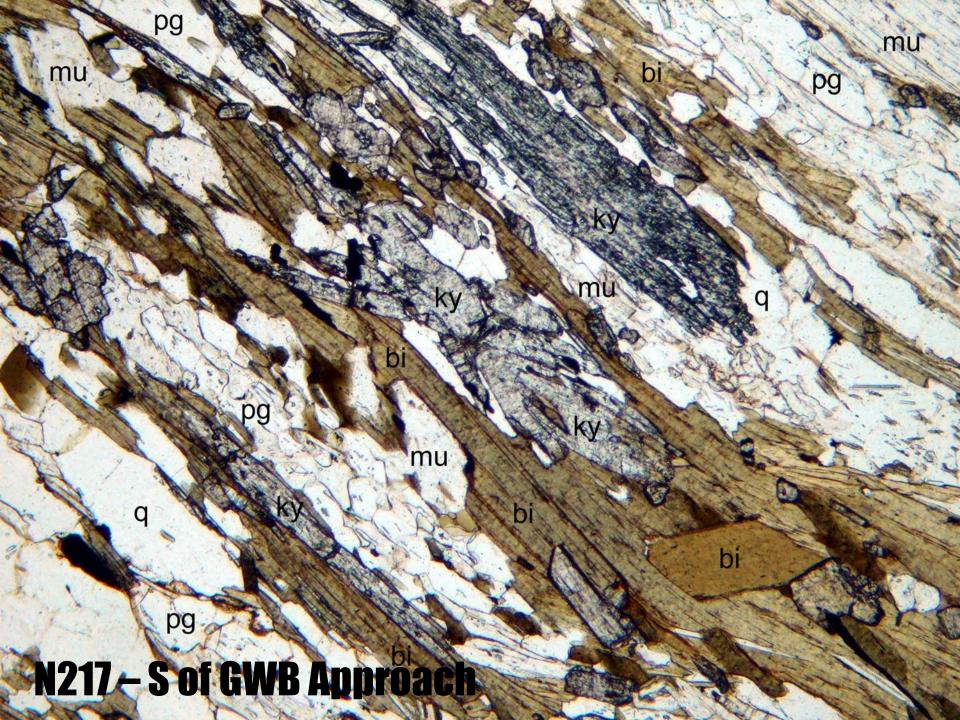




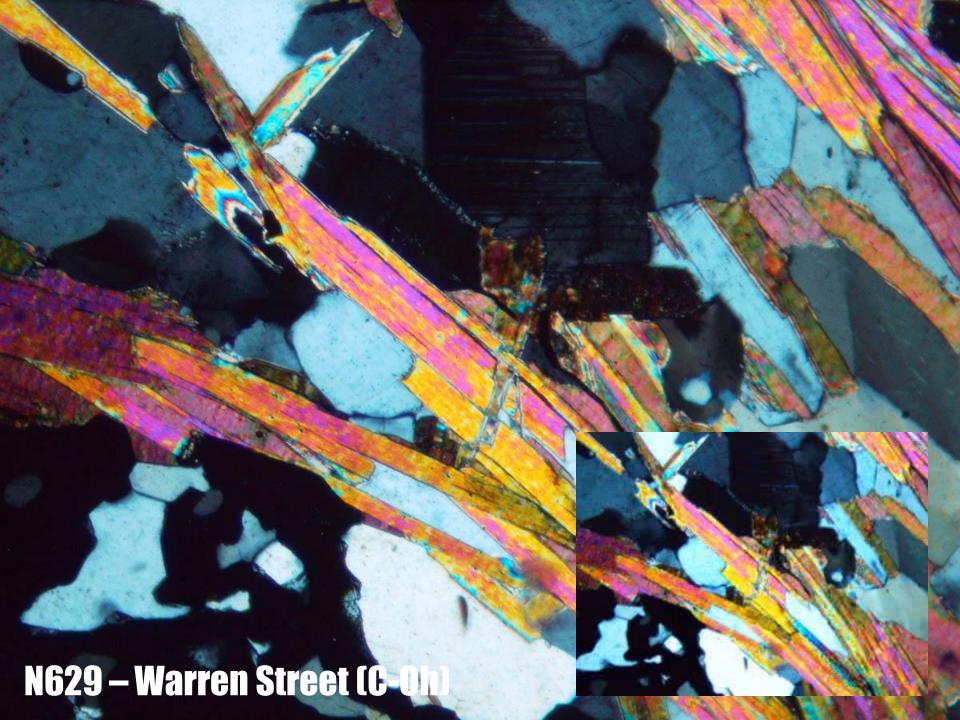
Manhattan Schist F₃ Folds of S₂ Central Park, NYC

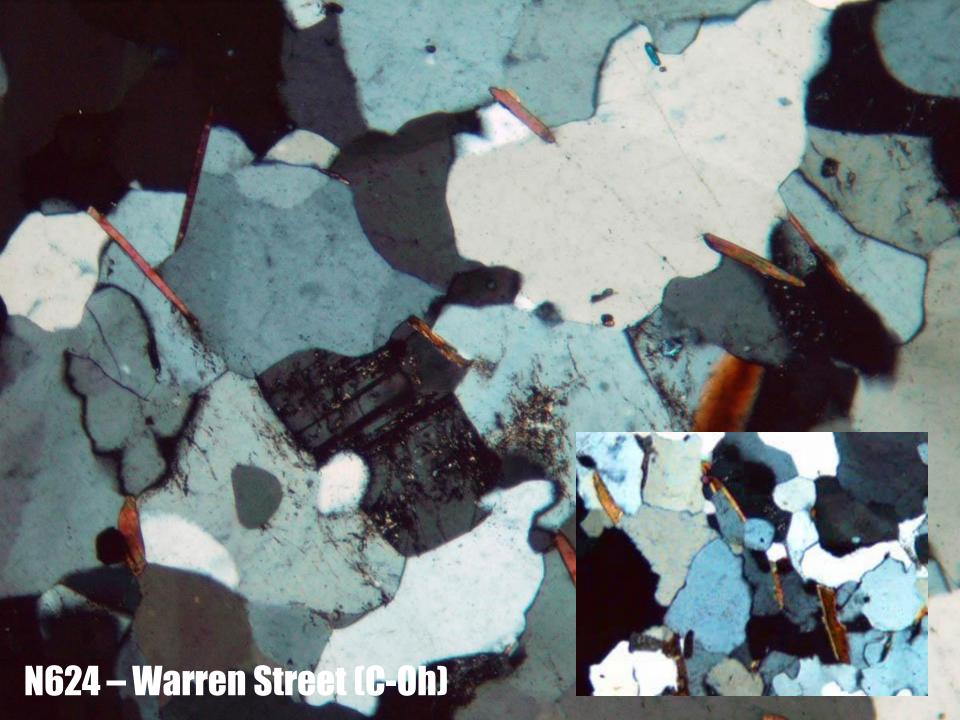


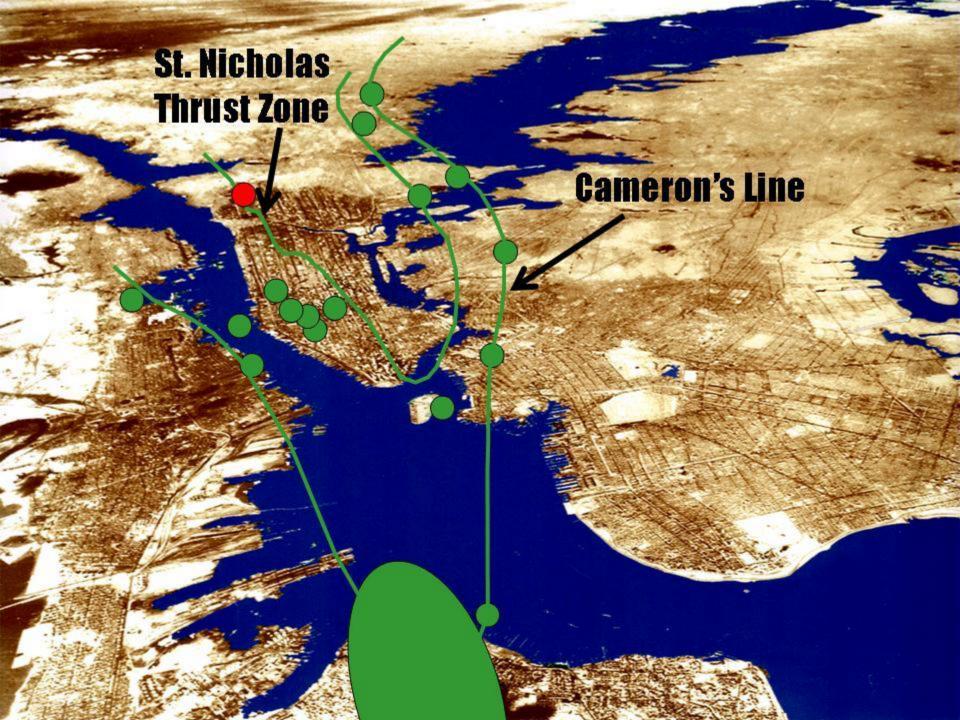












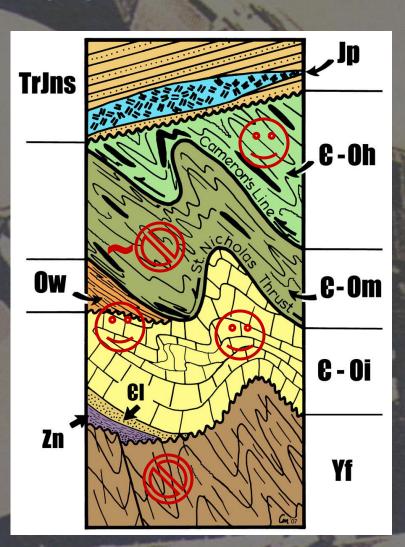
Factors: TBM Penetration Destiny

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- Faults/Joints
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- Hardness/Density
- Rock Type
- Texture/Metamorphic Grade
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Episodic Factors (Utilization)

- Convergent Fault Zones
- Unusual Rock Types/Structures
- Stress Popping/Heave
- Water Inflows





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