Rock Mass Properties and Hard Rock TBM Penetration Rate Investigations, Queens Tunnel Complex, NYC

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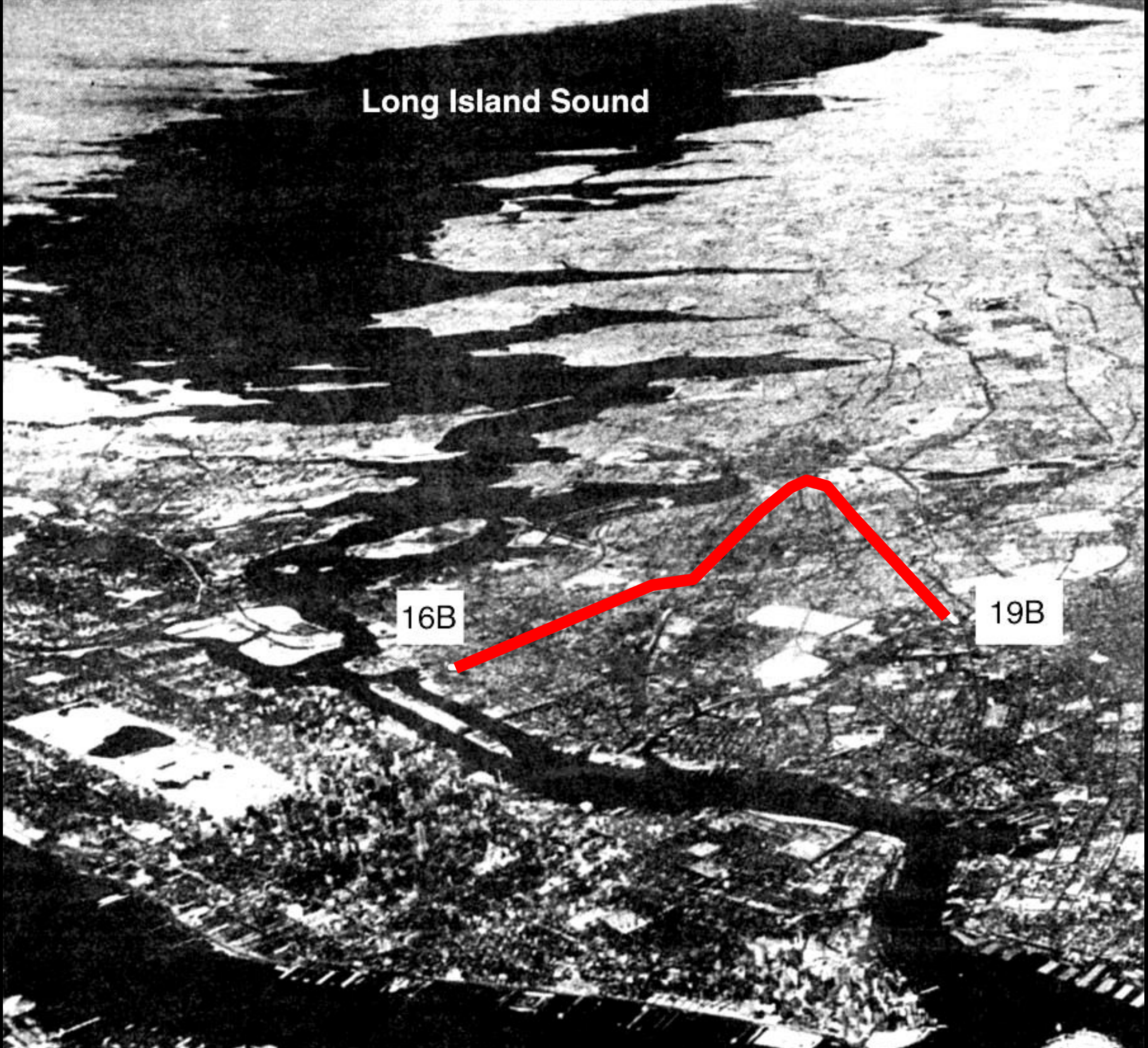
Dukelabs

HOFSTRA UNIVERSITY

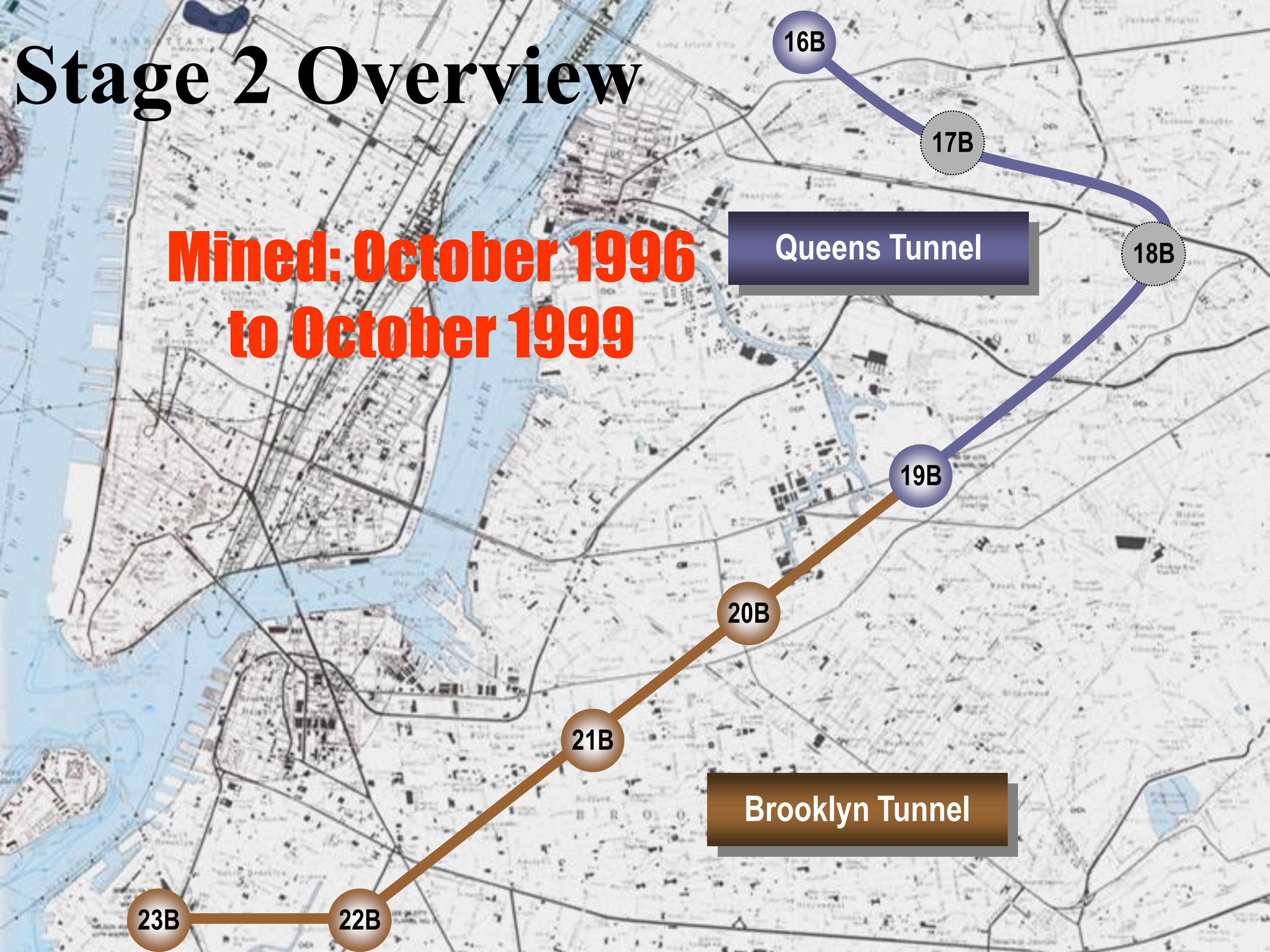
SCHOOL OF MINES
COLORADO
1874



Long Island Sound
16B
19B

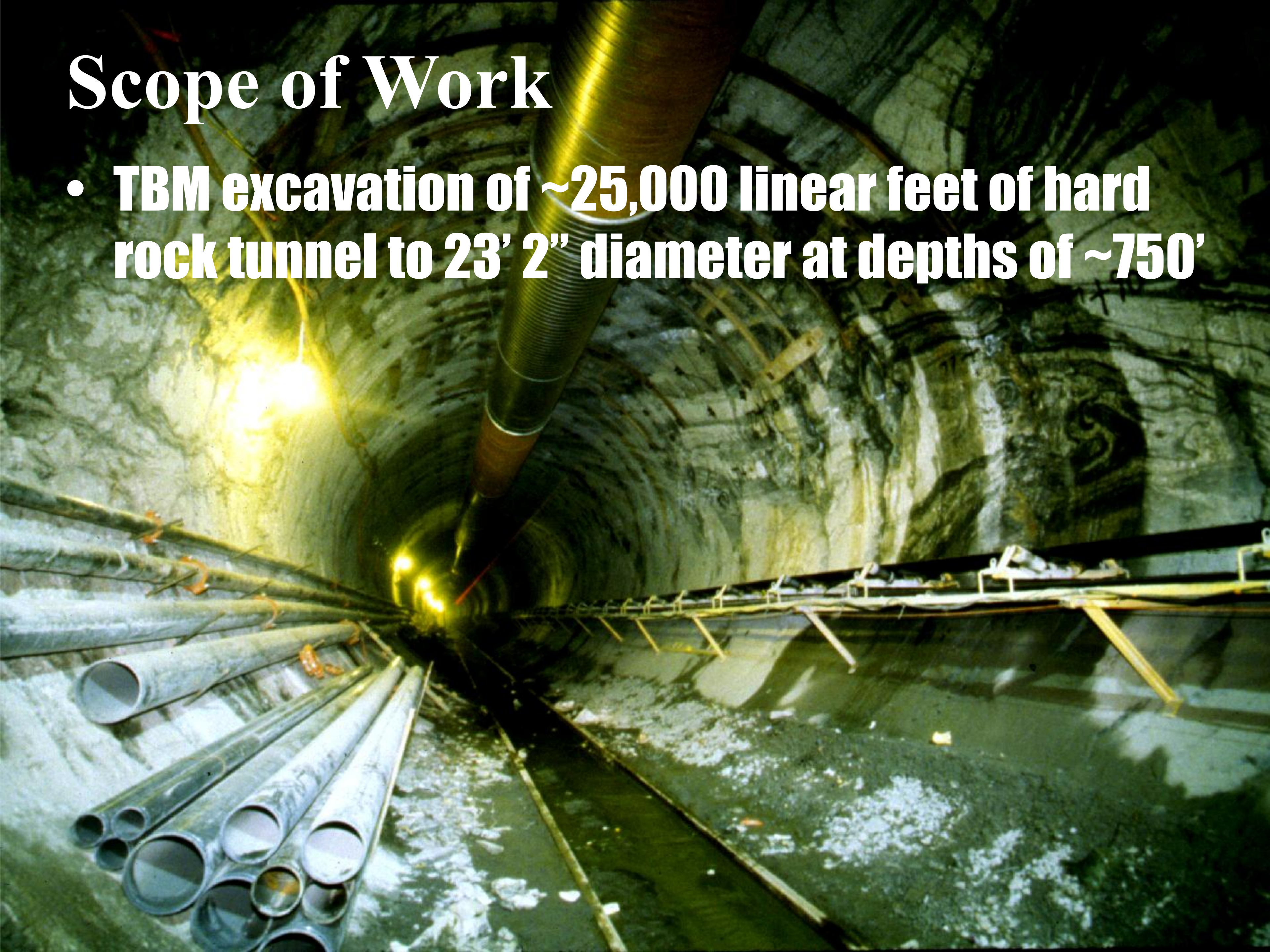
Stage 2 Overview

Mined: October 1996 to October 1999



Scope of Work

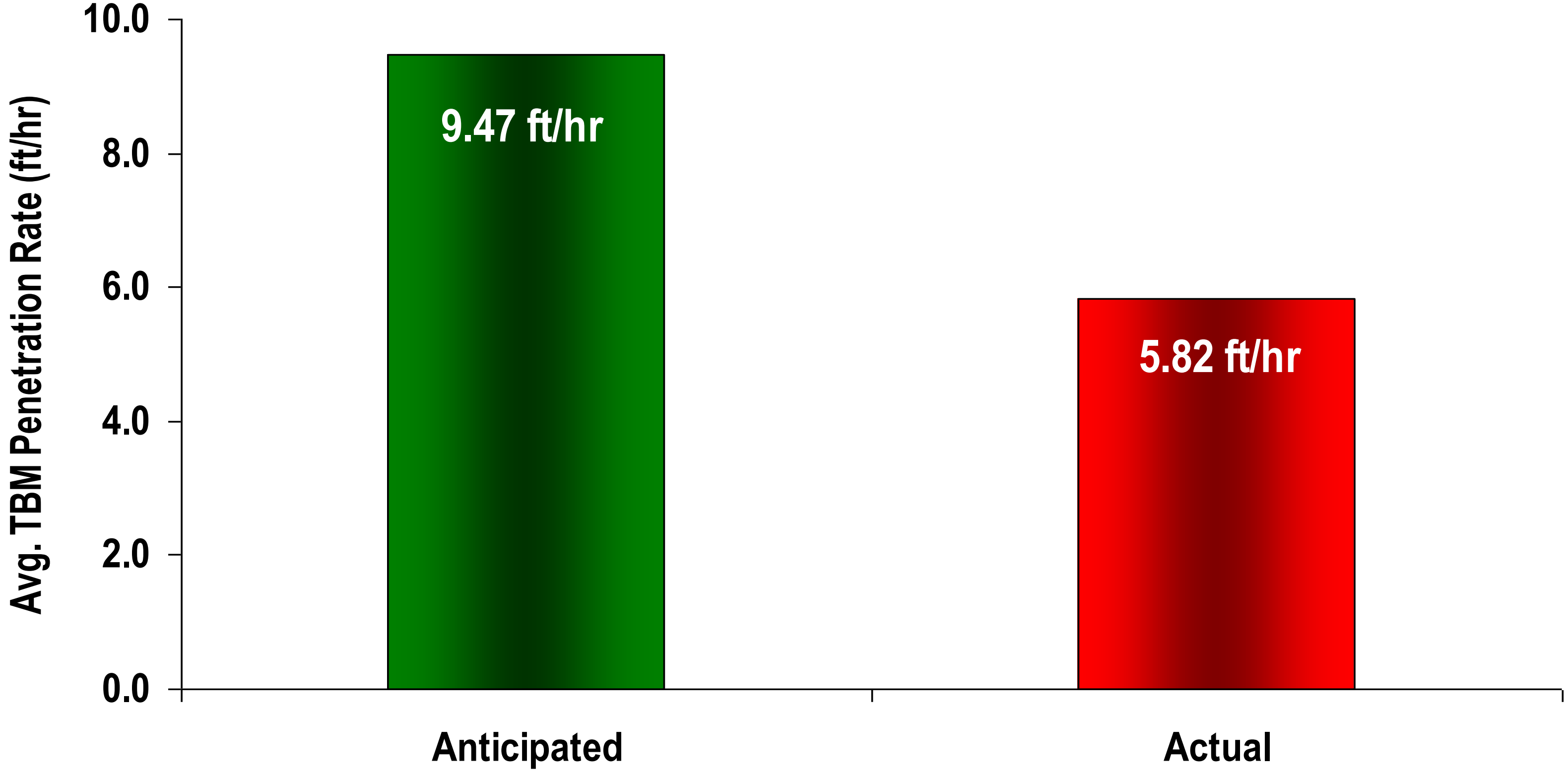
- TBM excavation of ~25,000 linear feet of hard rock tunnel to 23’ 2” diameter at depths of ~750’



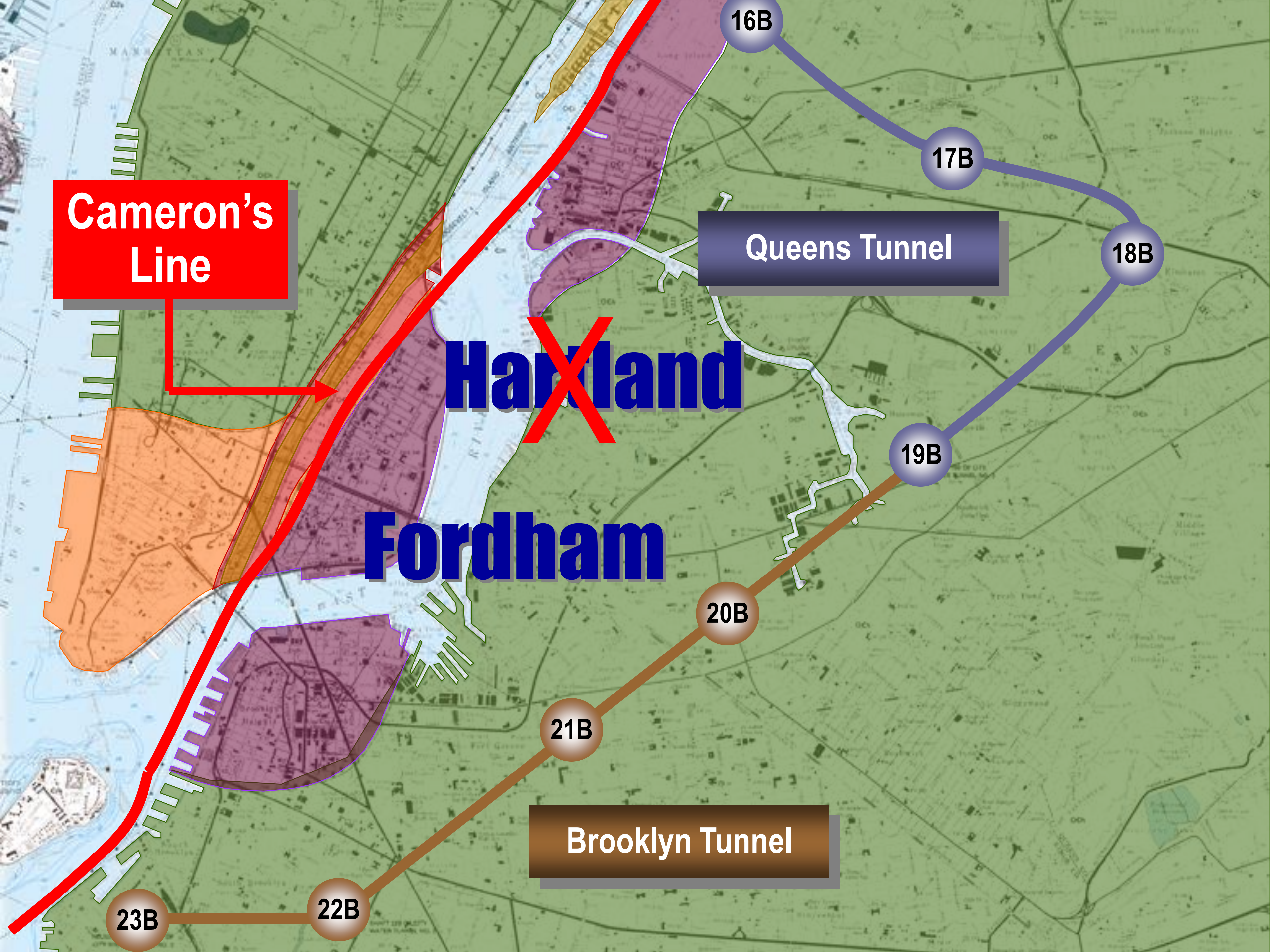
Excessive Fines


Blocky Ground
Short Stand-up Times

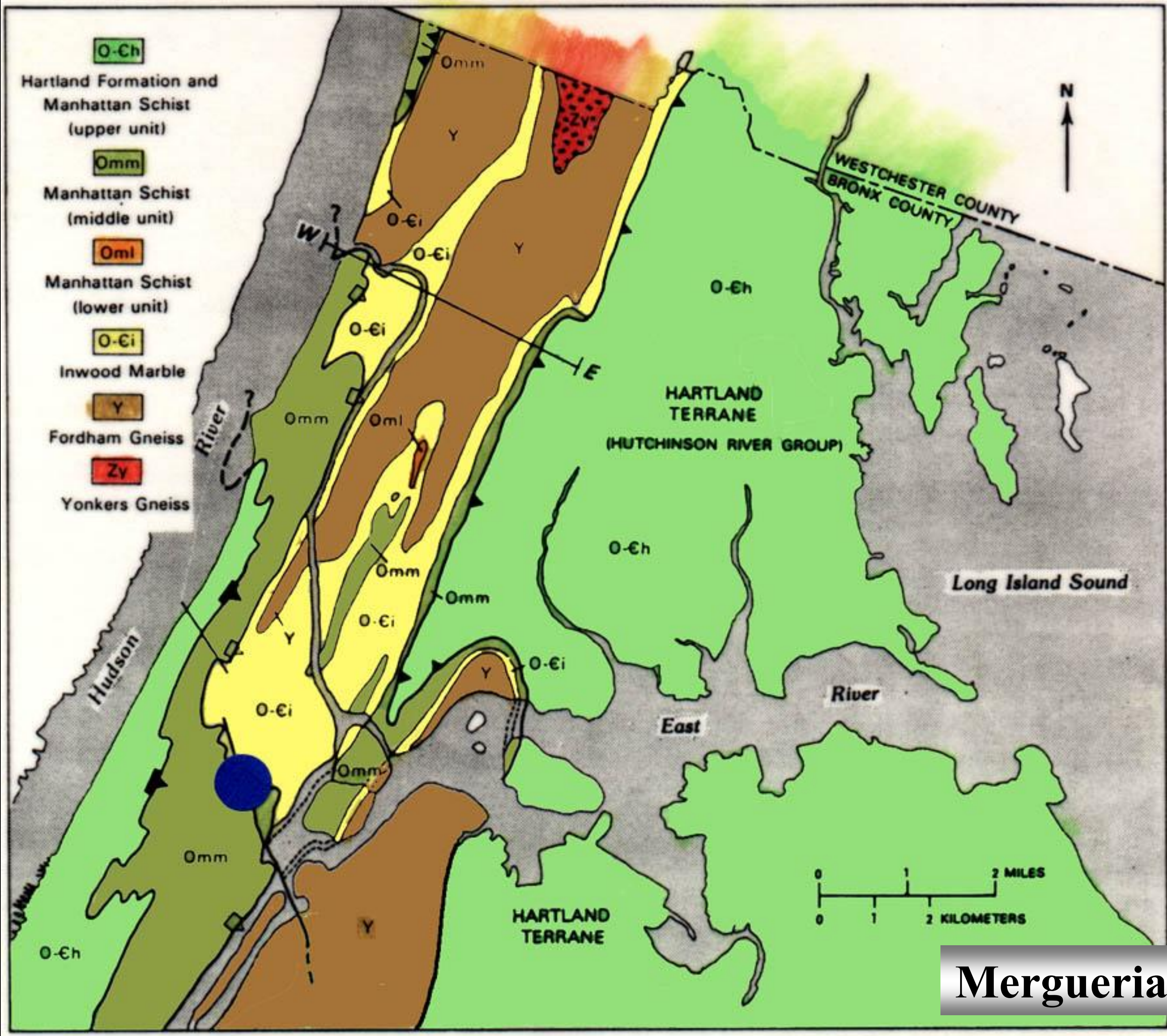
Anticipated vs. Actual Penetration Rate



Hartland is Micaceous, Well Foliated and Well Layered

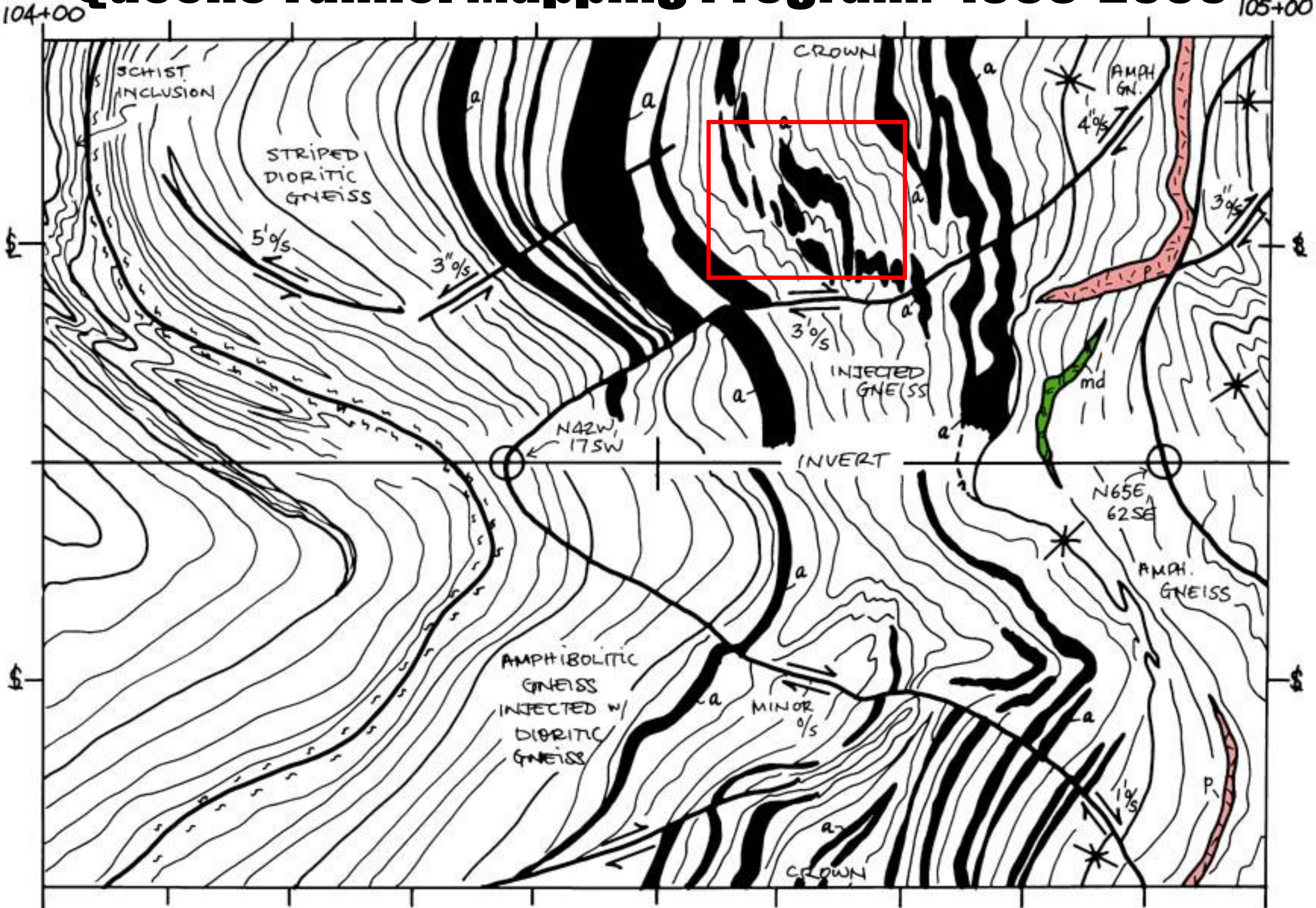


16B
17B
18B
19B
20B
21B
22B
23B
Cameron's Line
Queens Tunnel
Hartland
Fordham
Brooklyn Tunnel



Merguerian, 2002

Queens Tunnel Mapping Program: 1998-2000



Entire Tunnel Mapped at Scale 1 in. = 10 ft. (250 Map Sheets)

104+60
104+65

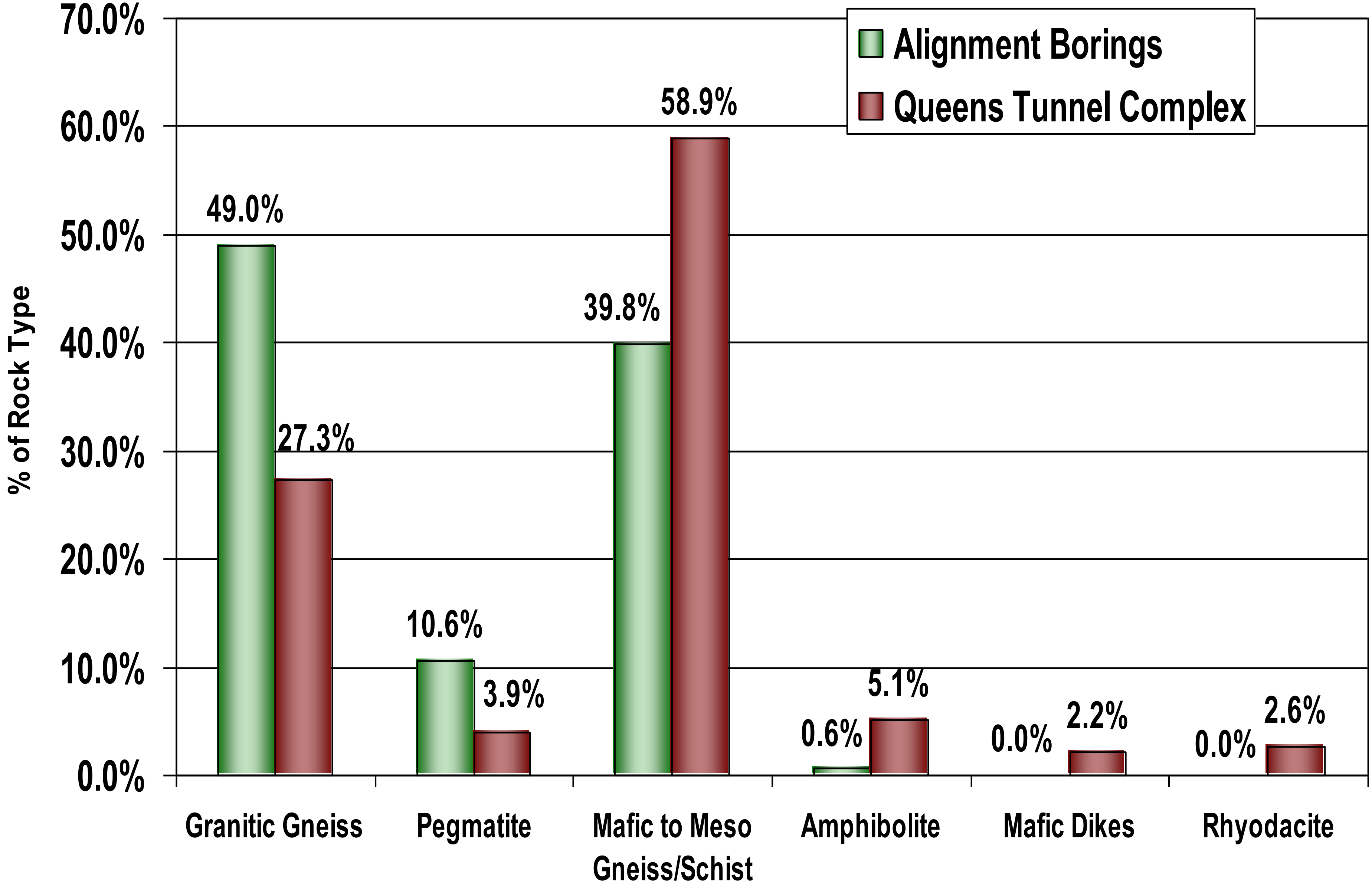
Granulite "Green" Coloration

Granulites have a subtle, distinctive color and appearance familiar to field geologists who have mapped granulites in Canada, Africa, Europe, and elsewhere.

According to Hyndman (1972): *"Quartzofeldspathic pyroxene-bearing gneisses are common in the granulite facies, greasy to waxy looking and are medium grayish-green to brown in color because of the color of the plagioclase"*.

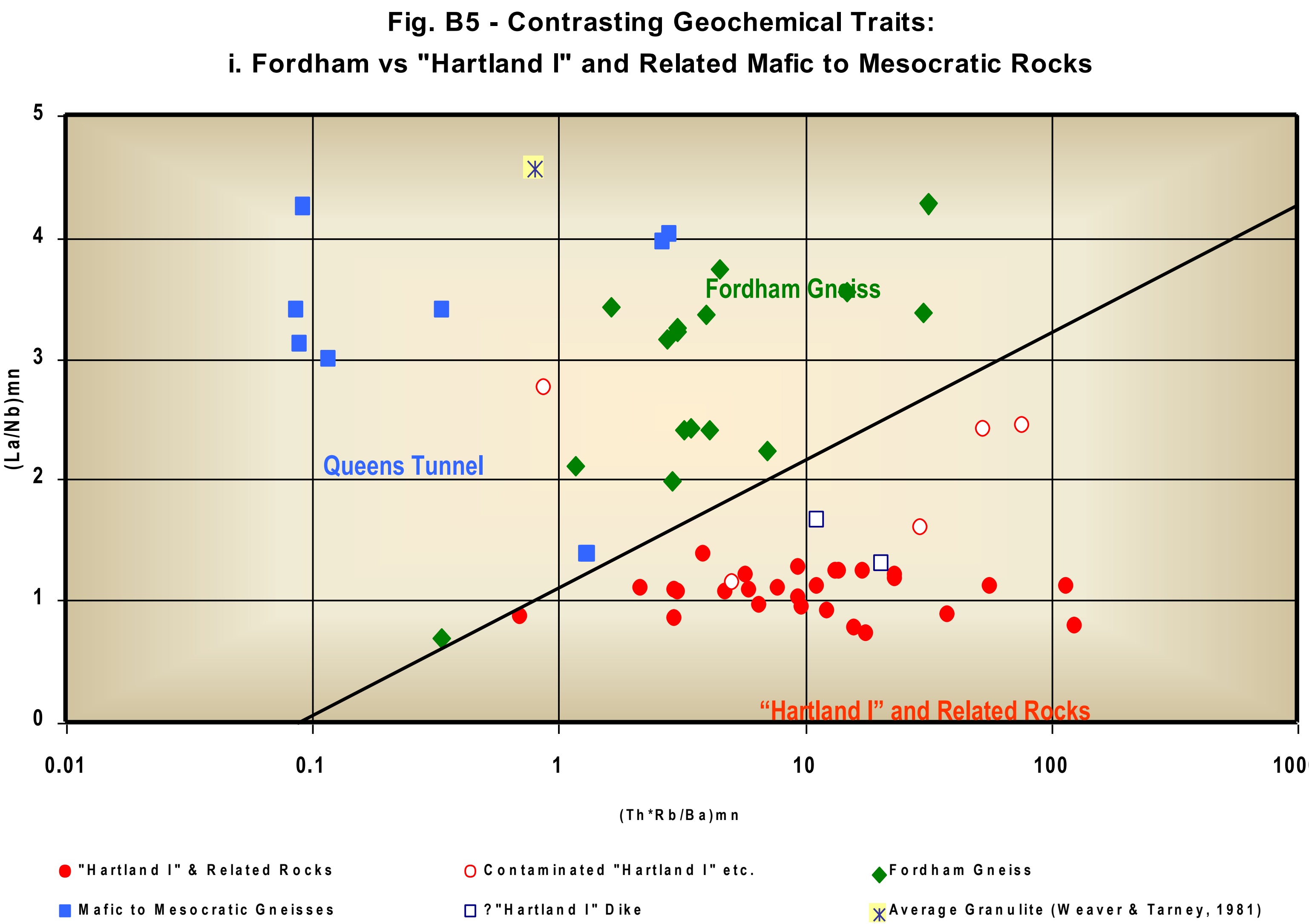
Many Queens Tunnel rocks show this characteristic; it reflects the substantial retention of their early granulite-facies feldspar.

Comparative Lithologic Analysis

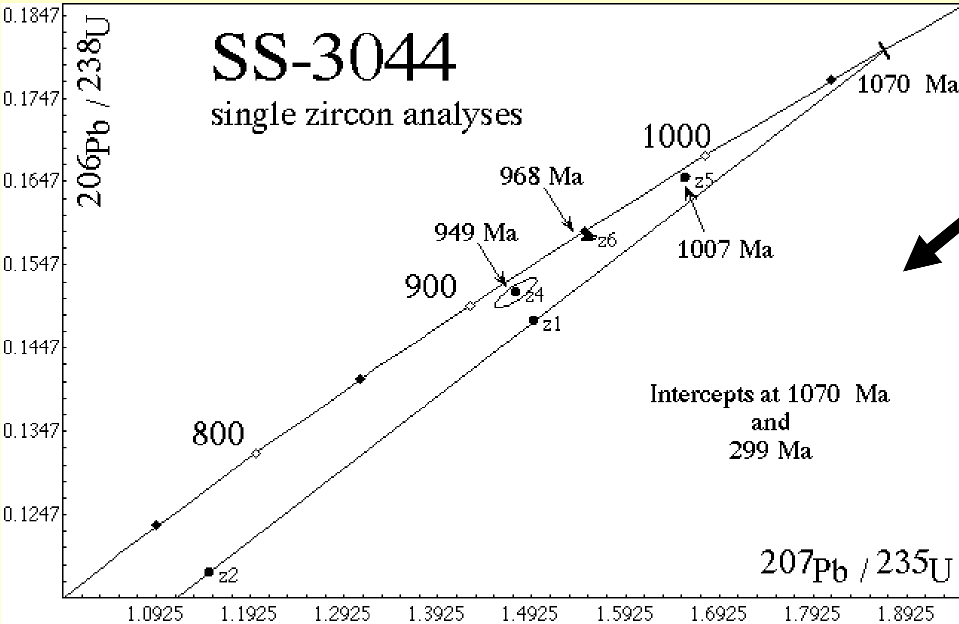


Geochemical Investigations

- Major elements, trace elements, rare earth elements (REE)

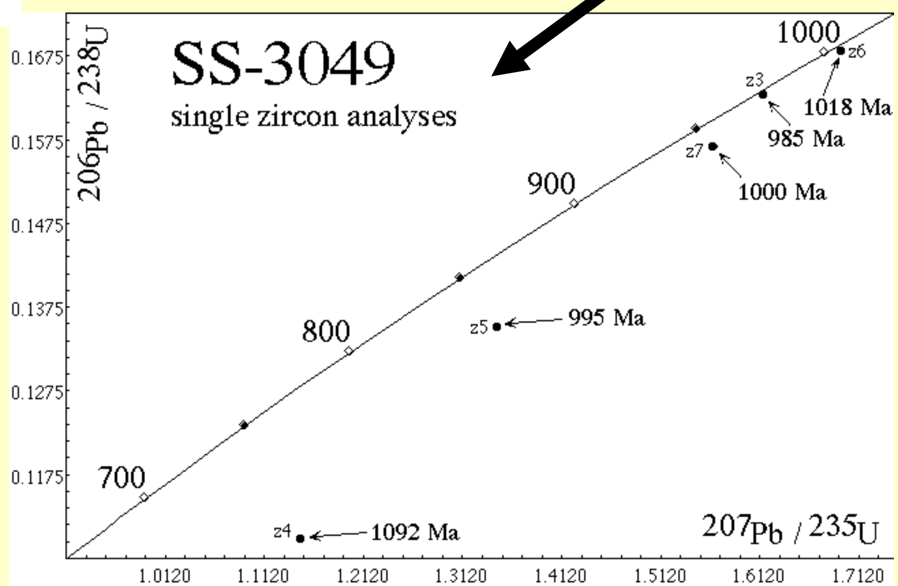


1.0 Ga U/Pb Geochronologic Analysis



Station 9+45

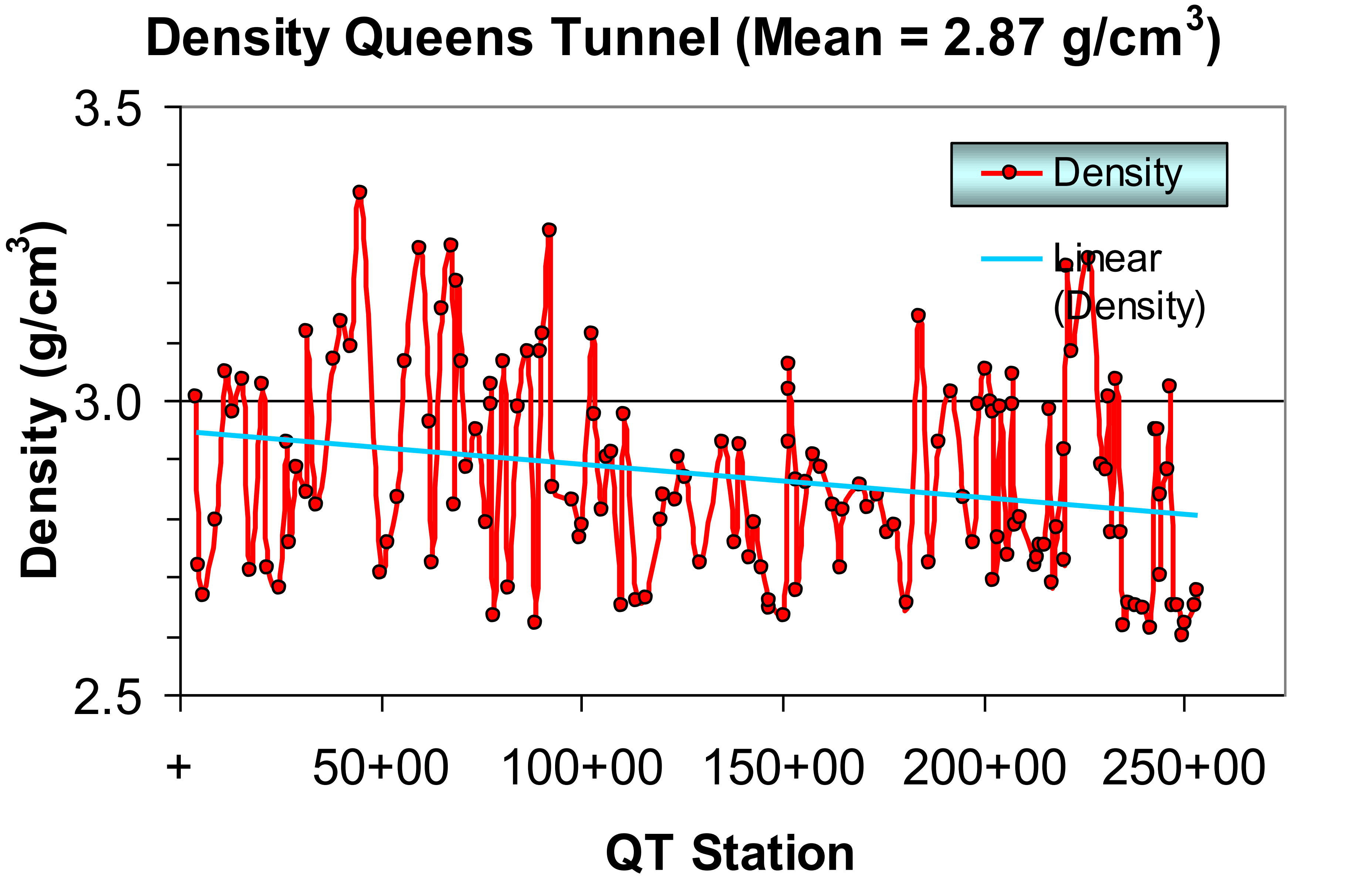
Station 68+15



Queens Tunnel Complex

Age Dating Verified

Fordham vs. Hartland



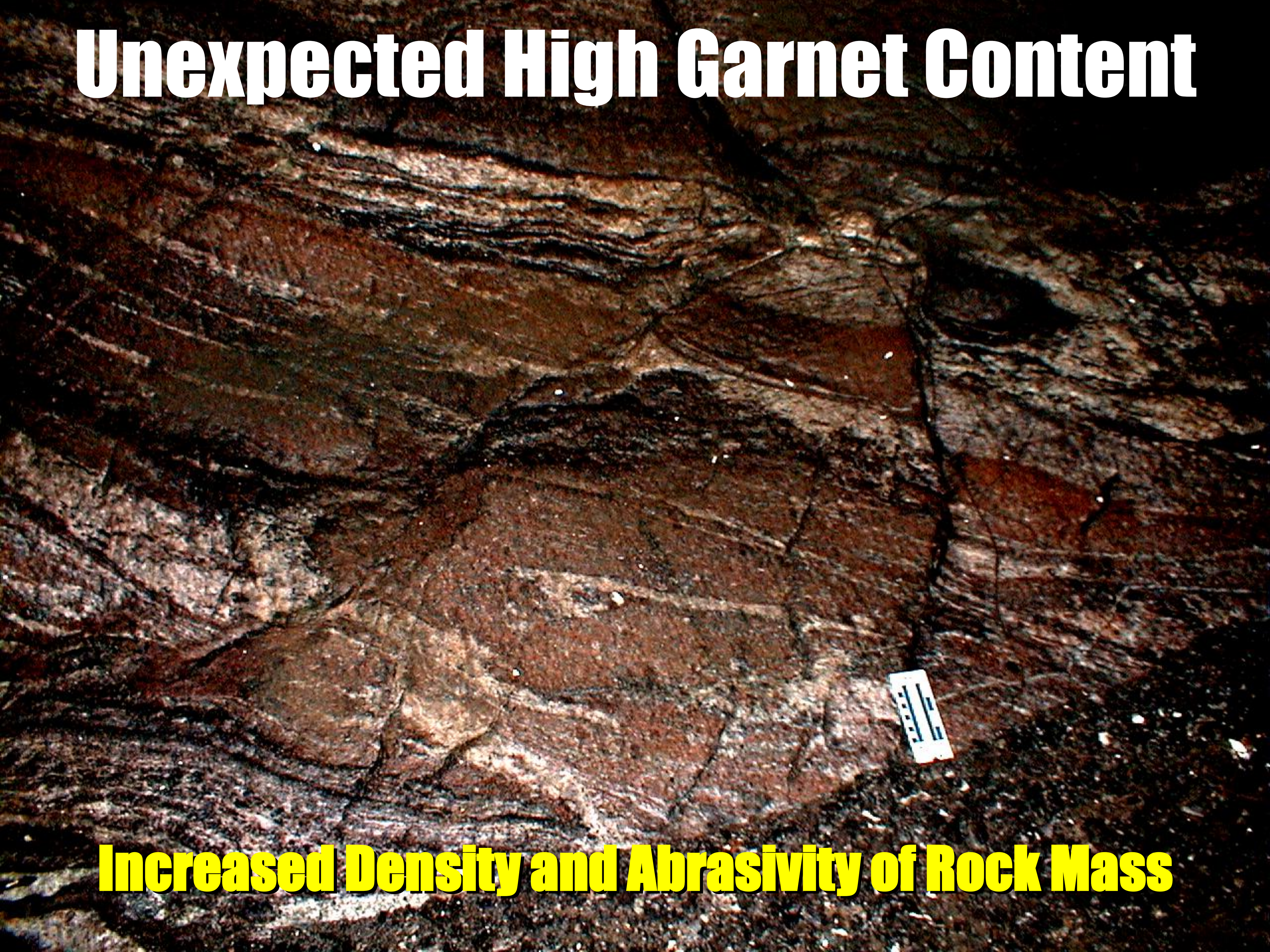
Density Queens Tunnel (Mean = 2.87 g/cm3)
3.5
3.0
2.5
Density (g/cm3)
Density
Linear (Density)
+
50+00
100+00
150+00
200+00
250+00
QT Station

Density Analysis

	Low	High	Mean 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)

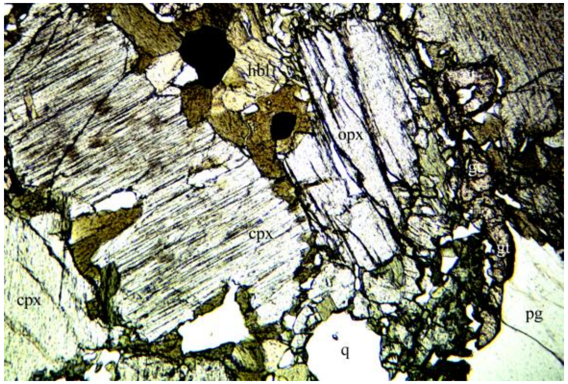
From: Clark (1966, p. 20)


Unexpected High Garnet Content
Increased Density and Abrasivity of Rock Mass

Unexpected High Garnet Content

- The boring logs cite the term garnetiferous throughout. To most geologists, "garnetiferous" rocks contain a few % garnet.
- Thirty two Queens Tunnel Garnet Zones mapped. They underlie 2,663' or 10.64% of as-built tunnel.
- The Queens Tunnel rocks contain up to 50% garnet.
- The Queens Tunnel Garnet Concentrations would be called "ore deposits" in many parts of the world.
- Results in abrasivity to cutters and production of excessive fines.

- **Petrographic Analysis (92 Samples)**
  - **Texture**
  - **Mineralogy**
  - **Internal Structure**
  - **Metamorphism**

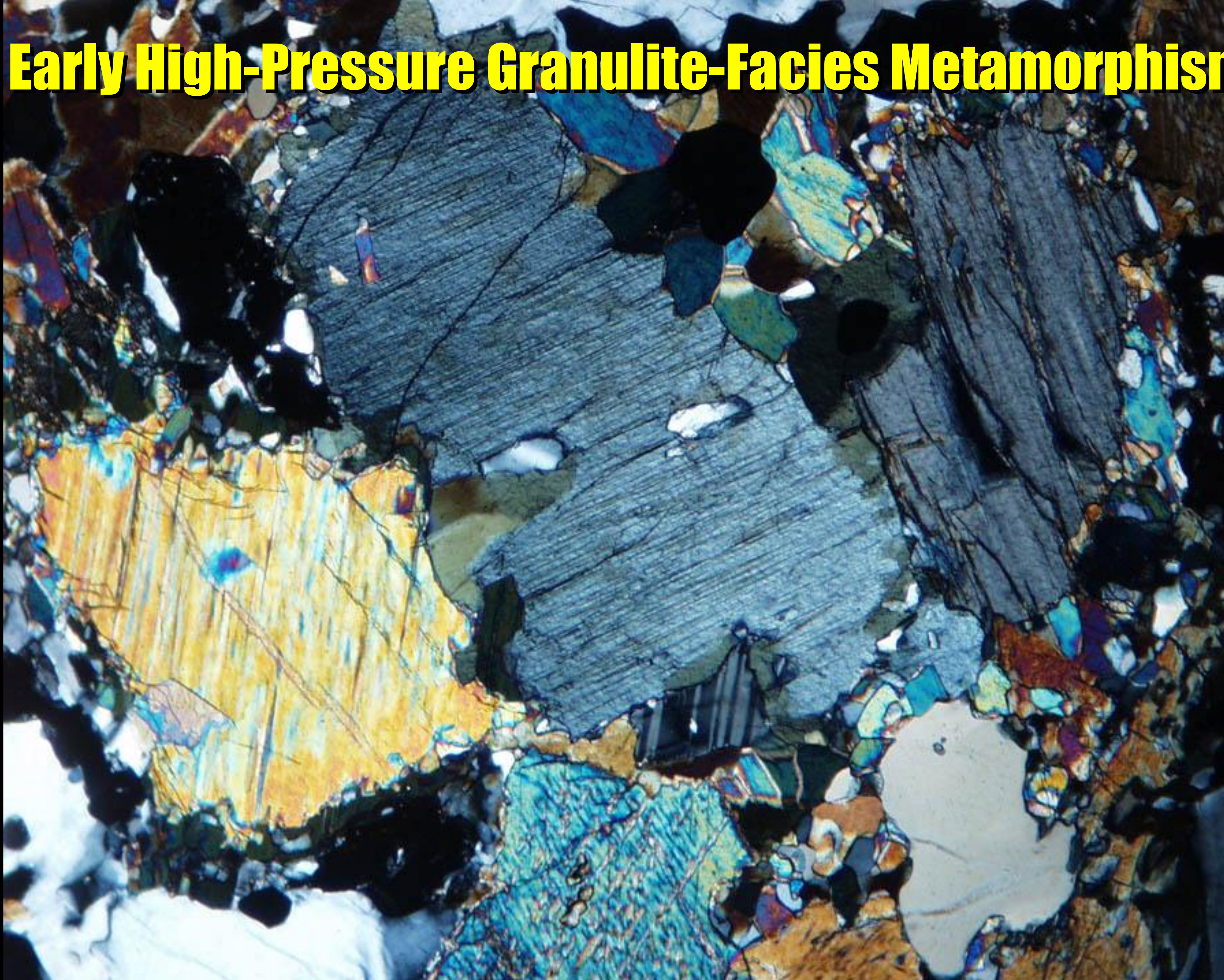


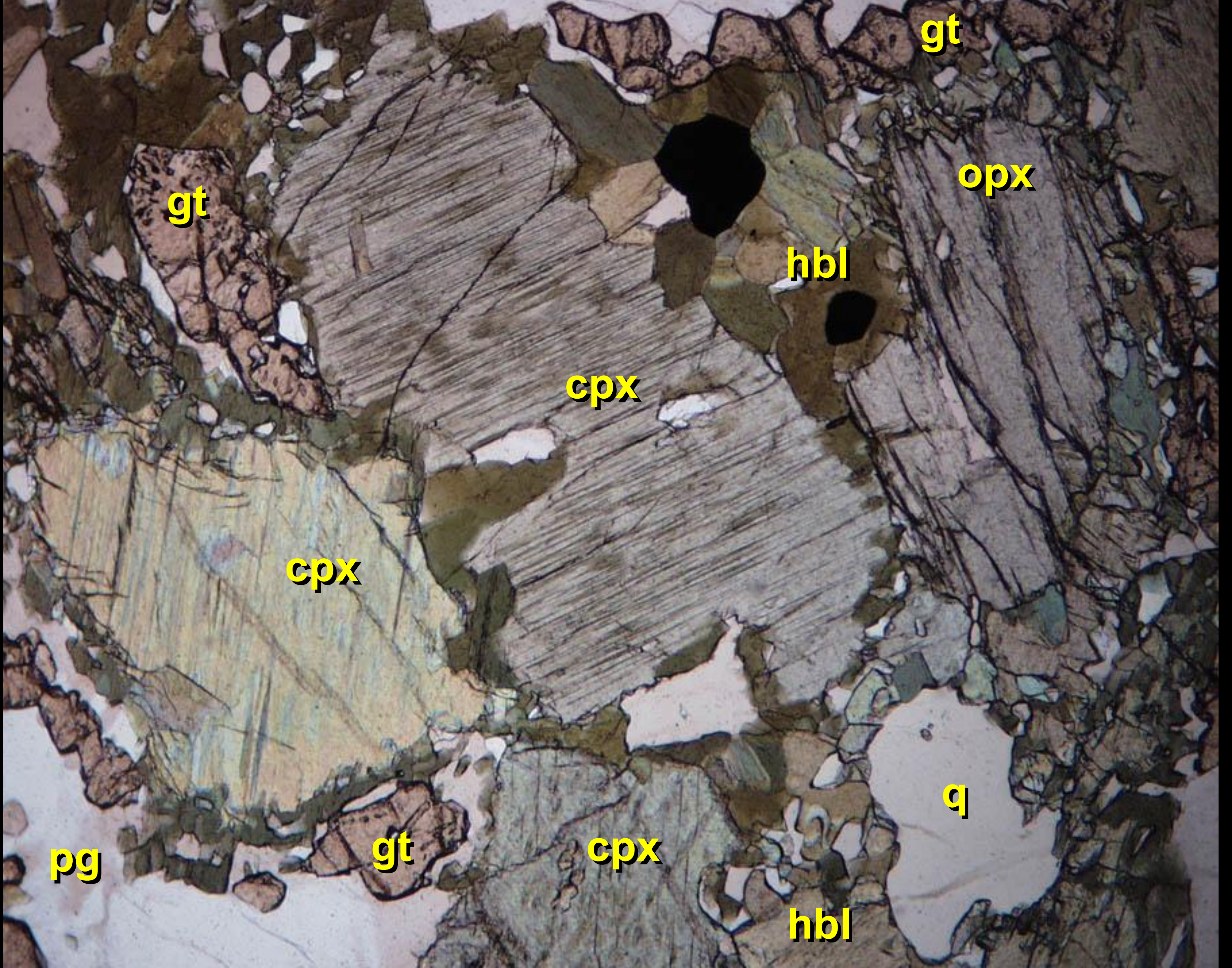
Thin section photomicrograph

Number	Location	Color	Density	Qtz	Kspar	Plagio/	**An**	Opx	Cpx	Hbld	Bio	Garnet	Opaque
Q109	004+80					M	35	M		M			
Q109	004+80	25	2.72	M		M	35			m	m	m	
Q110	006+42	10	2.66	M	tr+AP	M					m gnbk	tr	tr
Q111	009+25	25	2.79	M		M		m		tr	m	M py encl Q	tr
Q112	011+60	35	3.05	m		M	51		M exsol	m gnkh		M py	
Q114	015+90	45	3.03	m		M	53-39normal	M some Exsol	M Exsol	mgnkh		*m necklace*	tr
Q115	017+70	10	2.71	M	tr AP	M				m **bugn** sieve	m rbn	m porange	tr
Q117a	022+25	15	2.72	M	tr	m	27			m **dgygn**	m rbn	m porange sieve	tr
Q119	026+65	45	2.93	m 10-15	m	M	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		M		tr	M	M gnkh	m red	M	m
Q129	049+95	25	2.71	M	M	M	low				M kh	M	
Q130	051+83	15	2.76	40	tr	M					m obn	M.vermic/sieve rims	tr
Q133	059+95	55	3.26	m		M	38-29		M	Mkhtan	m	M	m
Q134	062+45	60	3.17	m		M	28-40	Rev Zoning	M	M **bugn** some vermic wi Qtz		M fine sieve/vermic vermi	10
068+10	068+10	5:50		M		M	55	m	M	m gn		*m vermic with plag*	m
070+60	070+60	45		M		M	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

Early High-Pressure Granulite-Facies Metamorphism




gt
gt
opx
hbl
cpx
cpx
q
pg
gt
cpx
hbl

Early M_1 Garnet

Produced during initial (M_1) high-grade metamorphism of Queens Tunnel Plutonic Complex

Coarse- grained and inclusion free with orangey cast

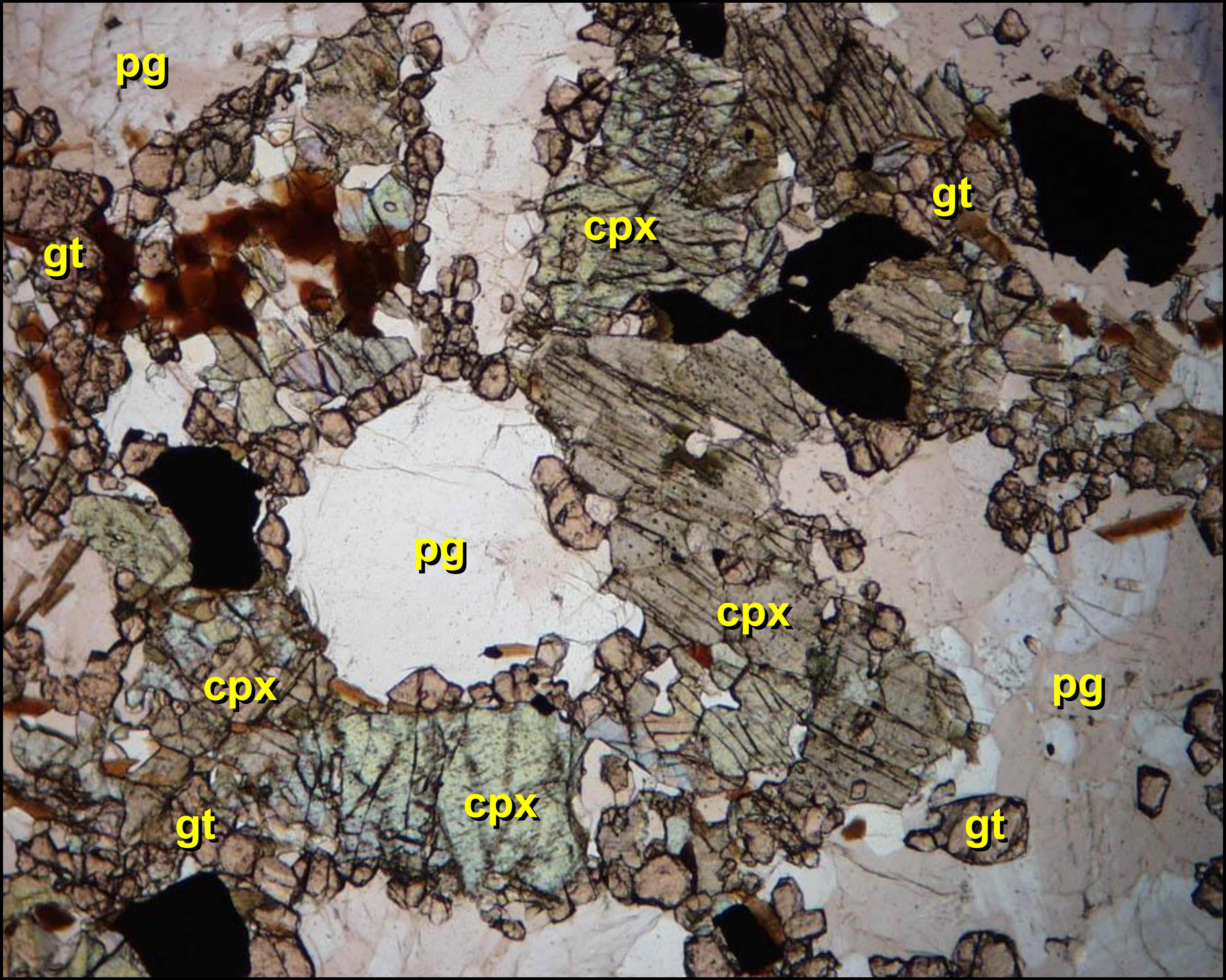
Intergrown with clino- and orthopyroxenes

Secondary M_2 Garnet

Finer- grained and pale-pink in color

Poikiloblastic habit with abundant inclusions

Forms symplectic rims around plagioclase and pyroxene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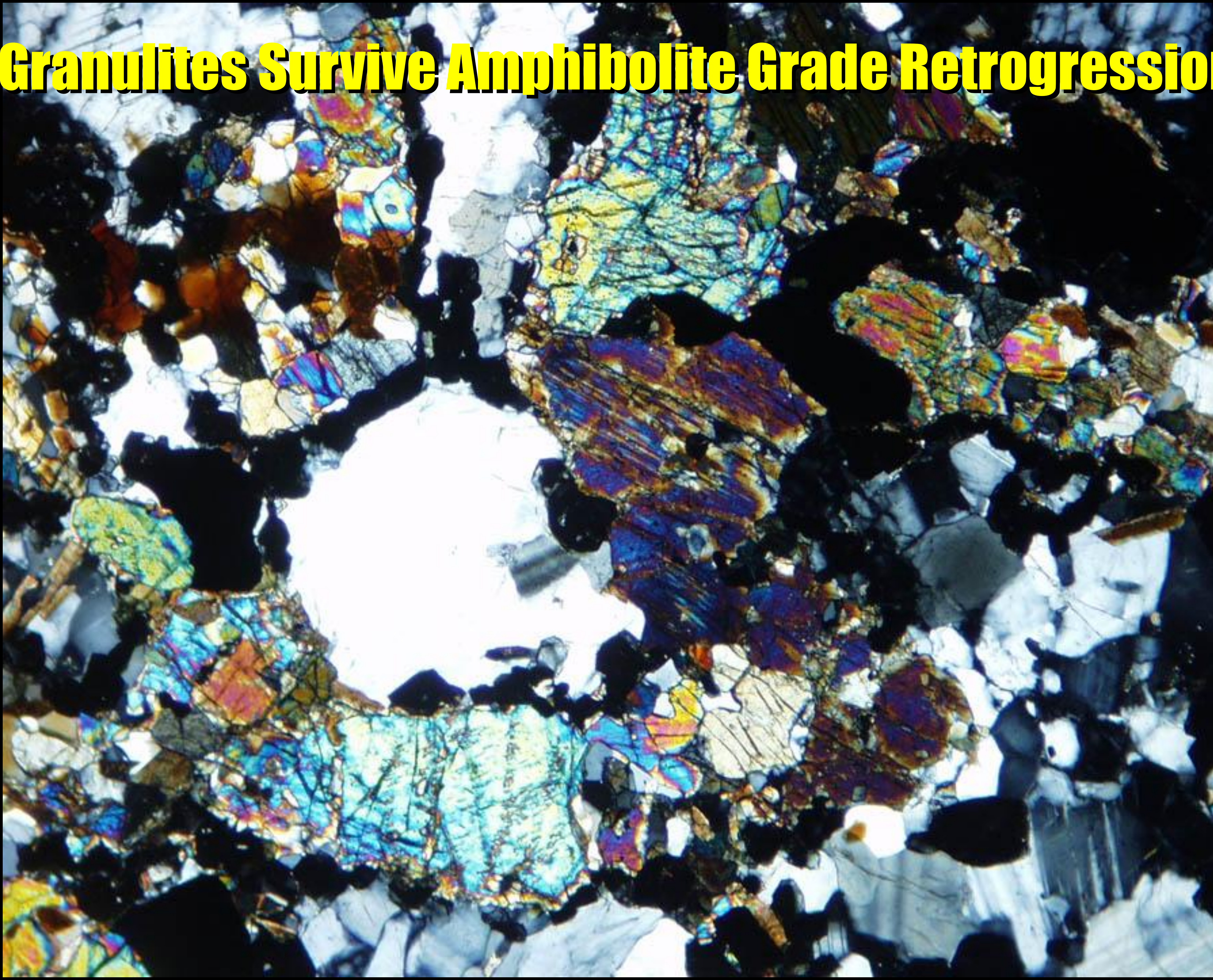
Granulites Survive Amphibolite Grade Retrogression



The Queens Tunnel Complex

Secondary (M_2) Metamorphism

Reactions produce hydrated mineral assemblages resulting in growth of hornblende, cummingtonite, biotite, and recrystallized garnet

Sample Retrograde Reactions

opx + cpx + plag = hbl + garnet

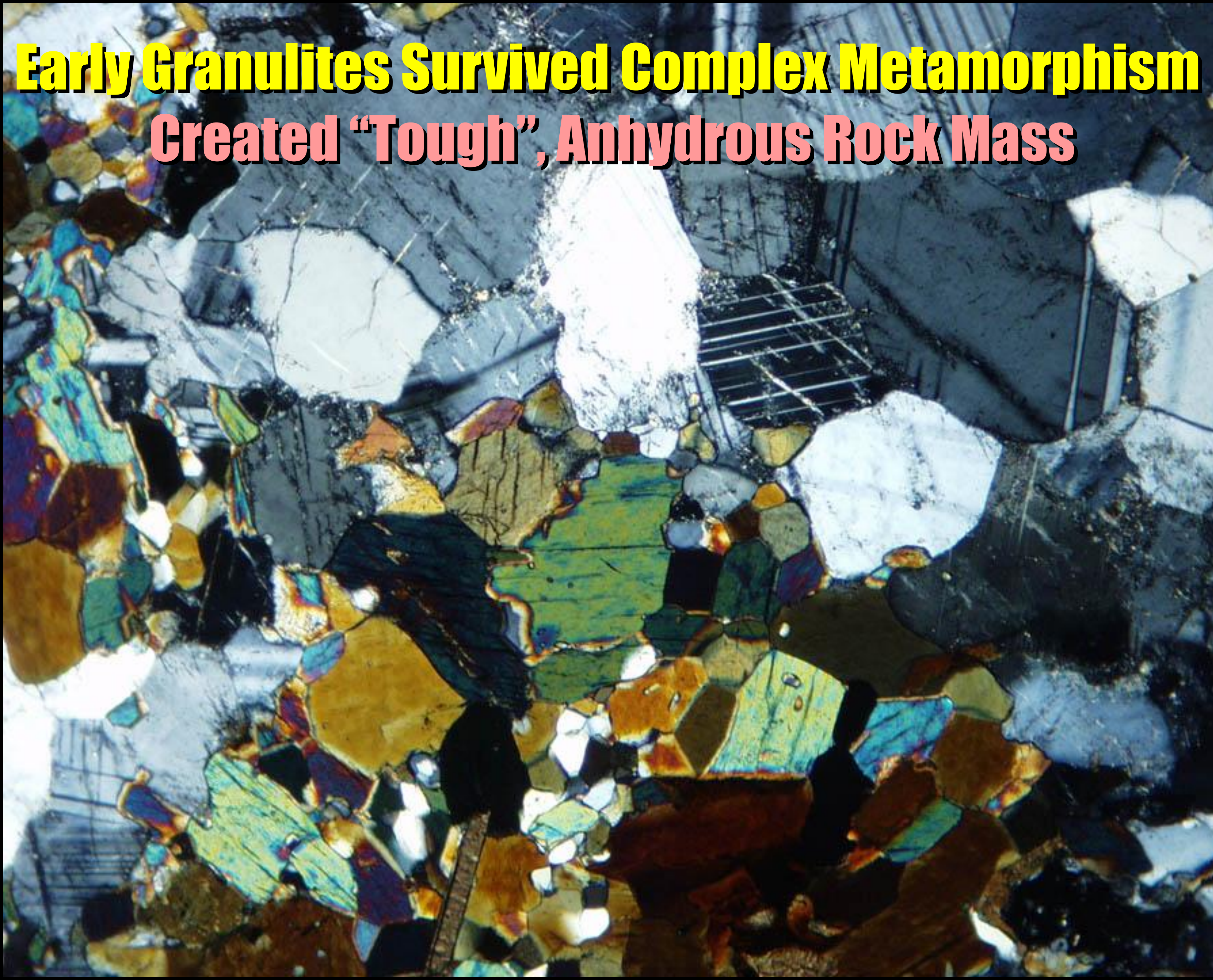
opx + quartz = cummingtonite

garnet + opx + plag = hbl + quartz

K-spar + opx = biotite + quartz

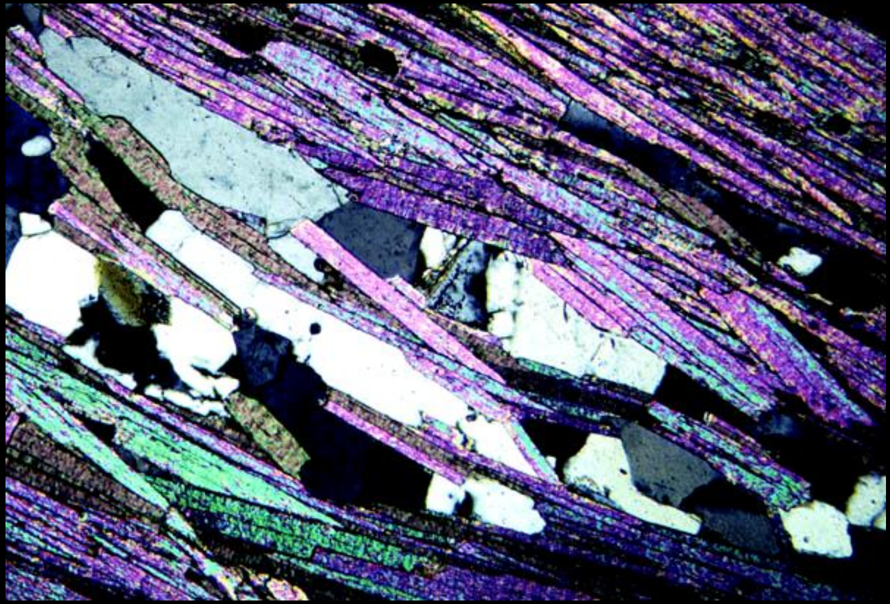
Early Granulites Survived Complex Metamorphism

Created "Tough", Anhydrous Rock Mass

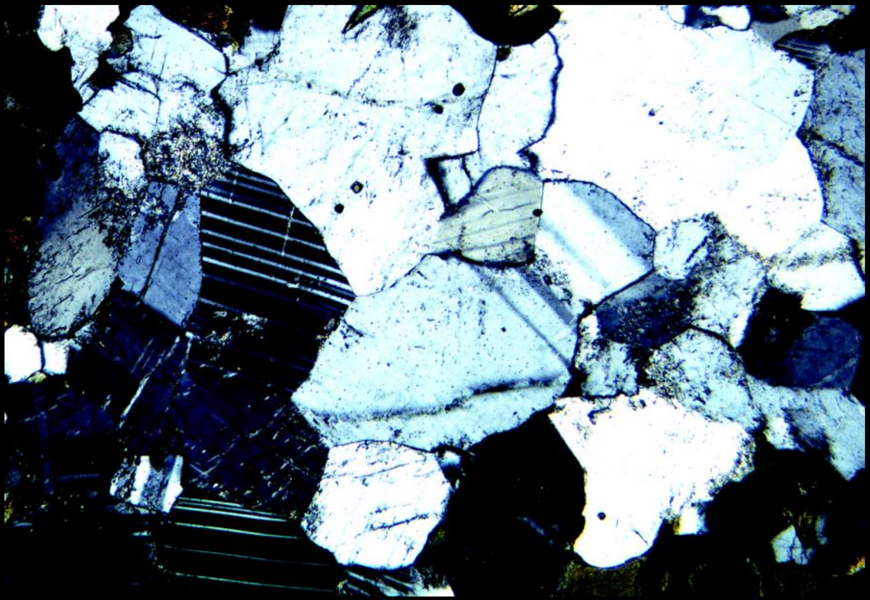


Hartland vs. Fordham Rock Fabric

- **Micaceous (+/- hornblende) penetrative foliation anticipated**
  - **Based on boring logs, pre-bid reports**
- **Weakly to non-foliated "granoblastic" rock mass found**

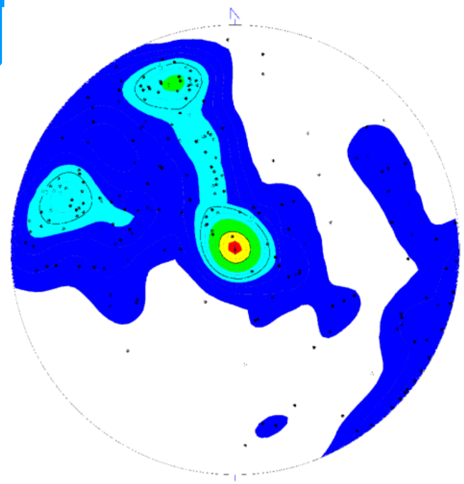


Typical Hartland



Typical Fordham

Orientation of Rock Layering



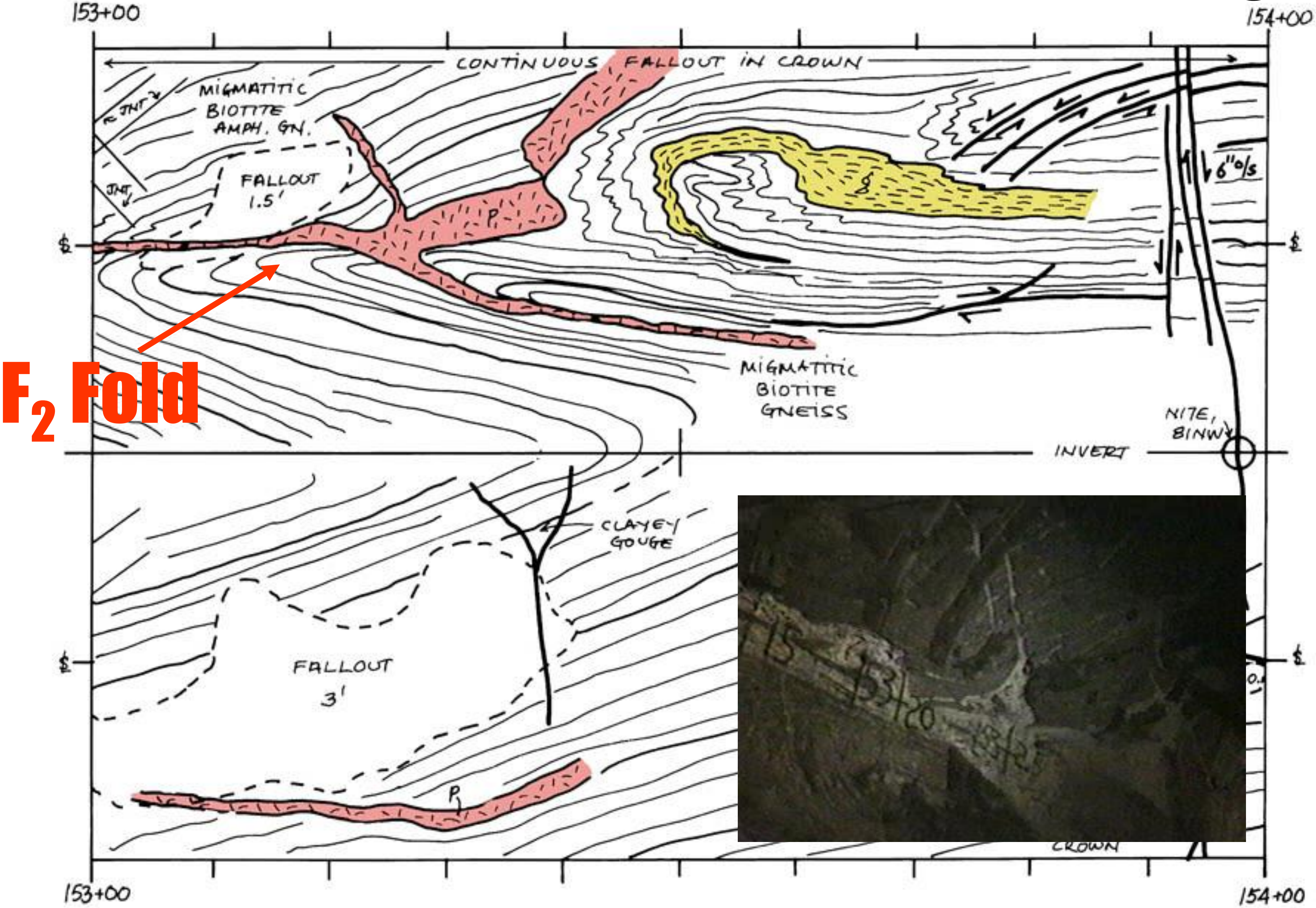
- NE strike and moderate 57 degree dip anticipated
  - [Based on borings, Chesman, Tarkoy]

- Highly variable trends found
  - Extended reaches of tunnel exhibit gentle dips

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

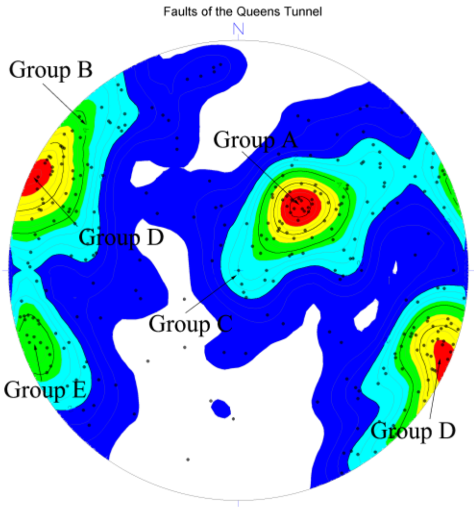
		NE Leg		NW Leg	
Gentle Dips		17/93	18%	44/139	32%
Moderate Dips		34/93	37%	28/139	20%
Steep Dips		42/93	45%	67/139	48%

Fallout from Reclined Folds and Flat Layering



Brittle Faults

- Hundreds of 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)

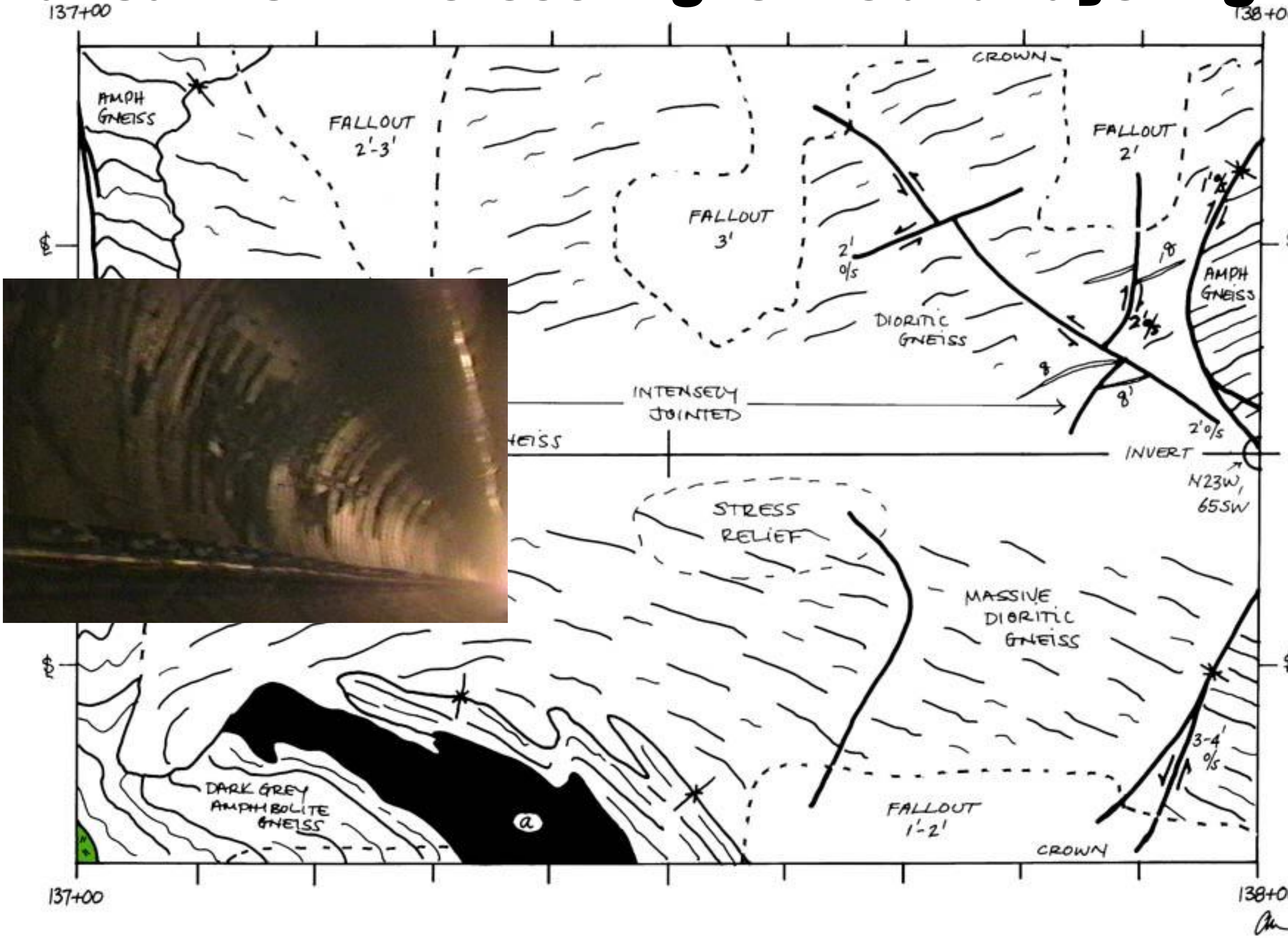
Group E = NNW-trending "Manhattanville" fault system


NW-Trending Fault Cut by NNE Fault
8' Gouge
214+30
214+40
Queens Tunnel Sta. 214+25

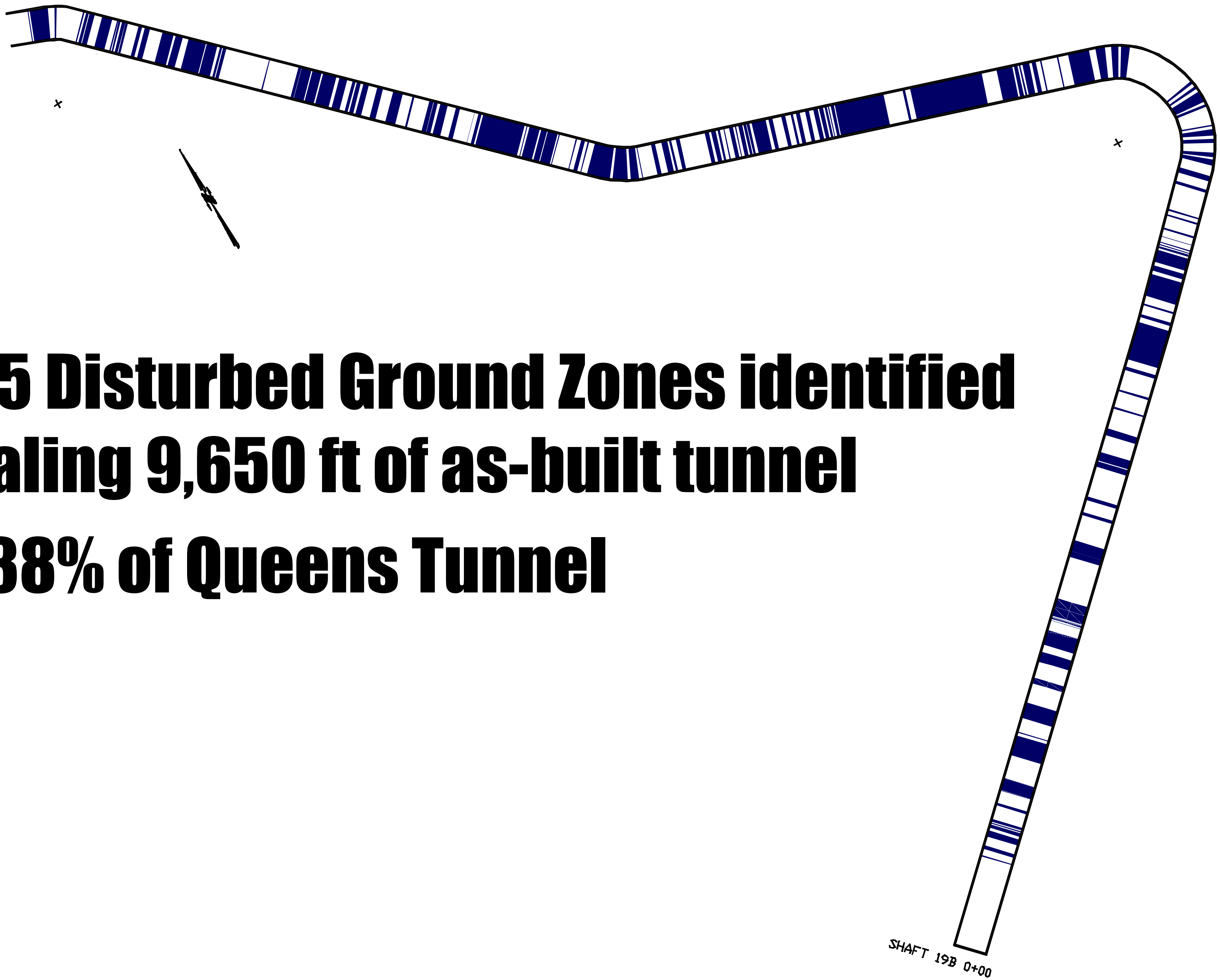
Gently Dipping NW-Trending Fault

Queens Tunnel Sta. 196+85

Fallout from Intersecting Joints and Layering



Disturbed Ground



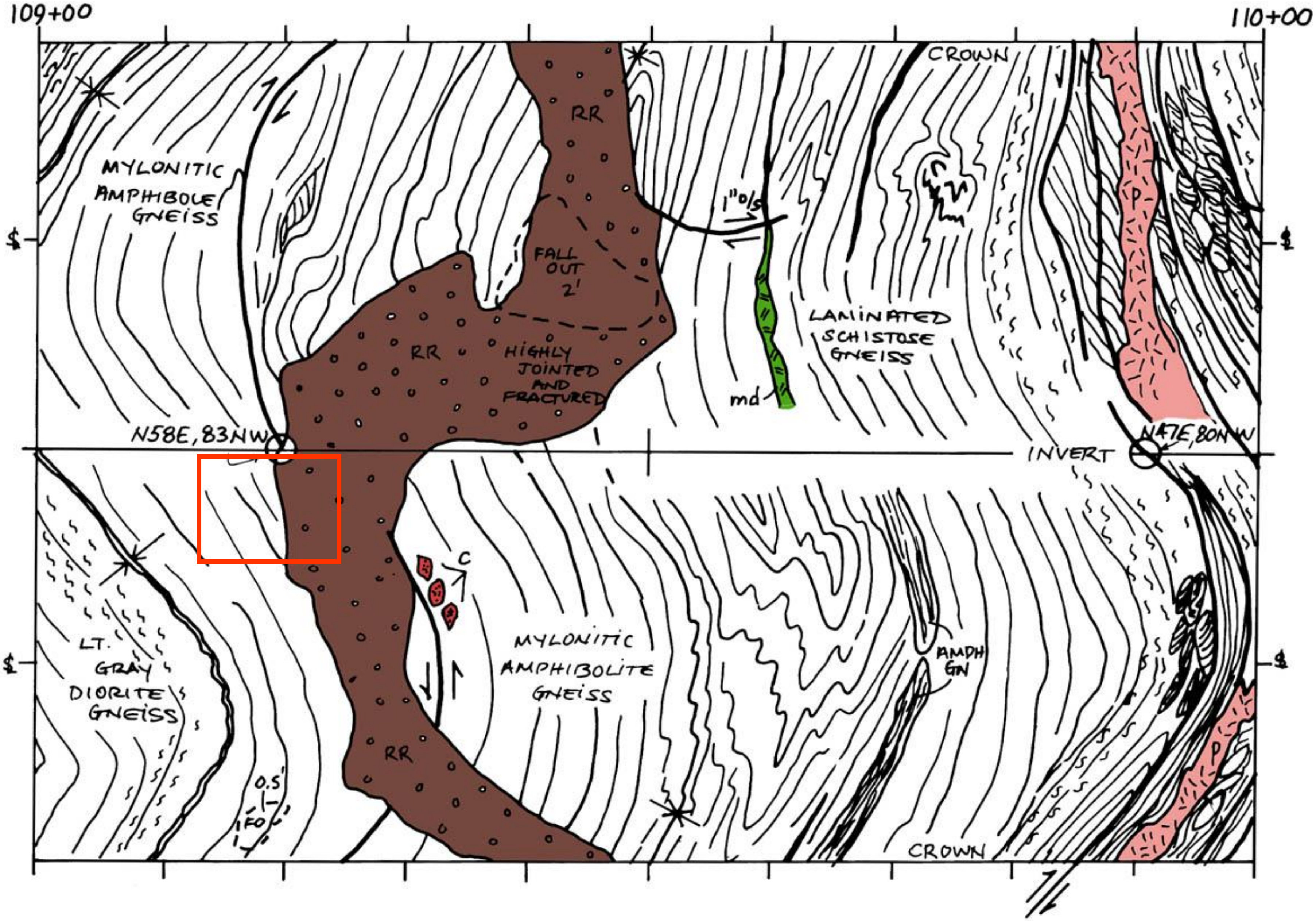
- 125 Disturbed Ground Zones identified totaling 9,650 ft of as-built tunnel
- ~38% of Queens Tunnel


CONTRACT 543B SHEET 1
SHEETS IN SET, 19
Dikes
18B
19B
20B
21B
22B
23B
17B
16B
543B
PROSPECT PARK
ROOSEVELT IS.
EAST RIVER
GOVERNORS IS.
UPPER BAY
MANHATTAN
BROOKLYN
NEW JERSEY
N.I.C. = Not in Contract 543B
City of New York
DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF ENVIRONMENTAL ENGINEERING
CITY TUNNEL NO.3, STAGE 2
LOCALITY MAP - CONTRACT 543B
Stage 2, City Tunnel 3

Five Laterally Extensive Dikes

	Stationing	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

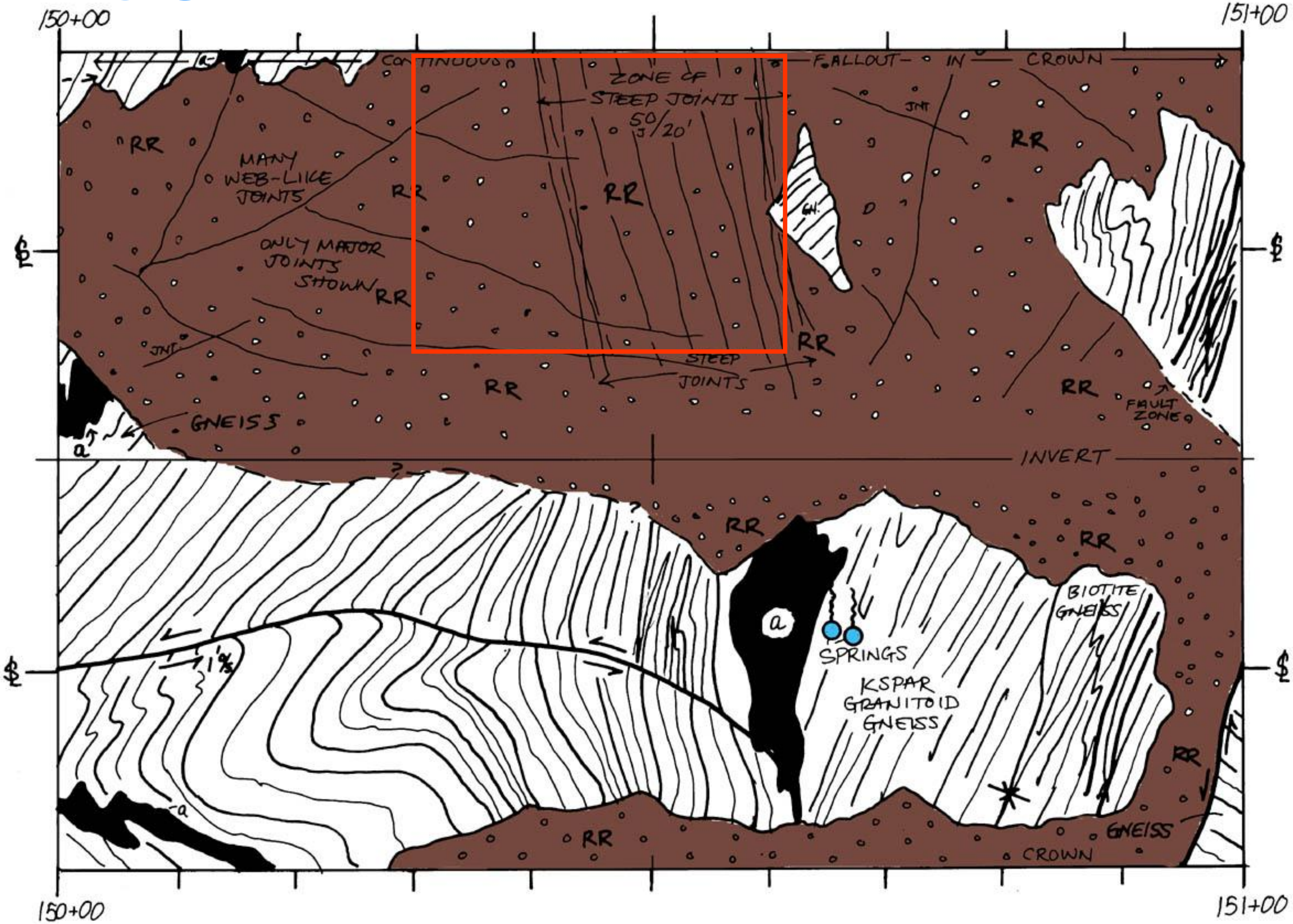
Dike 1



109+00
110+00
CROWN
MYLONITIC AMPHIBOLE GNEISS
RR
FALL OUT 2'
1"o/s
md
LAMINATED SCHISTOSE GNEISS
P
RR
HIGHLY JOINTED AND FRACTURED
N58E, 83NW
N47E, 80NW
INVERT
C
LT. GRAY DIORITE GNEISS
MYLONITIC AMPHIBOLITE GNEISS
AMPH GN
RR
0.5'
CROWN


Station 109+20, Right Wall
Cooling joints extend 10' into country rock

Dike 5



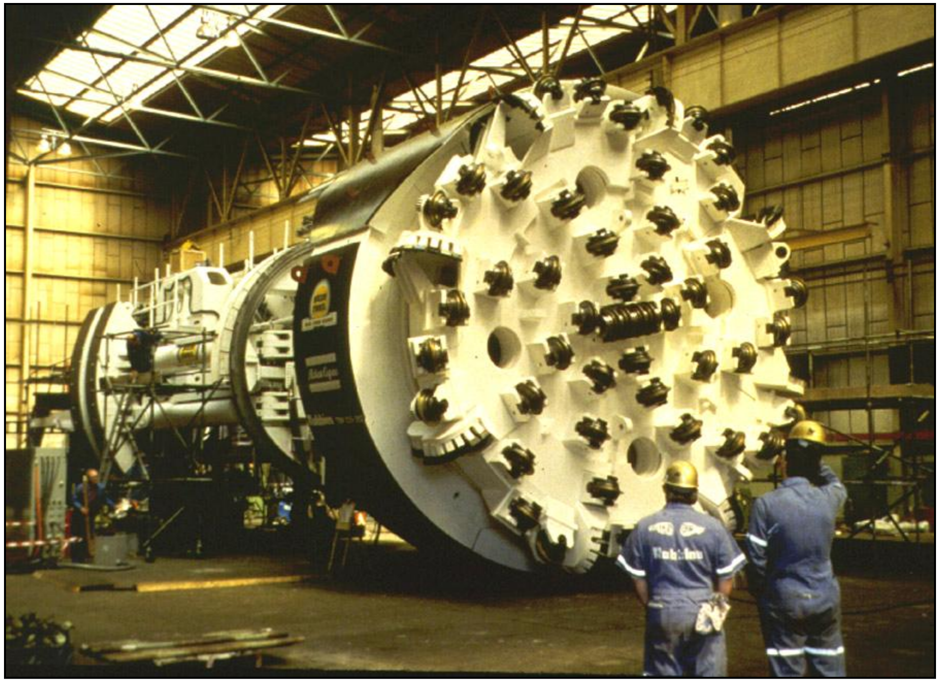
150+00
151+00
CONTINUOUS
FALLOUT IN CROWN
ZONE OF STEEP JOINTS
50/20'
RR
MANY WEB-LIKE JOINTS
ONLY MAJOR JOINTS SHOWN
JNT
GNEISS
GN.
STEEP JOINTS
FAULT ZONE
INVERT
SPRINGS
KSPAR GRANITOID GNEISS
BIOTITE GNEISS
CROWN
a


12:05PM
5/15/1998

Tunneling Difficulties

Reduced TBM Penetration Rate Investigation

(Queens Tunnel TBM)



Machine Diameter: 23'2"

Cutters: 50 cutters, 19" diameter, 70000 lbs maximum load

Cutterhead Power: 4,220 hp

Cutterhead Torque: 2,669,000 ft-lb

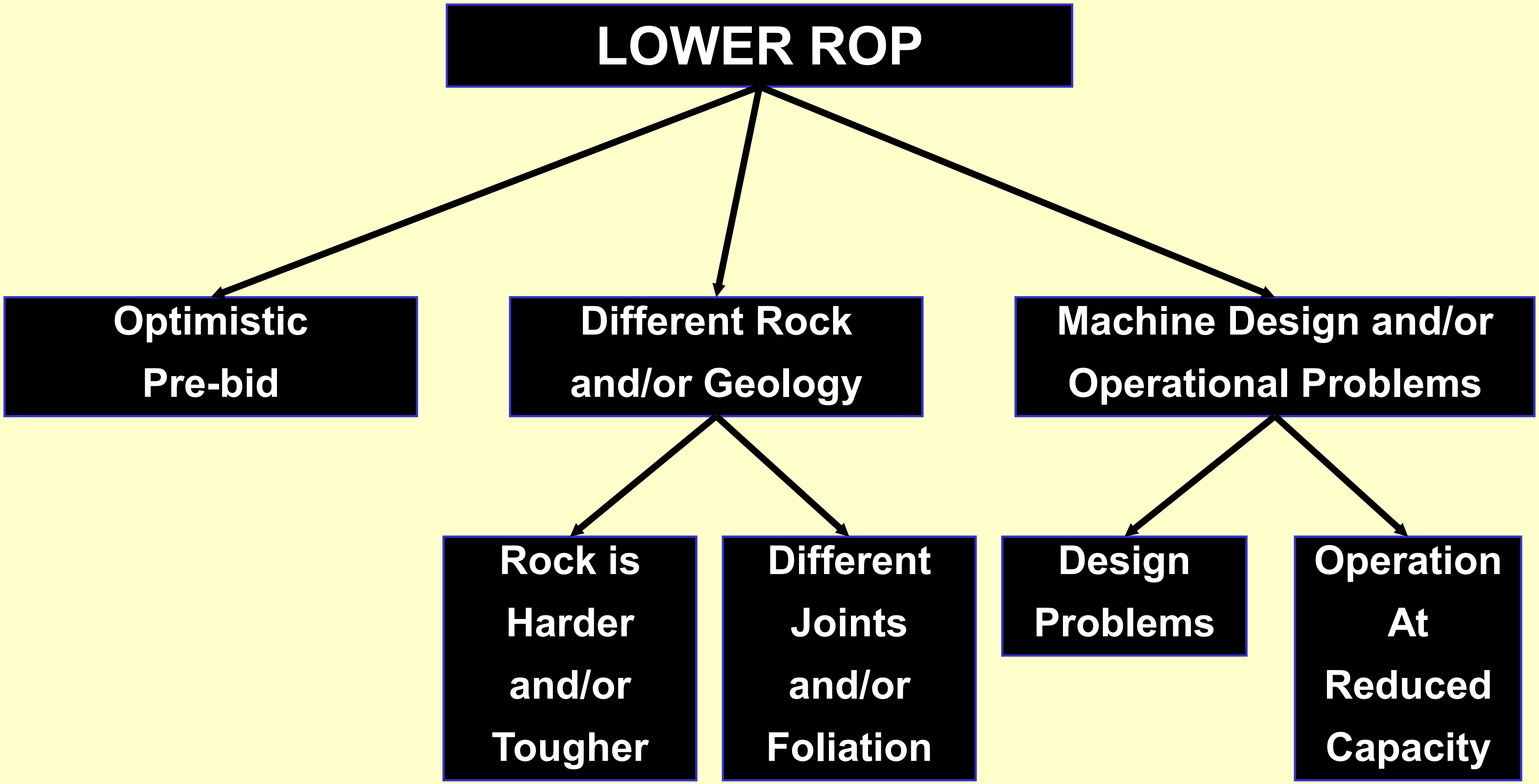
Cutterhead Thrust: 3,500,000 lbs (1,750 tons)

TBM Weight: 640 tons

Conveyor Capacity: 650 ft^3/hr

Reduced TBM Penetration Rate Investigation

(Why lower ROP than anticipated?)



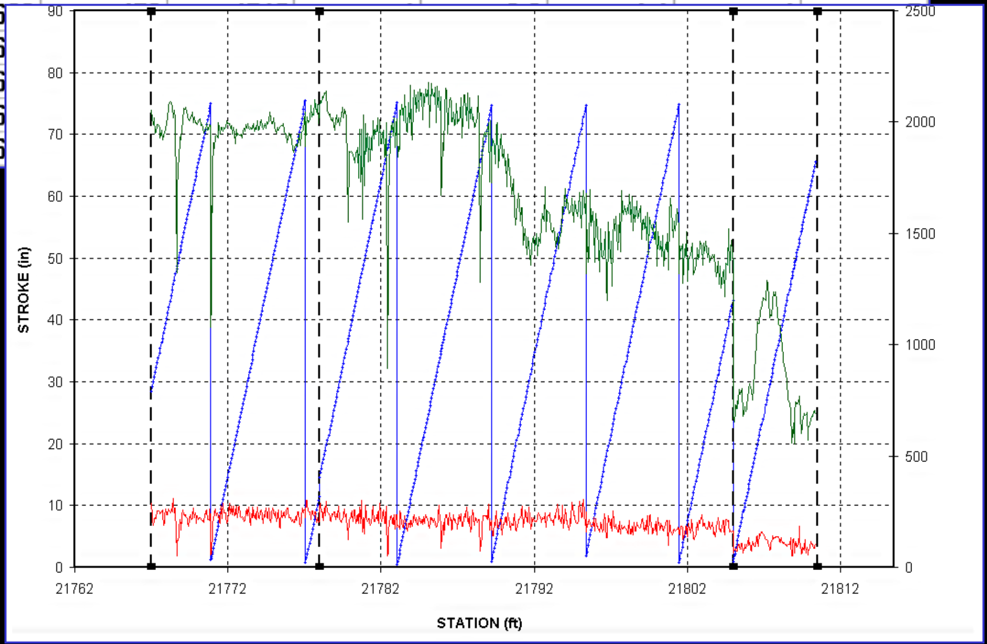
Reduced TBM Penetration Rate Investigation

(TBM Data Logger)

The Queens Tunnel TBM utilized a CIC-200 Data Recorder capable of continuous data gathering.

Robbins	TBM	235-282	Queens										

File	opened	on	Thu	4/1/1999	0:00:04								
	1	2	3	4	5	6	7	8	9	10	11	12	13
DATE	TIME	SPARE	STROK	FT/HR	VOLTS	SPARE	AMPS	TONS	BORNG	L.SID	R.SID	PGRIP	M1_M10SI
4/1/1999	2:09:10	0	36.2	0	488	701	36	643	1	-3.8	-1.4	1	7
4/1/1999	2:09:40	0	36.4	1.3	490	701	54	1026	1	-3.8	-1.4	1	7
4/1/1999	2:10:10	0	36.5	1.3	488	698	85	1419	1	-3.8	-1.4	1	7
4/1/1999	2:10:40	0	37	3.6	485	695	151	1511	1	-3.8	-1.4	1	7
4/1/1999	2:11:10	0	37.4	5.2	483	6							
4/1/1999	2:11:40	0	38.1	5.9	480	6							
4/1/1999	2:12:10	0	38.8	8.2	481	6							
4/1/1999	2:12:40	0	39.7	7.5	478	6							
4/1/1999	2:13:10	0	40.5	8.2	480	6							



Data logger recorded the TBM data every 30 seconds

Reduced TBM Penetration Rate Investigation

(Cutterload Calculations from TBM Data Logger)

$$CL = \frac{GT - (0.05GT) - 15}{N_{eff}}$$ → **Method 1: 75,472 lbs**

$$CL = \frac{GT - 120 - 15}{N_{eff}}$$ → **Method 2: 74,146 lbs**

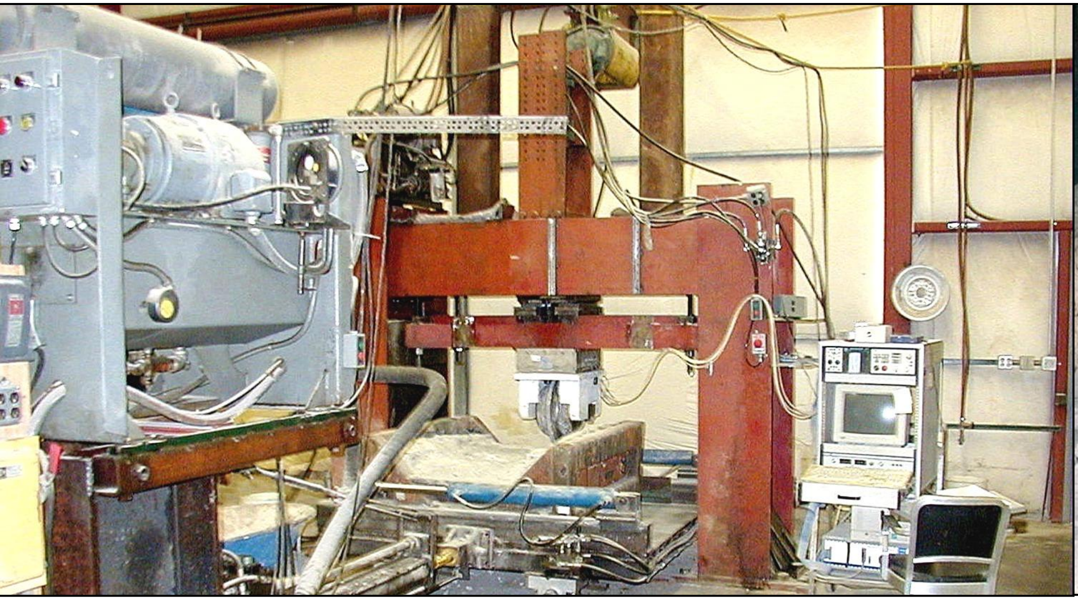
$$CL = \frac{GT}{N_t}$$ → **Method 3: 72,131 lbs**

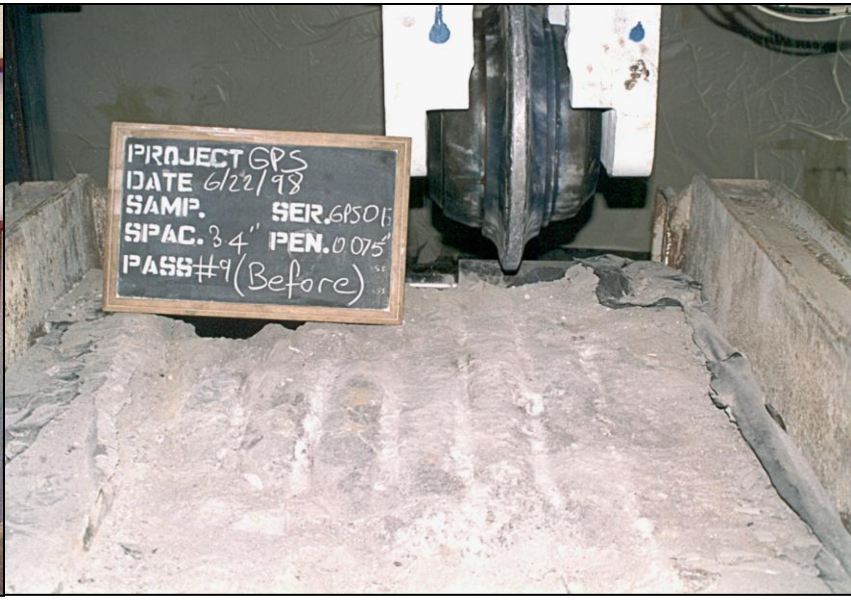
CL = Cutter load
GT = Gross thrust

N_{eff} = Effective number of cutters
N_t = Total number of cutters

Reduced TBM Penetration Rate Investigation

(LCM Testing)





LCM cutter force measurement: 72,120 lbs

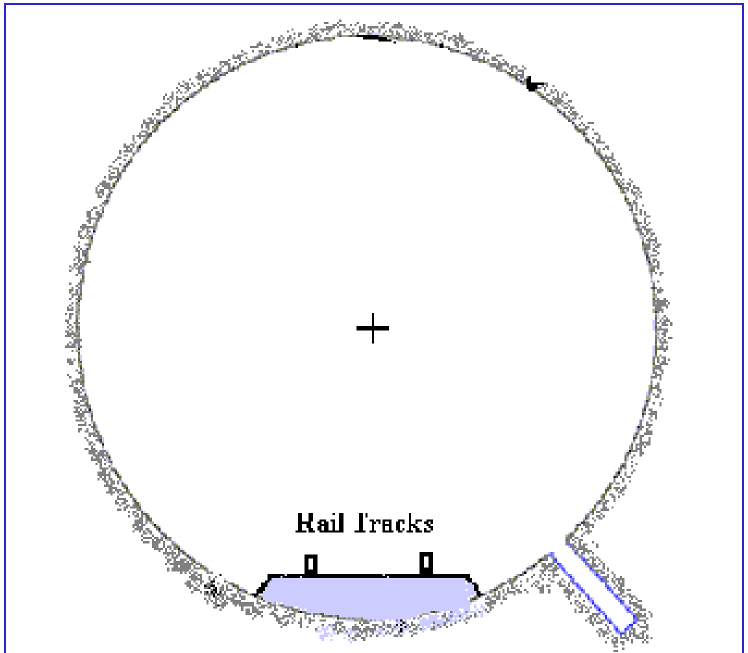
Field Cutterload from TBM data logger: 75,920 lbs

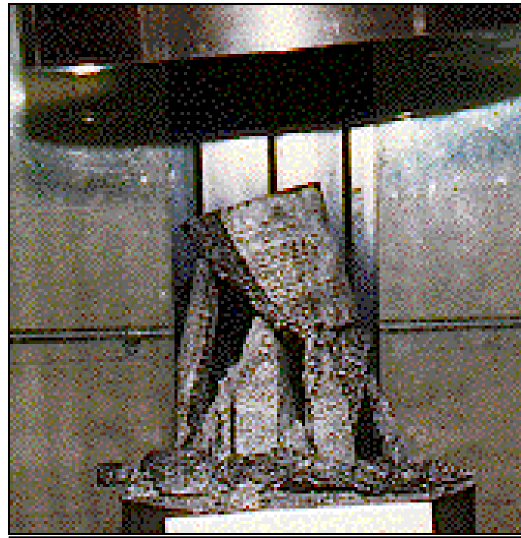
(@Station 100+31 ft, Drift 18B)

These cutter load values are very close, within 5% of each other. Such agreement gives further confirmation that the Queens TBM was operated at cutterloads at or above the manufacturer recommended 70 kip loads

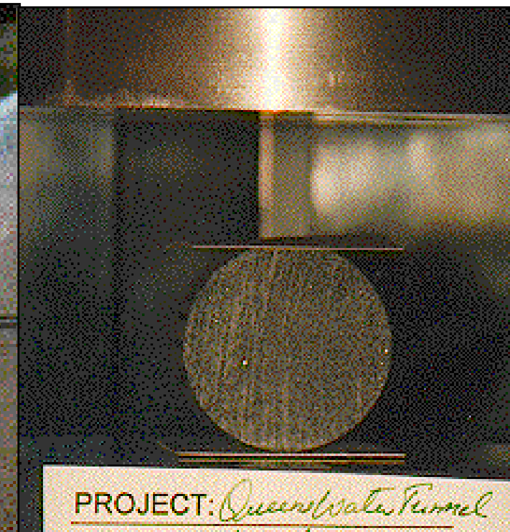
Reduced TBM Penetration Rate Investigation

(Rock Coring and Testing)





Unconfined Compressive Strength



Brazilian Tensile Strength

Punch Penetration Index Test

Reduced TBM Penetration Rate Investigation

(Harder/Tougher Rock Mass Conditions)

- The actual rock compressive strength was found to be about 14% higher than what was reported pre-bid

- The tensile strength across foliation, which corresponds to machine operation when foliation is more or less parallel to tunnel axis, was found to be about 38% higher than along foliation

- The Punch Penetration Index (PPI) for the Queens Tunnel was found to be about 30% higher than the standard index for hard rocks

Summary – QT Low Penetration

- **Queens Tunnel: Fordham, not Hartland**
  - Tougher, much older deep-seated granulite terrane
  - More highly metamorphosed and structurally complex than the anticipated Hartland
  - Weakly foliated near-isotropic orthogneiss rock mass
  - Decreased TBM penetration rate deemed the result of tougher Fordham rock
- **Collapsing face, crown, and sidewalls forced installation of additional support because of:**
  - Broad zones of subhorizontal fabrics and shear zones
  - Tunnel cut by >300 fractured (faulted) zones
  - Rhyodacite cooling fracture pattern and contact effects

HERRENKNECHT TBM ADVERTISEMENT

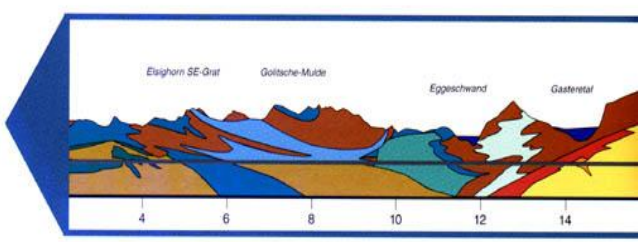
Rock Does Not Equal Rock

At Herrenknecht, maximum tunnelling performance and the greatest possible safety are the ultimate goals for the development of tunnelling machines. Expert analysis of the geological conditions result in a "tailored hard rock machine".

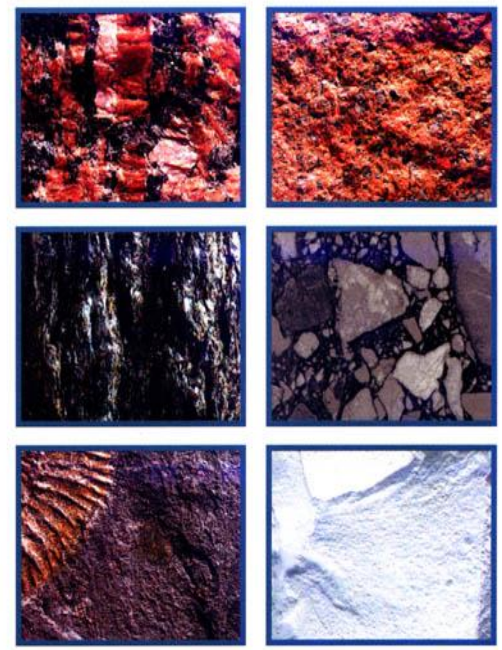
Whether it is solid rock, abrasive rock or rock under high pressure, weathered transition zones with high ground water pressure or caverns, the variety of the geological conditions in a planned tunnel route is virtually unlimited. At Herrenknecht, the geological analysis of the ground conditions is always taken into consideration in the machine design. Cutters and cutterhead are ideally adapted to the varying degrees of hardness and abrasion in sedimentary, metamorphic or igneous rock.

All Experts On One Team

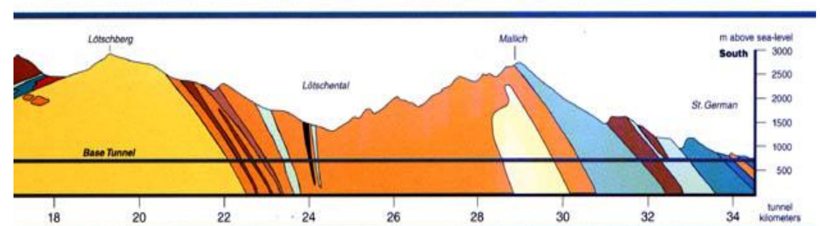
The excavation process in hard rock takes place in the peak state of the shear and compression resistance as well as tensile strengths of the rock. At the same time, the best possible tunnelling performance has to be achieved. At Herrenknecht, a team of internal specialists from the disciplines of rock mechanics, mechanical engineering and process technology find the optimum project solution for developing the machine design.



Mechanical rock excavation is confronted by rock with varying degrees of hardness, e.g. with extremely hard gneiss (top left) and granite (top right), medium hard mica schist (center left), breccia (center right) and claystone (bottom left) as well as limestone (bottom right).



The formation of each mountain range is unique. Lötschberg in Switzerland consists of a wide variety of rock formations along the tunnel route. Herrenknecht supplied two single gripper machines (Ø 9.43 m), which enable mechanical rock stabilization as close as 4.2 m behind the cutterhead.



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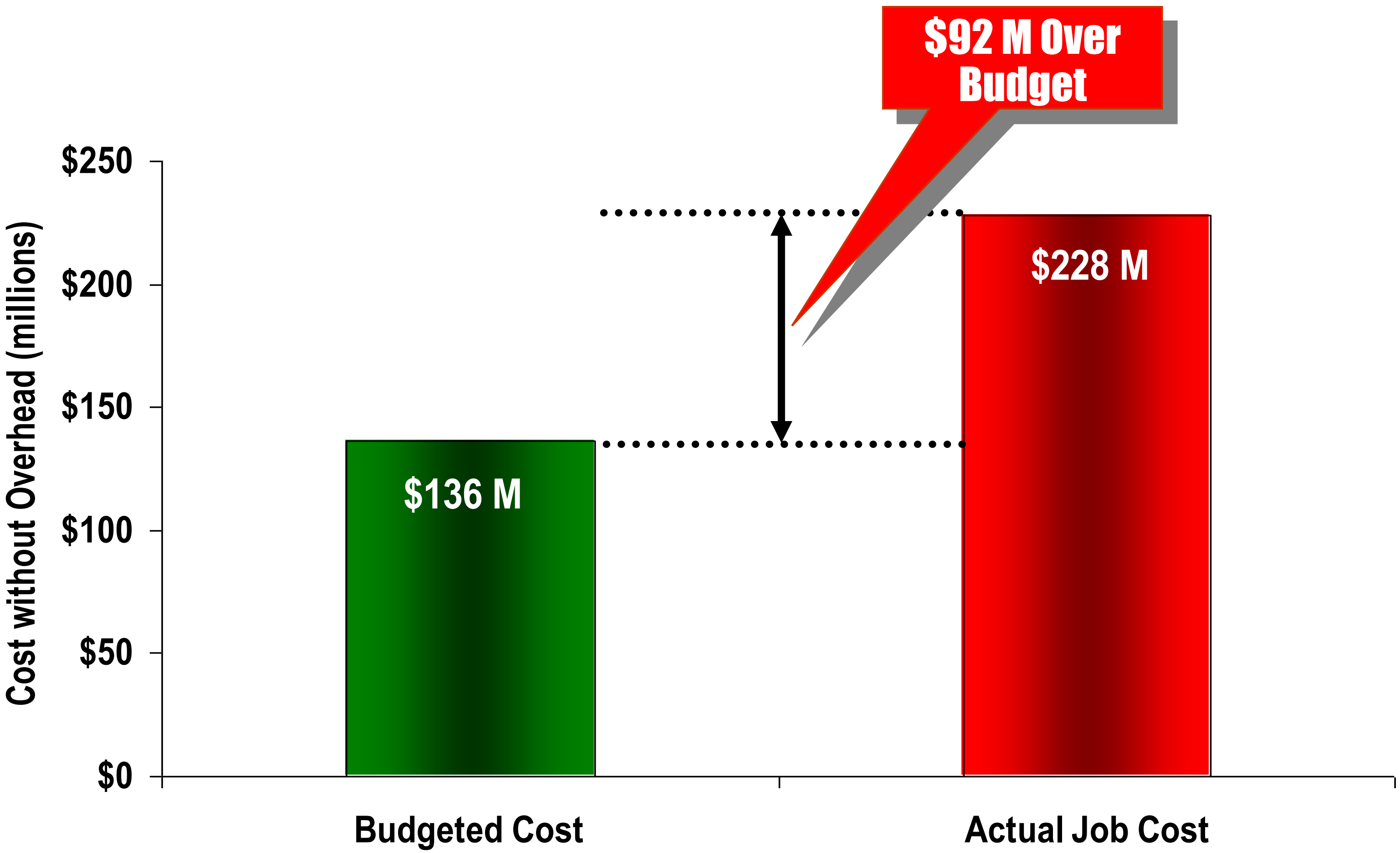
- Extra Slides

Anticipated vs. Actual Cost



The Queens Tunnel Complex

Younger (M_3) Metamorphism

Late stage biotite, chlorite, carbonate, and sericite, particularly obvious near pegmatites and other granitoid intrusives.

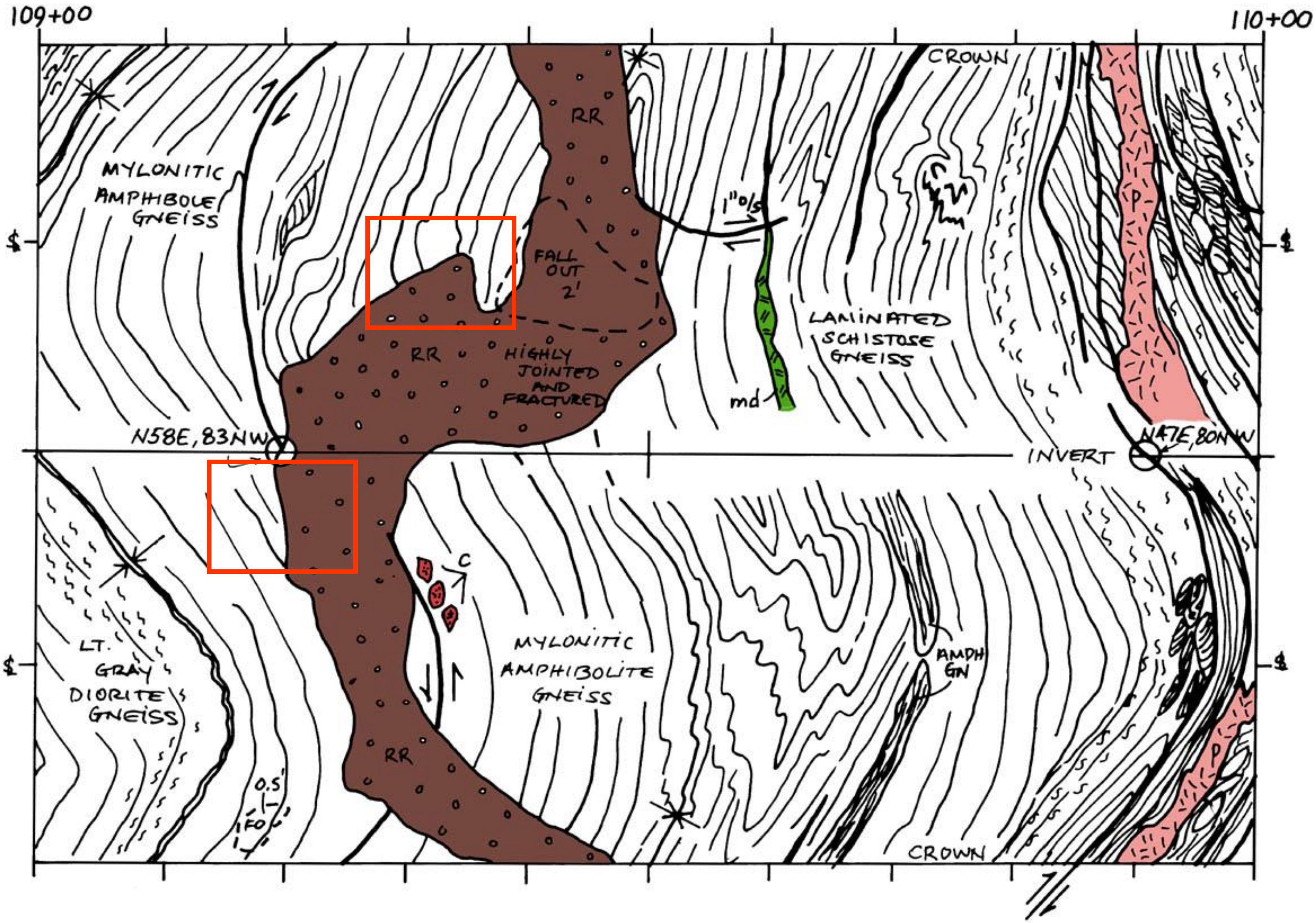
Sample Reaction

K-spar + opx = biotite + quartz

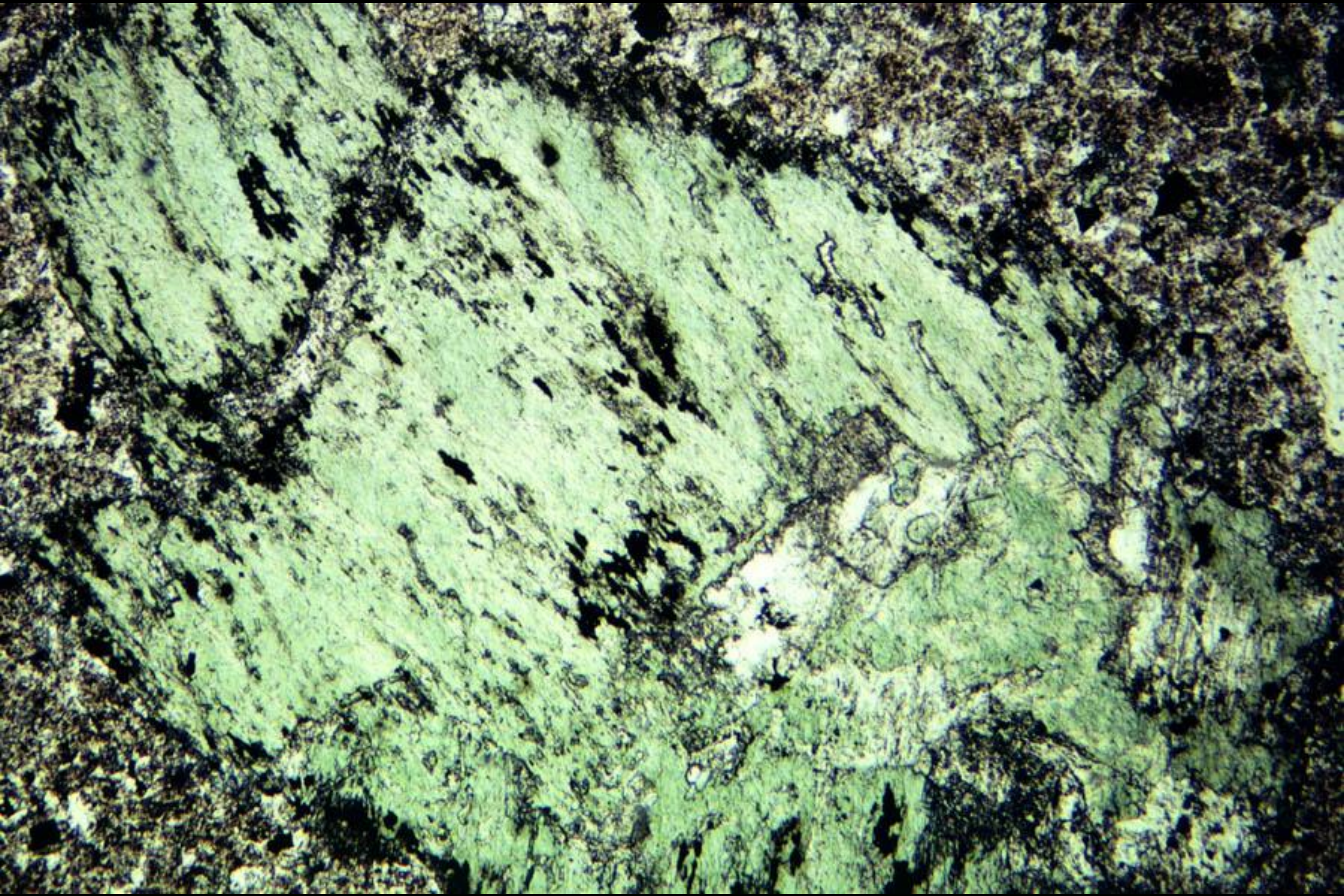
The younger low-temperature retrogression involved introduction of hydrous minerals into the gneisses, and took place at significantly higher H_2O activity than did the previous metamorphisms (M_1+M_2). Retrogression along shear zones.

Walloomsac = Graphitic 'Red" Biotite Schist

Dike 1


109+00
110+00
CROWN
MYLONITIC AMPHIBOLE GNEISS
RR
FALL OUT 2'
RR
HIGHLY JOINTED AND FRACTURED
1"o/s
LAMINATED SCHISTOSE GNEISS
md
P
N58E, 83NW
INVERT
N47E, 80NW
C
MYLONITIC AMPHIBOLITE GNEISS
LT. GRAY DIORITE GNEISS
AMPH GN
RR
0.5'
FO
P
CROWN


109



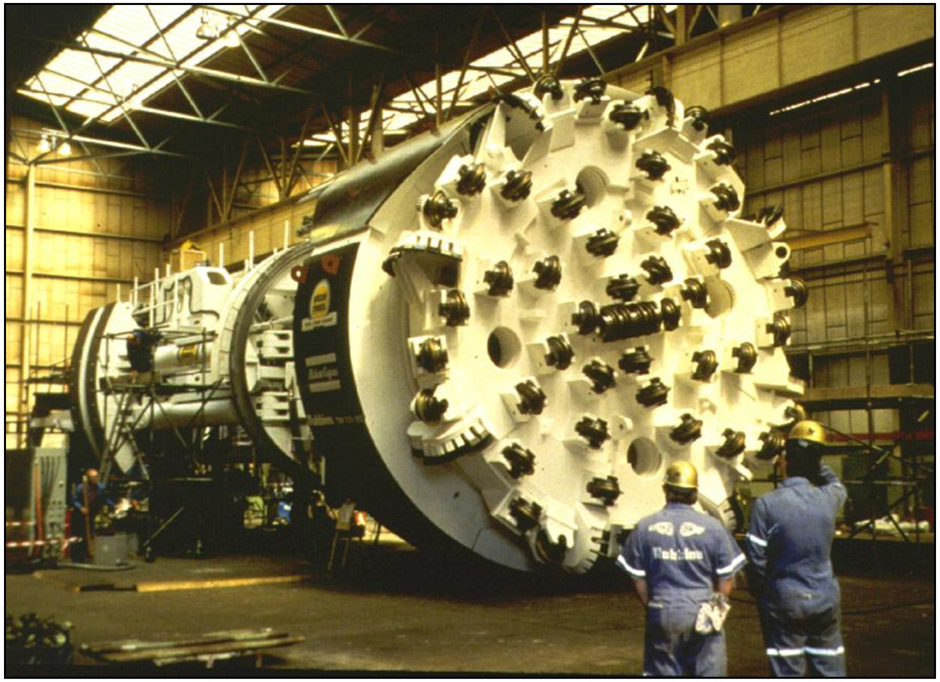
DEP Borings – QTL-13

Permian Lava Flows in Woodside?

Levent's Slides

Reduced TBM Penetration Rate Investigation

(Queens Tunnel TBM)



Machine Diameter: 23'2"

Cutters: 50 cutters, 19" diameter, 70000 lbs maximum load

Cutterhead Power: 4,220 hp

Cutterhead Torque: 2,669,000 ft-lb

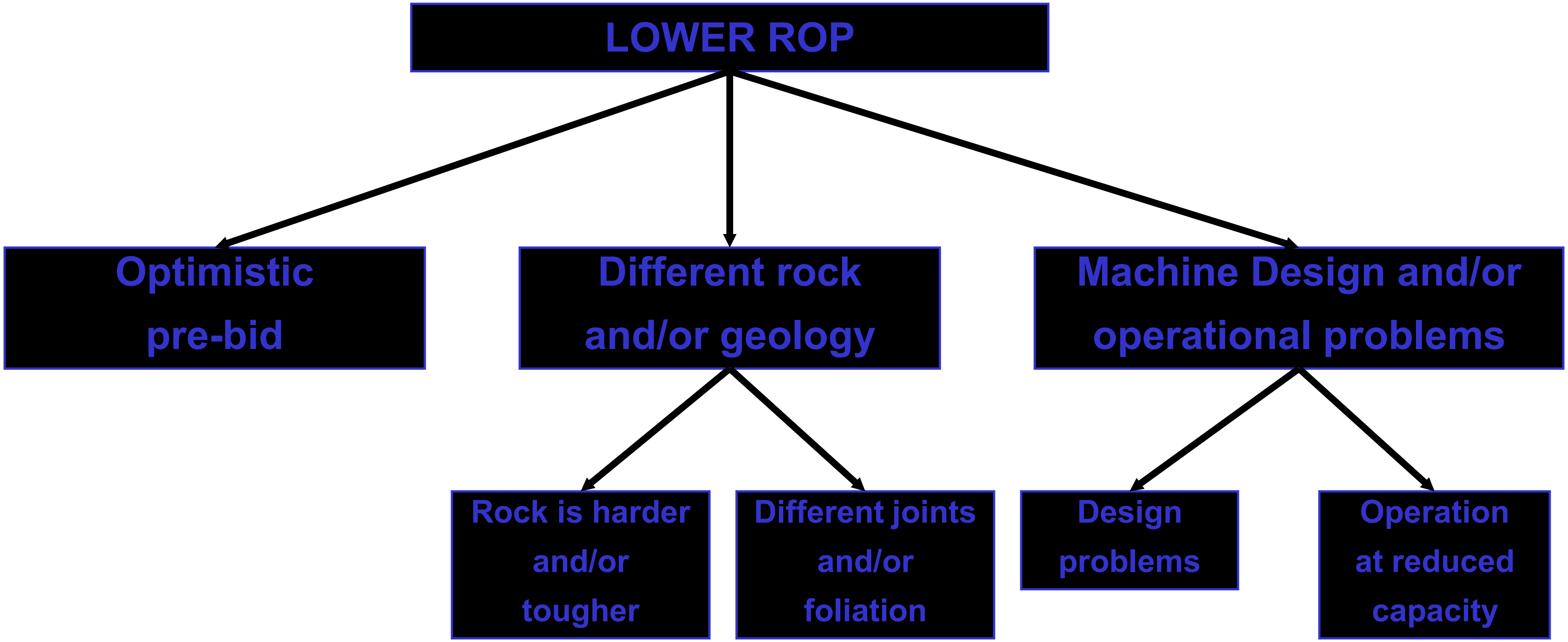
Cutterhead Thrust: 3,500,000 lbs (1,750 tons)

TBM Weight: 640 tons

Conveyor Capacity: 650 ft^3/hr

Reduced TBM Penetration Rate Investigation

(Why lower ROP than anticipated?)



Reduced TBM Penetration Rate Investigation

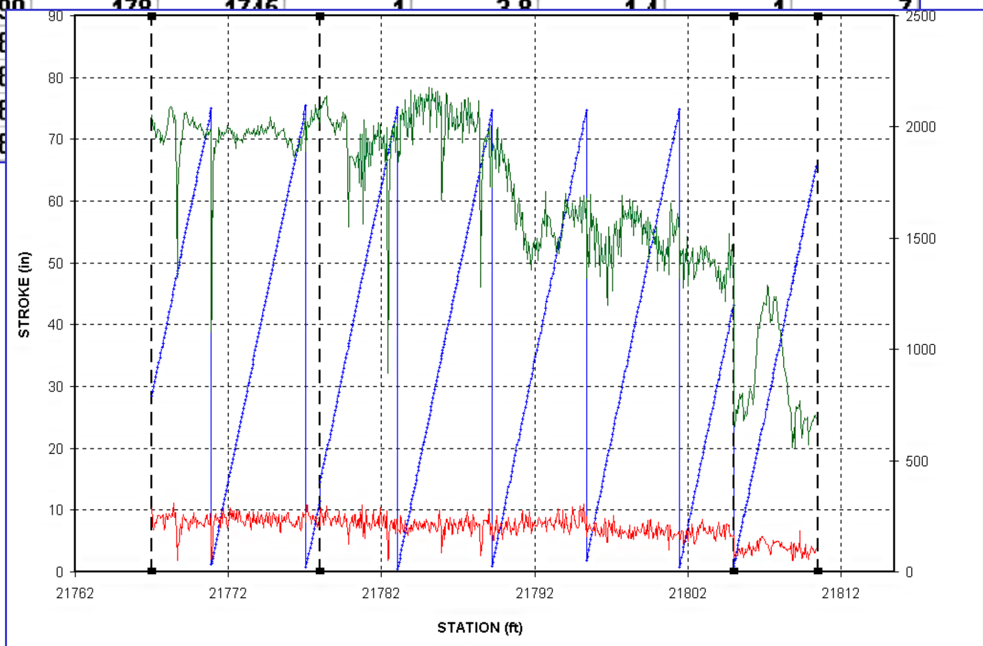
(TBM Data Logger)

The Queens TBM utilized a CIC-200 Data Recording system capable of continuous data gathering and recording.

Robbins	TBM	235-282	Queens									

File	opened	on	Thu	4/1/1999	0:00:04							
	1	2	3	4	5	6	7	8	9	10	11	12	13
DATE	TIME	SPARE	STROK	FT/HR	VOLTS	SPARE	AMPS	TONS	BORNG	L.SID	R.SID	PGRIP	M1_M10SI
--													
4/1/1999	2:09:10	0	36.2	0	488	701	36	643	1	-3.8	-1.4	1	7
4/1/1999	2:09:40	0	36.4	1.3	490	701	54	1026	1	-3.8	-1.4	1	7
4/1/1999	2:10:10	0	36.5	1.3	488	698	85	1419	1	-3.8	-1.4	1	7
4/1/1999	2:10:40	0	37	3.6	485	695	151	1511	1	-3.8	-1.4	1	7
4/1/1999	2:11:10	0	37.4	5.2	483	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4/1/1999	2:11:40	0	38.1	5.9	480	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4/1/1999	2:12:10	0	38.8	8.2	481	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4/1/1999	2:12:40	0	39.7	7.5	478	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4/1/1999	2:13:10	0	40.5	8.2	480	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Data logger recorded the data every 30 seconds.



Reduced TBM Penetration Rate Investigation

(Cutterload Calculations from TBM Data Logger)

[redacted] → **Method 1: 75,472 lbs**

[redacted] → **Method 2: 74,146 lbs**

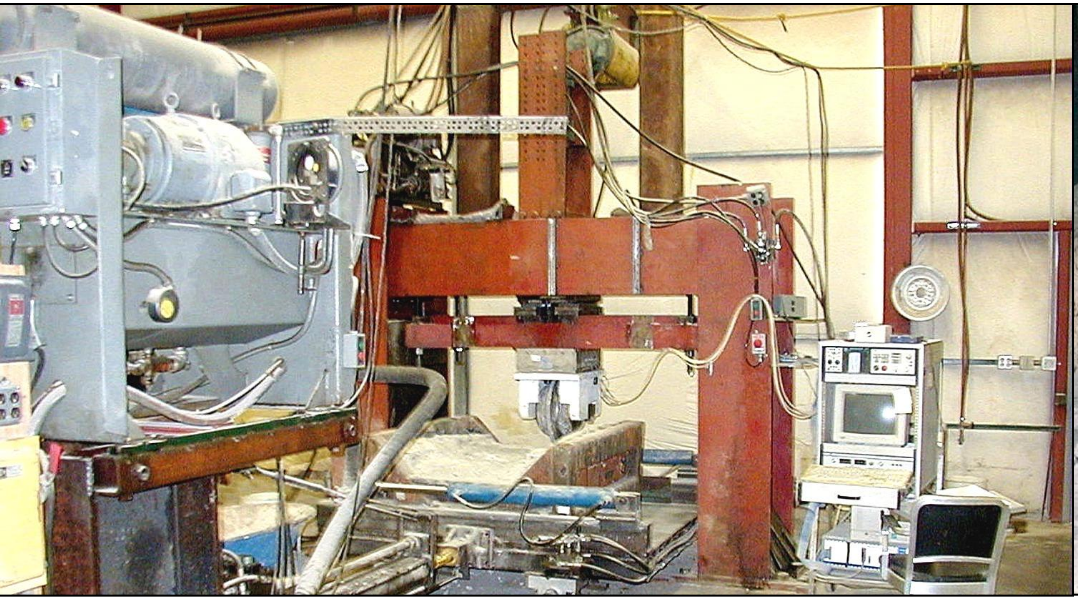
[redacted] → **Method 3: 72,131 lbs**

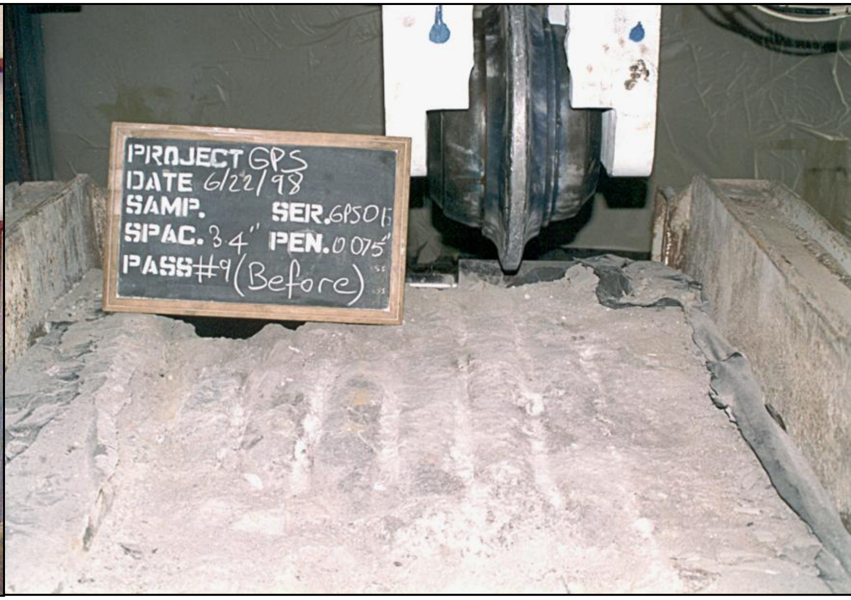
CL = Cutter load
GT = Gross thrust

N_{eff} = Effective number of cutters
N_t = Total number of cutters

Reduced TBM Penetration Rate Investigation

(LCM Testing)





LCM cutter force measurement: 72,120 lbs

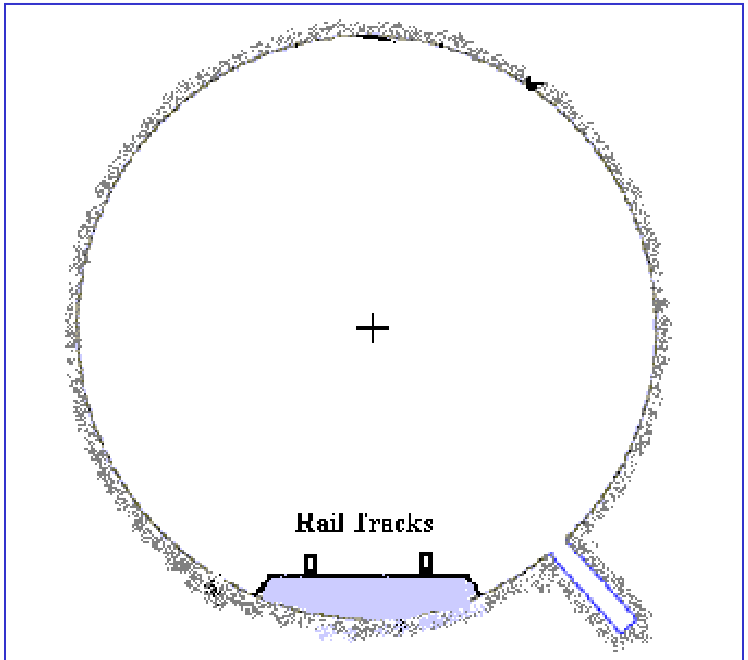
Field Cutterload from TBM data logger: 75,920 lbs

(@Station 100+31 ft, Drift 18B)

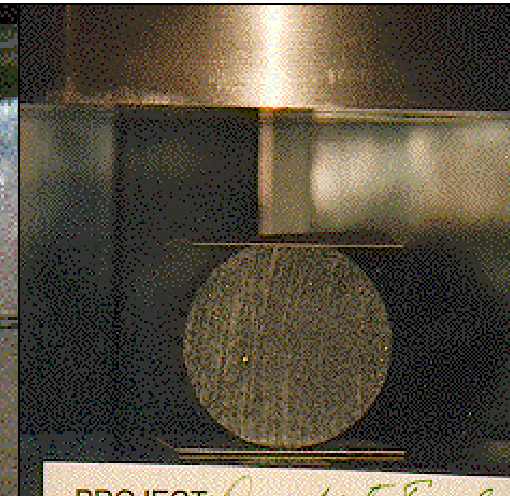
These cutter load values are very close, within 5% of each other. This close agreement gives further confirmation that the Queens TBM was operated at cutterloads at or above the manufacturer recommended 70 kips loads.

Reduced TBM Penetration Rate Investigation

(Rock Coring and Testing)



Unconfined Compressive Strength



Brazilian Tensile Strength

Punch Penetration Index Test

Reduced TBM Penetration Rate Investigation

(Harder/Tougher Rock Mass Conditions)

- **The actual rock compressive strength was found to be about 14 percent higher than what was reported pre-bid.**

- **The tensile strength across foliation, which corresponds to machine operation when foliation is more or less parallel to tunnel axis, was found to be about 38 percent higher than along foliation.**

- **The Punch penetration index for the Queens tunnel was found to be a bout 30 percent higher than the standard index for hard rocks.**