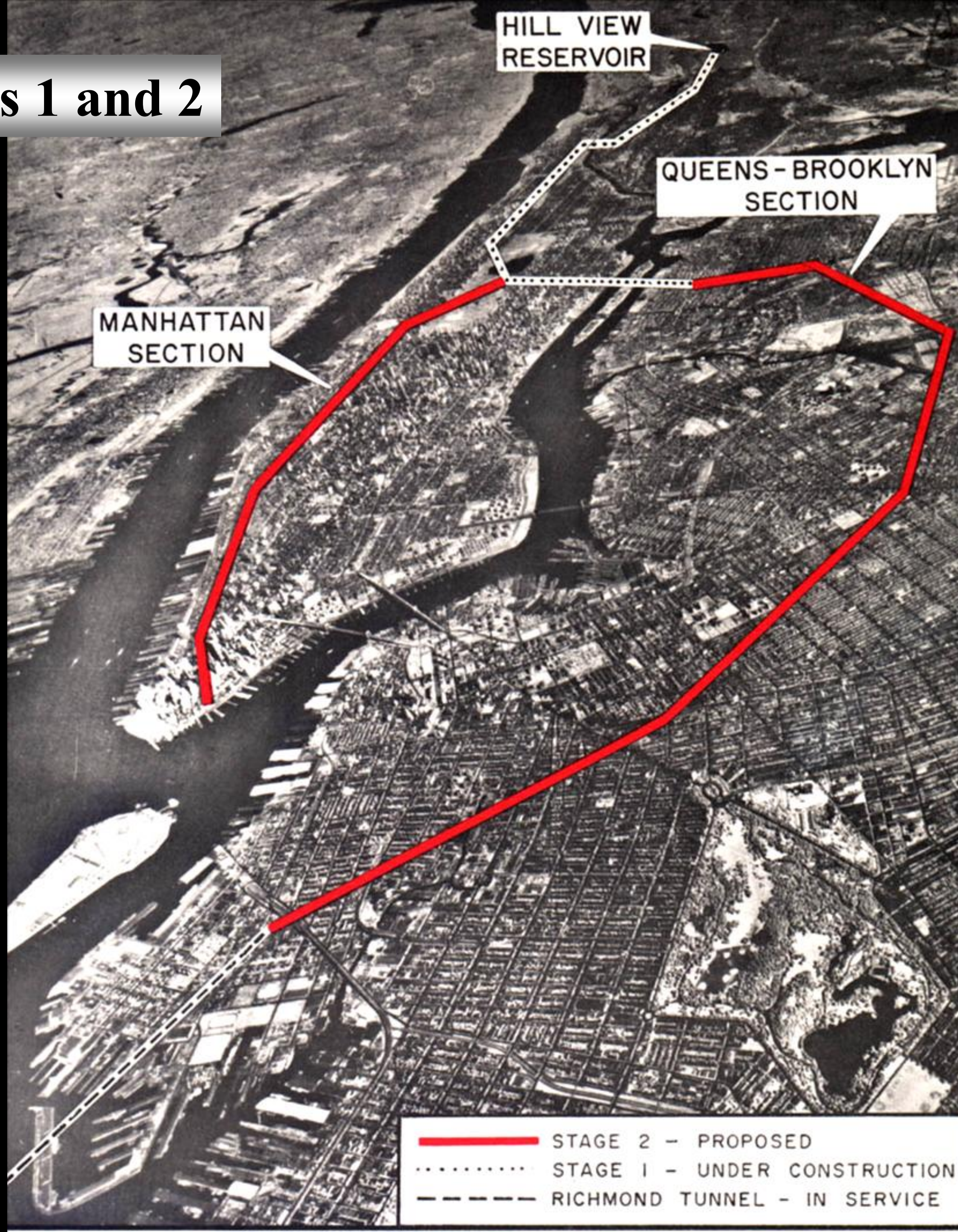
Sigma Xi – C.W. Post University
Geological Wonders of
The Queens Tunnel

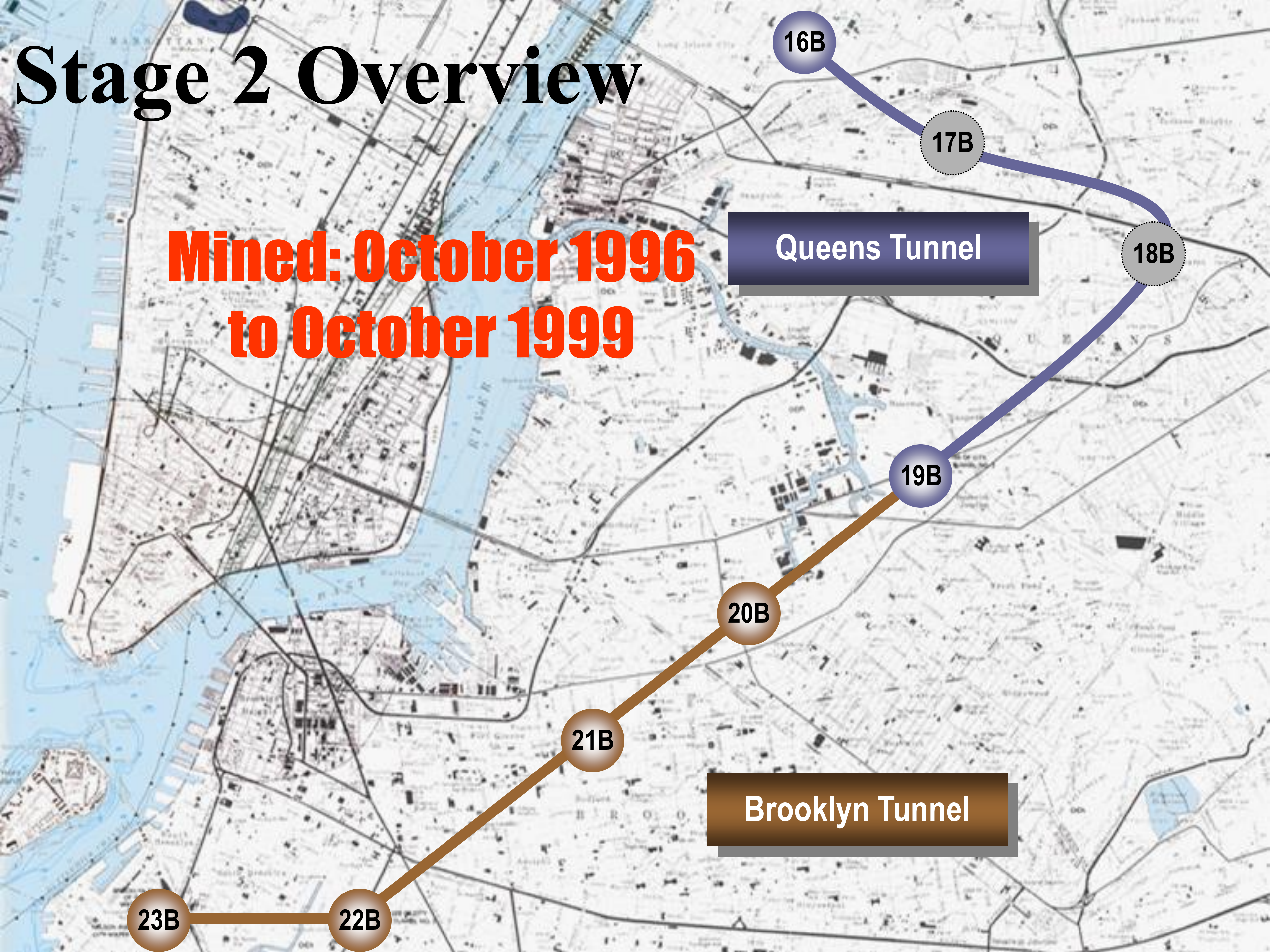
Charles Merguerian

HOFSTRA UNIVERSITY

CT3, Stages 1 and 2

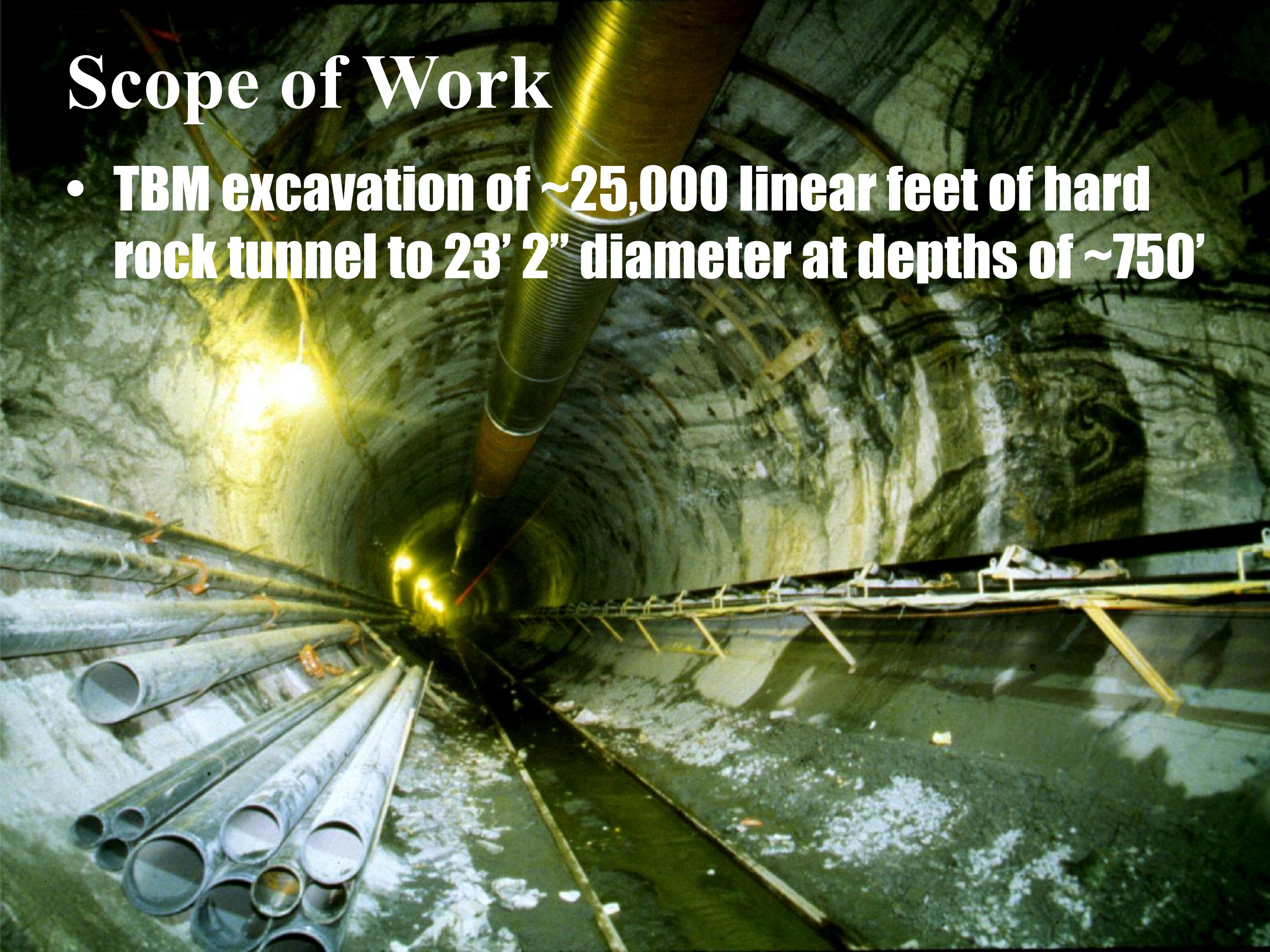


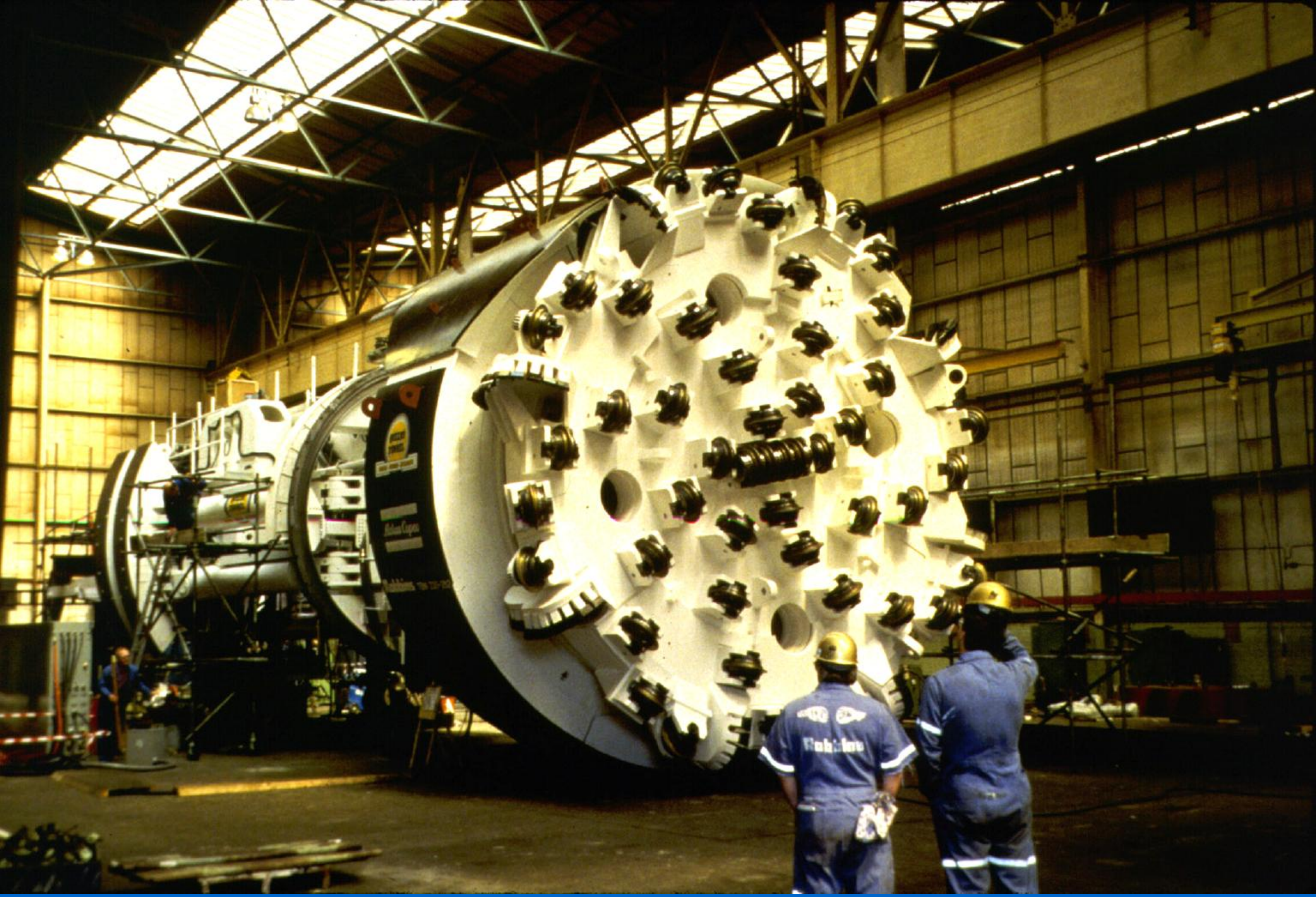
Stage 2 Overview



Scope of Work

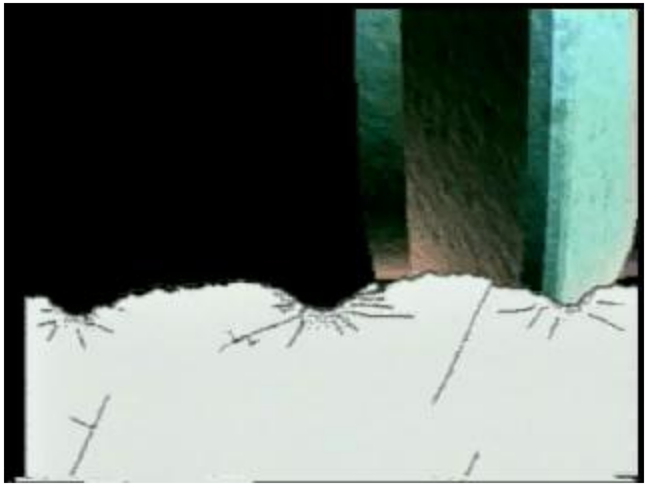
- TBM excavation of ~25,000 linear feet of hard rock tunnel to 23' 2" diameter at depths of ~750'

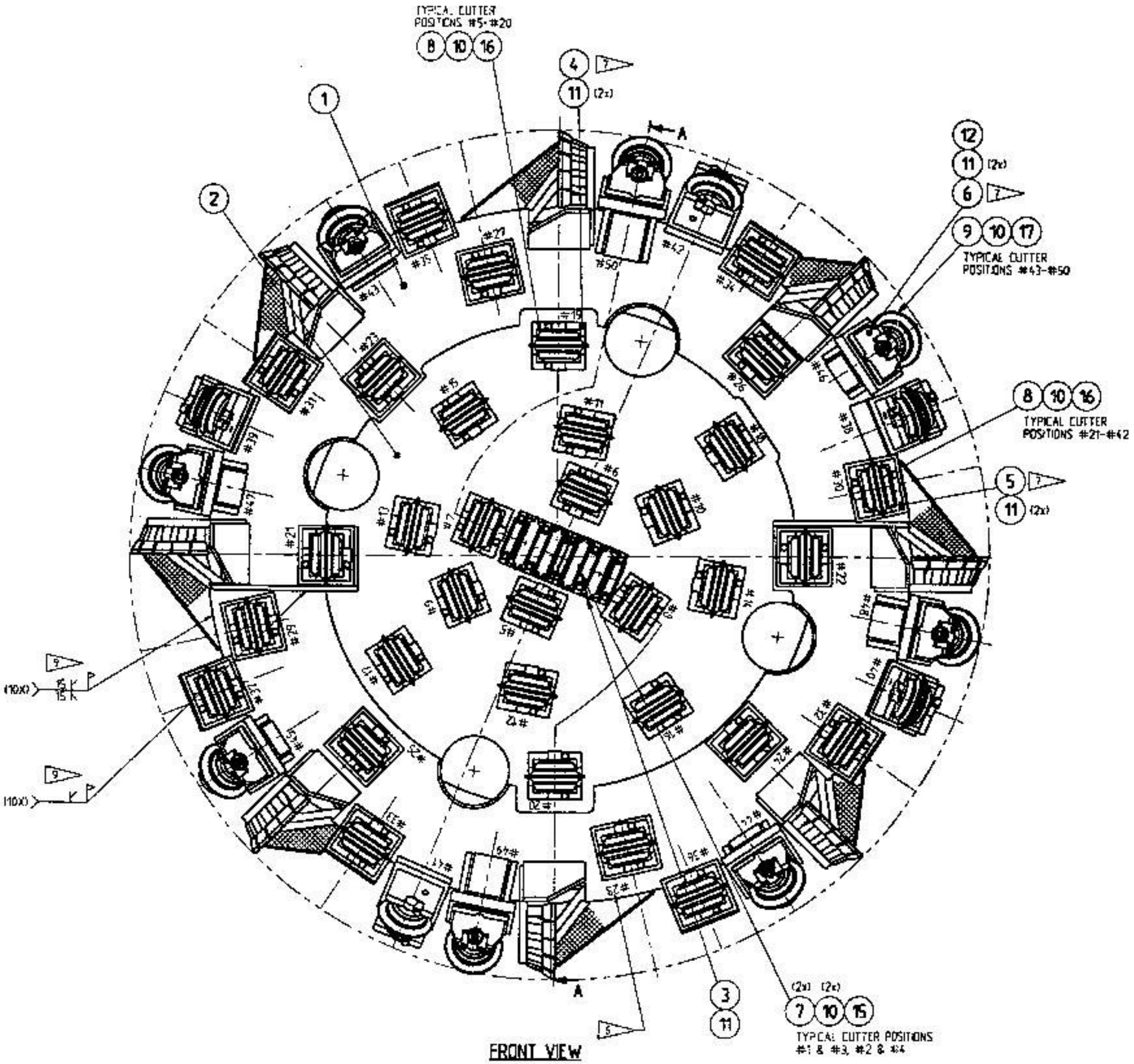


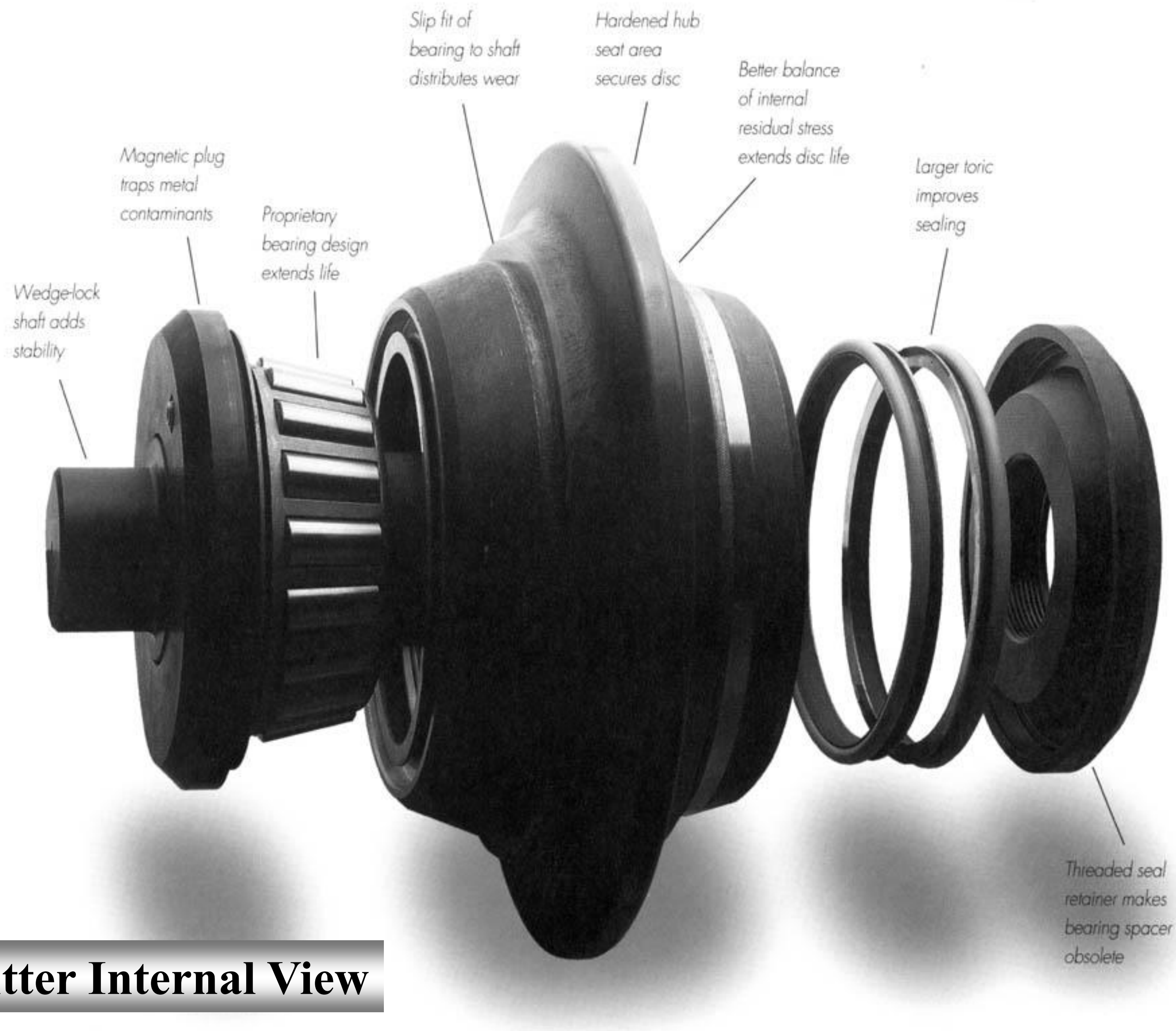


Robbins 235-282 HP TBM

TBM Chip Production

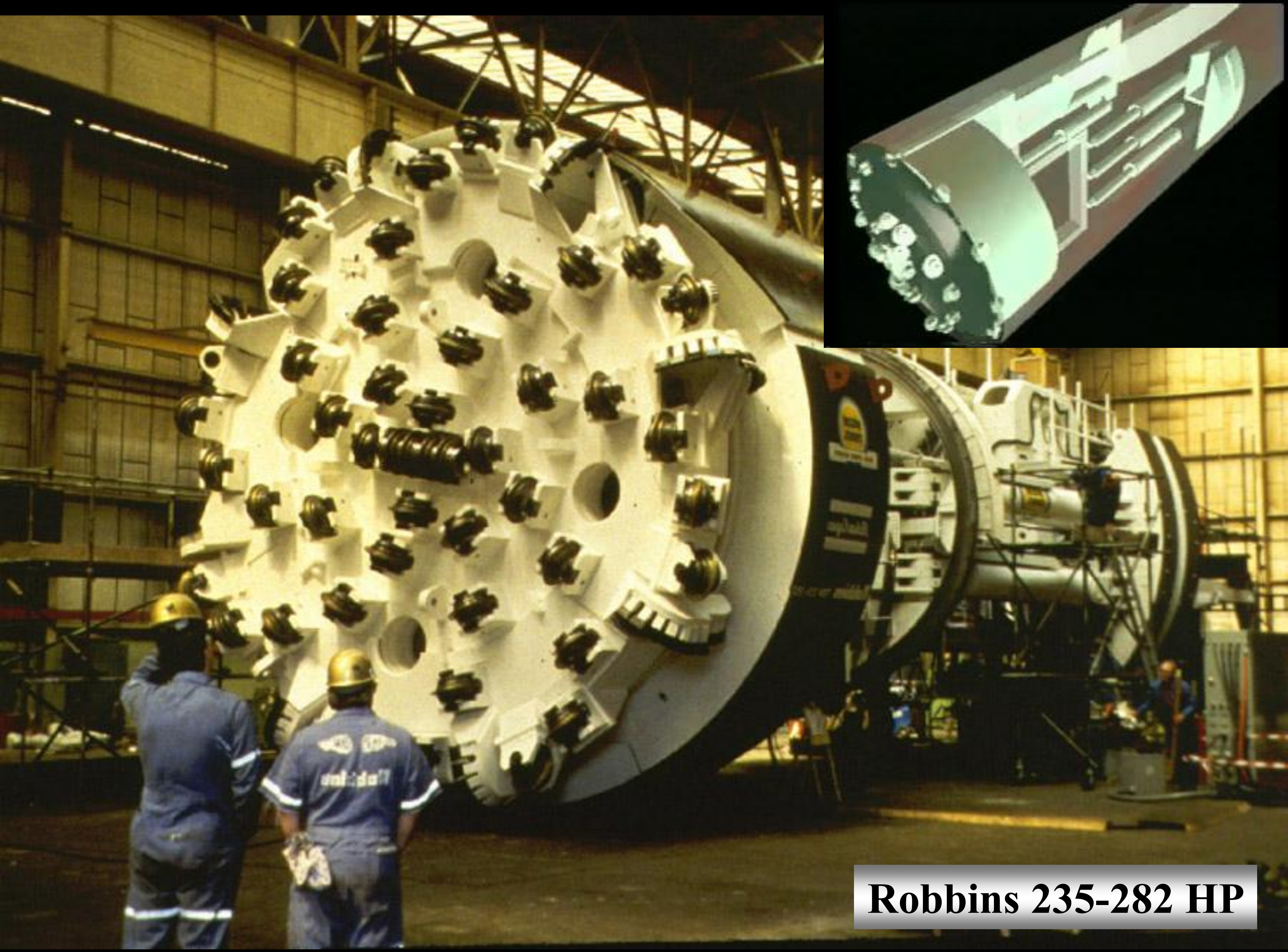




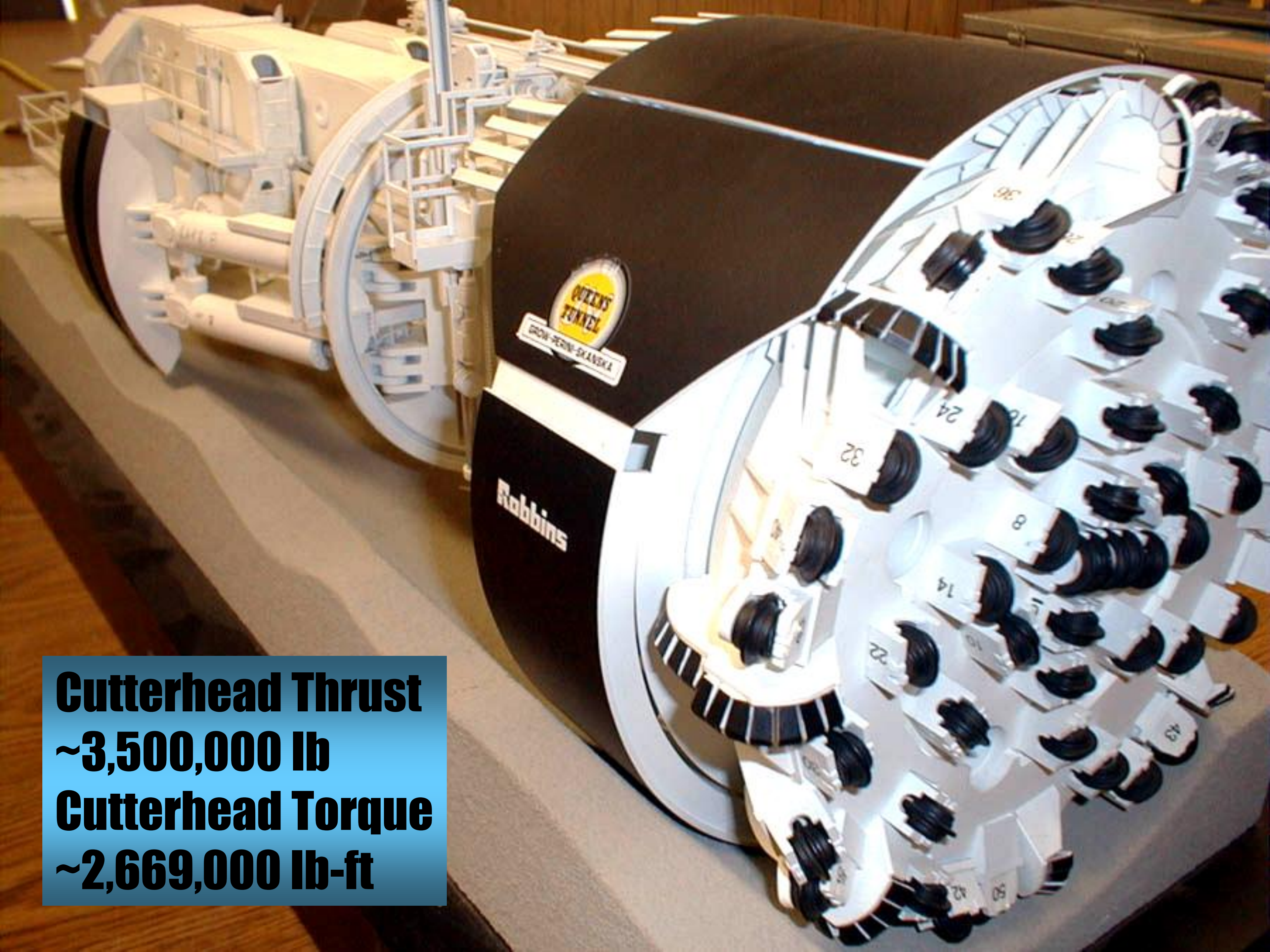


Cutter Internal View


Normal TBM Chips



Robbins 235-282 HP



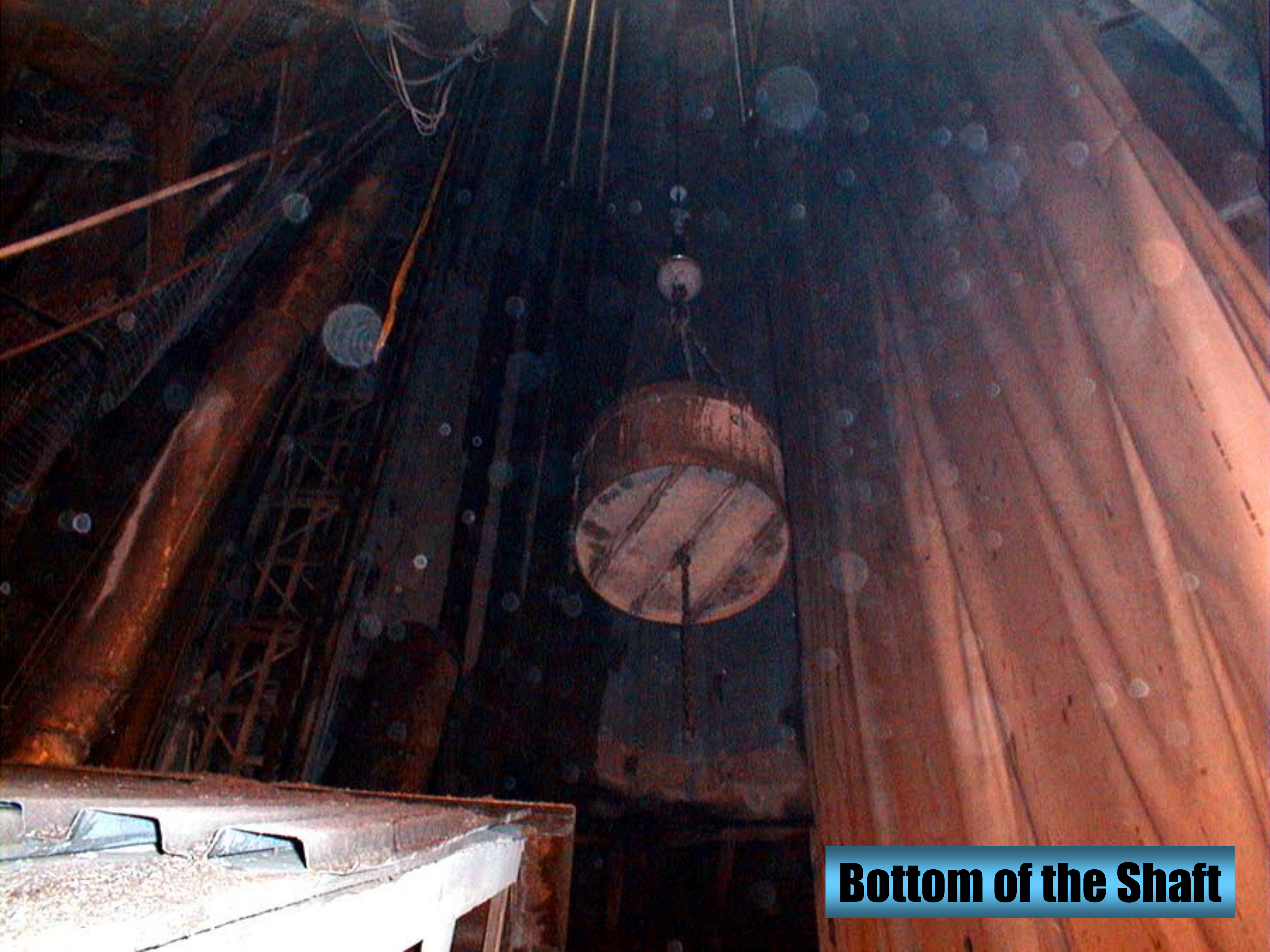
Cutterhead Thrust
~3,500,000 lb
Cutterhead Torque
~2,669,000 lb-ft

Kerf Pattern in Hard Rock

Stage 2, City Tunnel 3

Shaft 19B – Built by Grow Tunneling in 1993

Man Cage



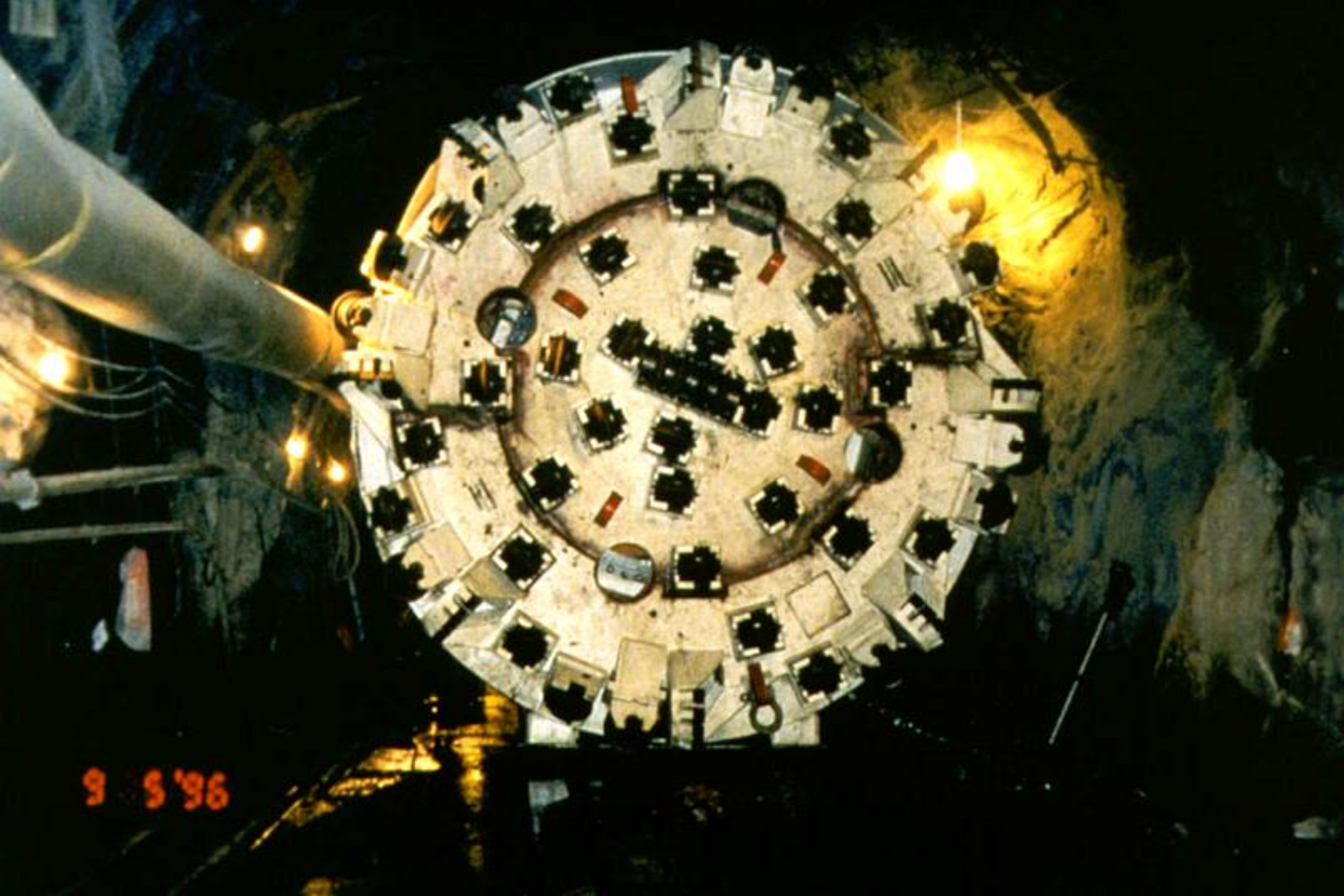
Bottom of the Shaft

Drilling Bellout for Blasting

Lowering TBM Mainbeam

Flipping TBM Cutterhead

TBM Ready for Insertion



View into Starter Tunnel

Poured Starter Tunnel

Robbins 235-282 HP TBM
A Wild Ride


Upper TBM Platform

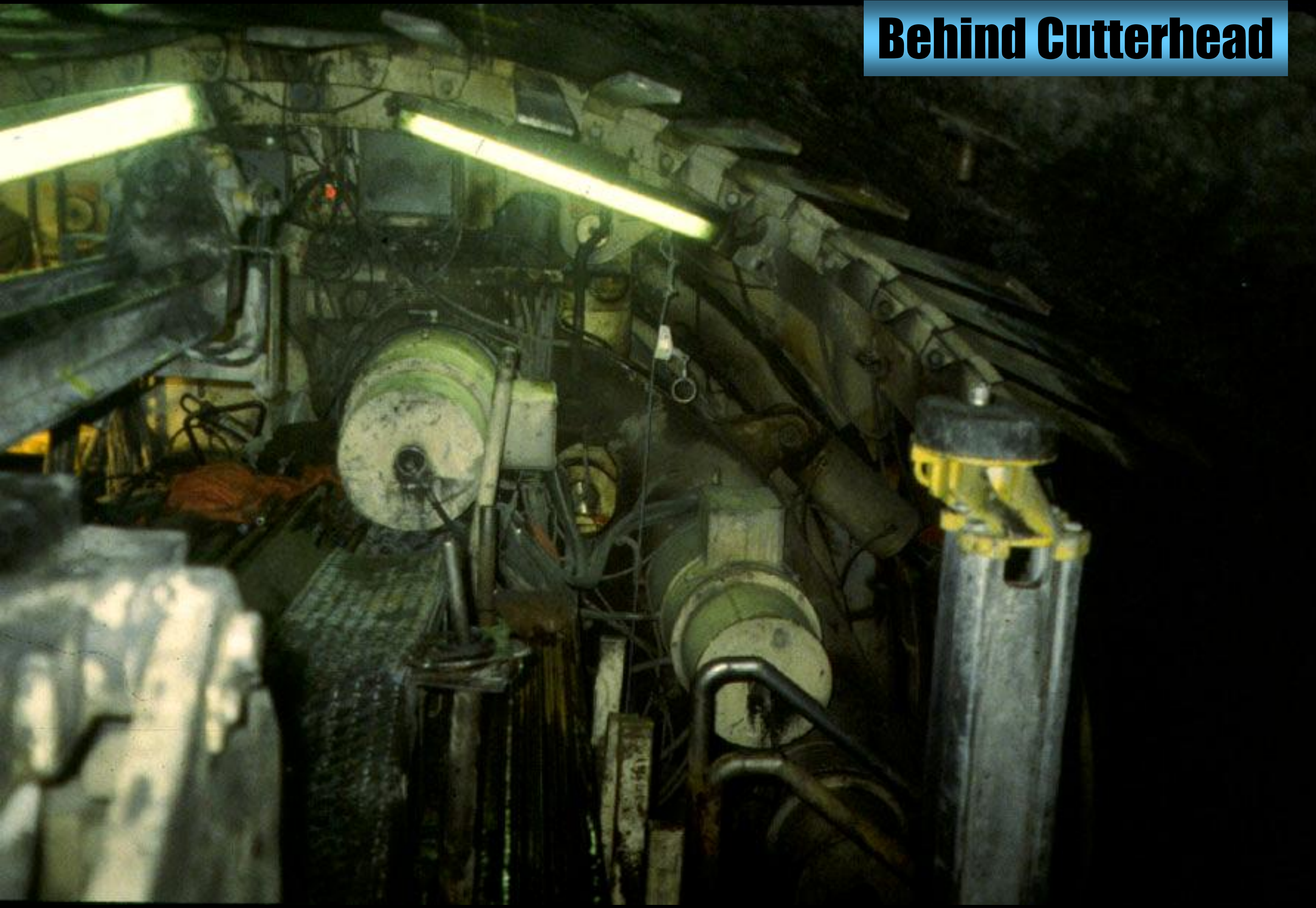

Scrubbers


Right Gripper

TBM Cabin

Steering Reticle and Tiltmeter

Behind Cutterhead



Back of Cutter Head

Stairway to Lower TBM Platform

Staircase to Heaven?

Lower TBM Platform

Lower TBM Platform

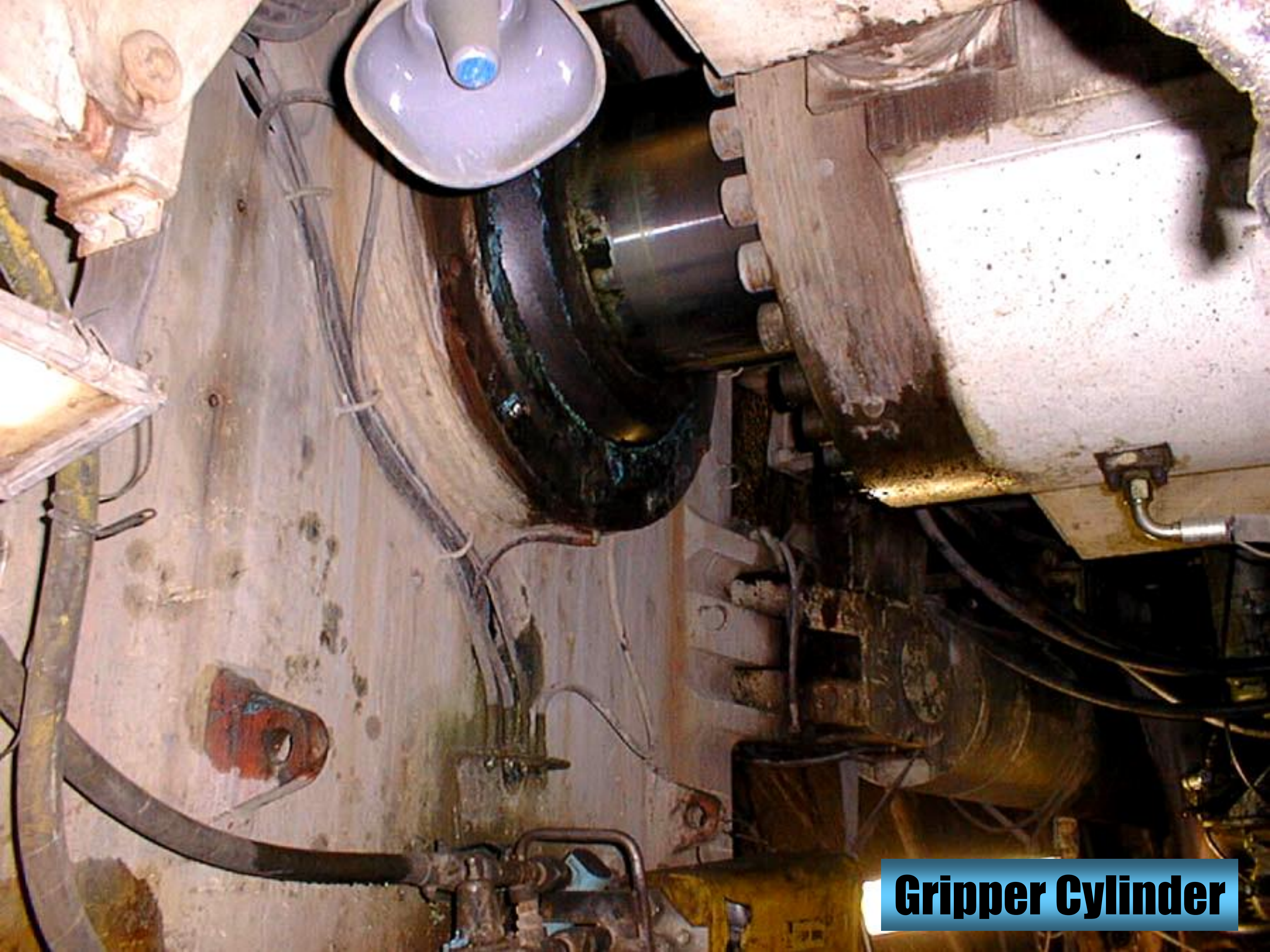
Lower TBM Platform

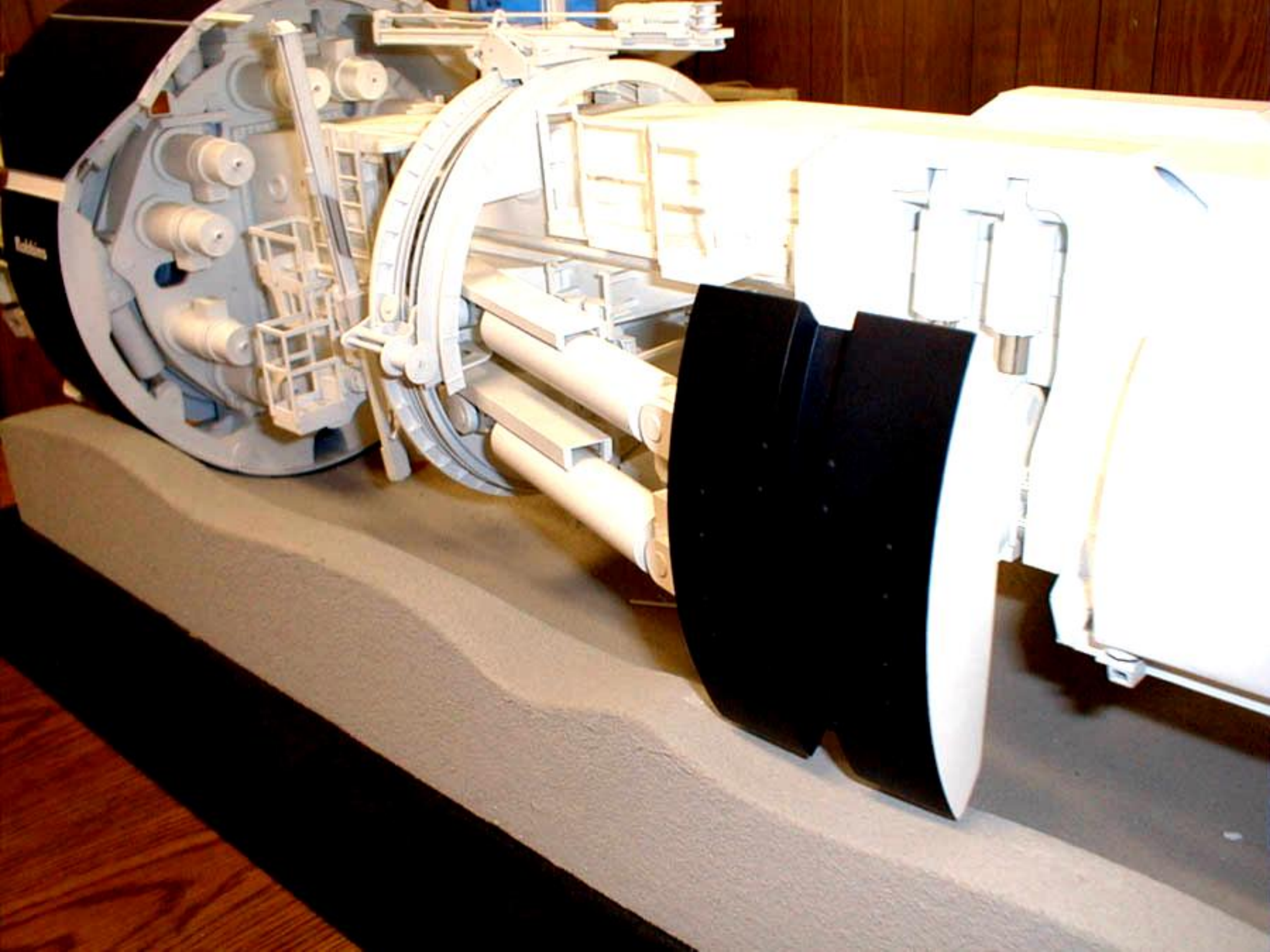

In the Belly of the Beast


12:31PM
5/15/1998
00:24:59:29
In the Belly of the Beast

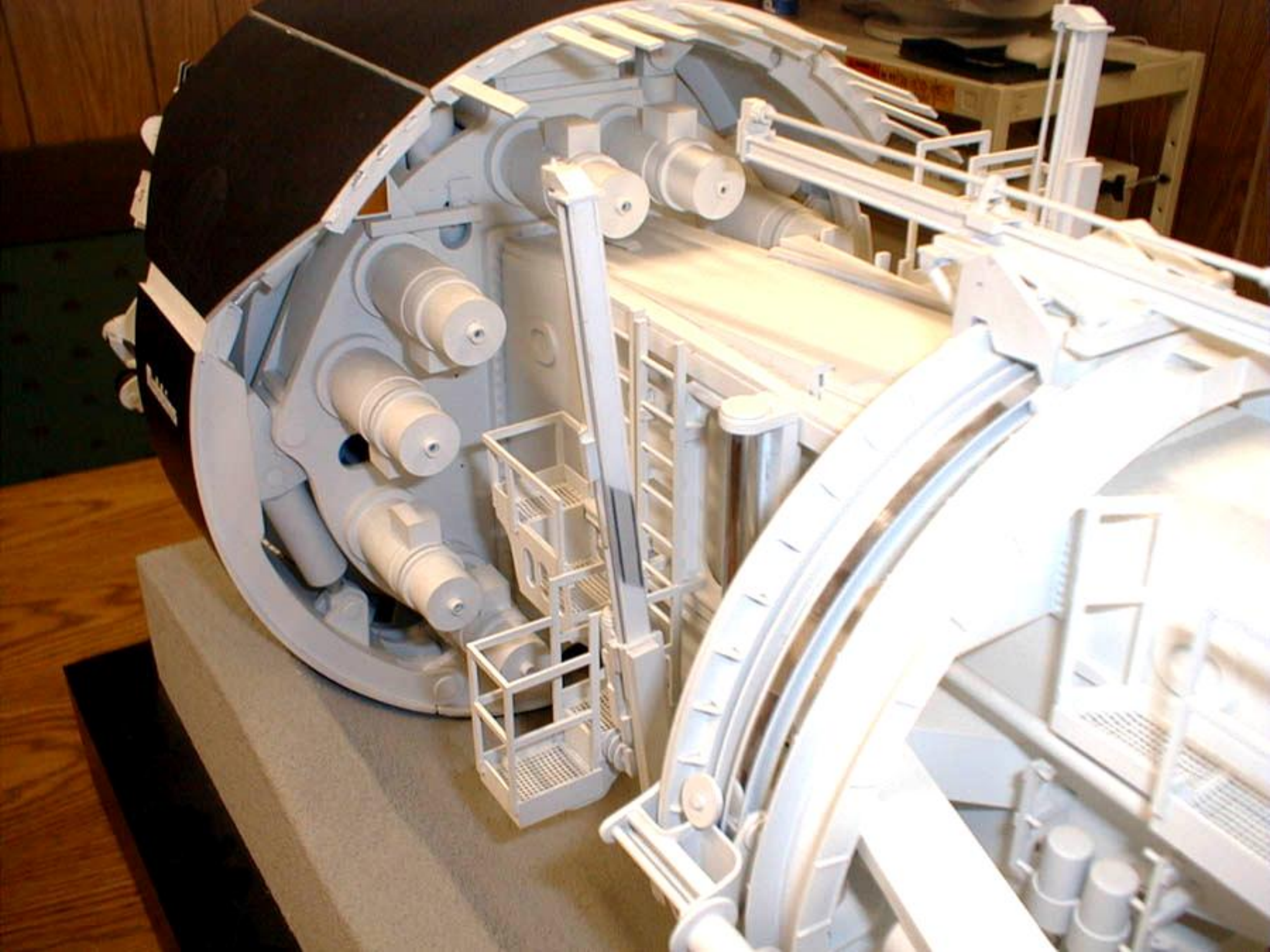

In the Belly of the Beast

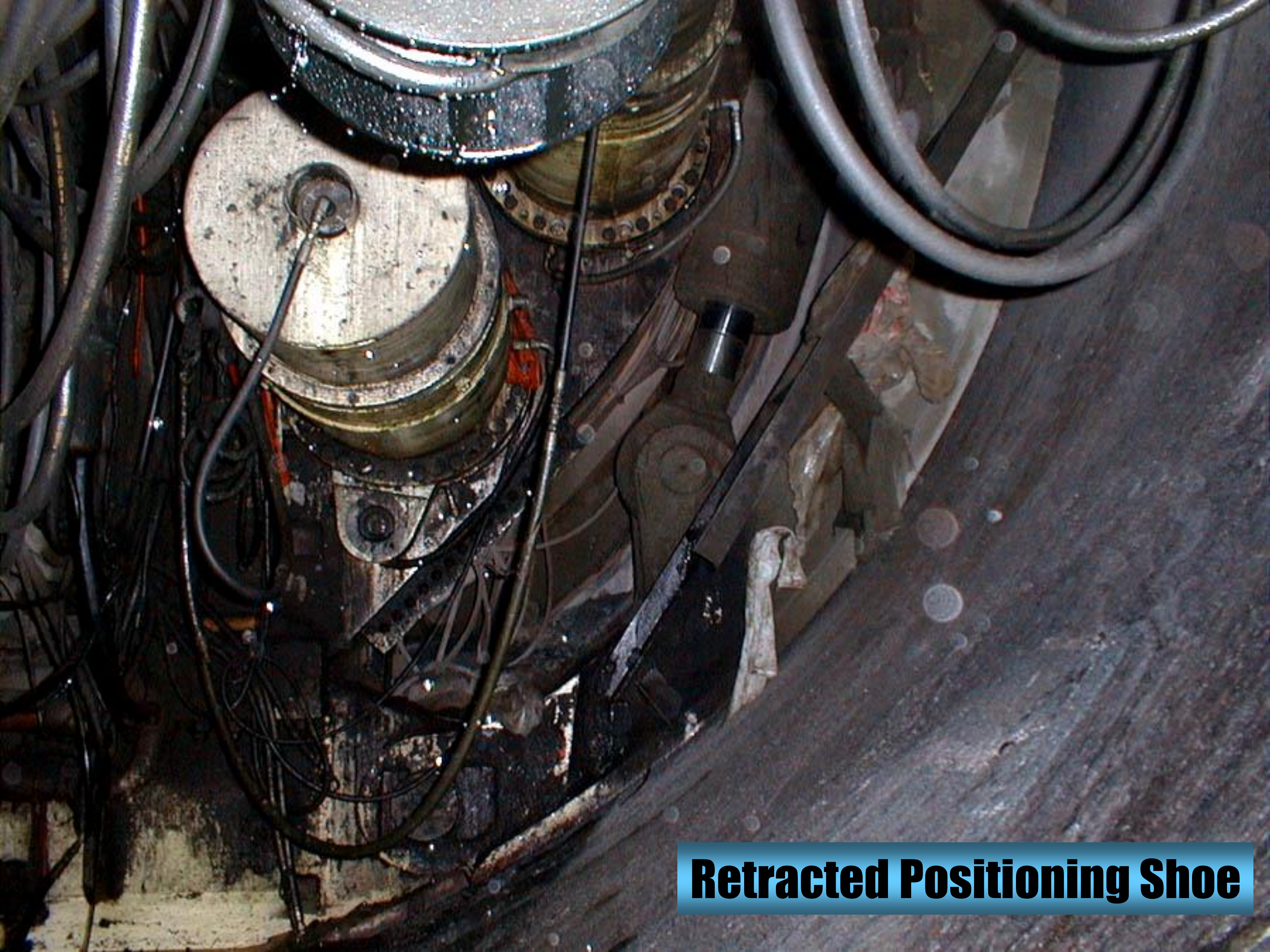

Grippers


Gripper Cylinder



Left Front Positioning Shoe





Retracted Positioning Shoe

TBM Motors
422 HP
Water Cooled,
Three Phase
Electric Motors

10 Motors Total
Usually 8 Online
Rotates Cutterhead
At 8.3 Rev/Min

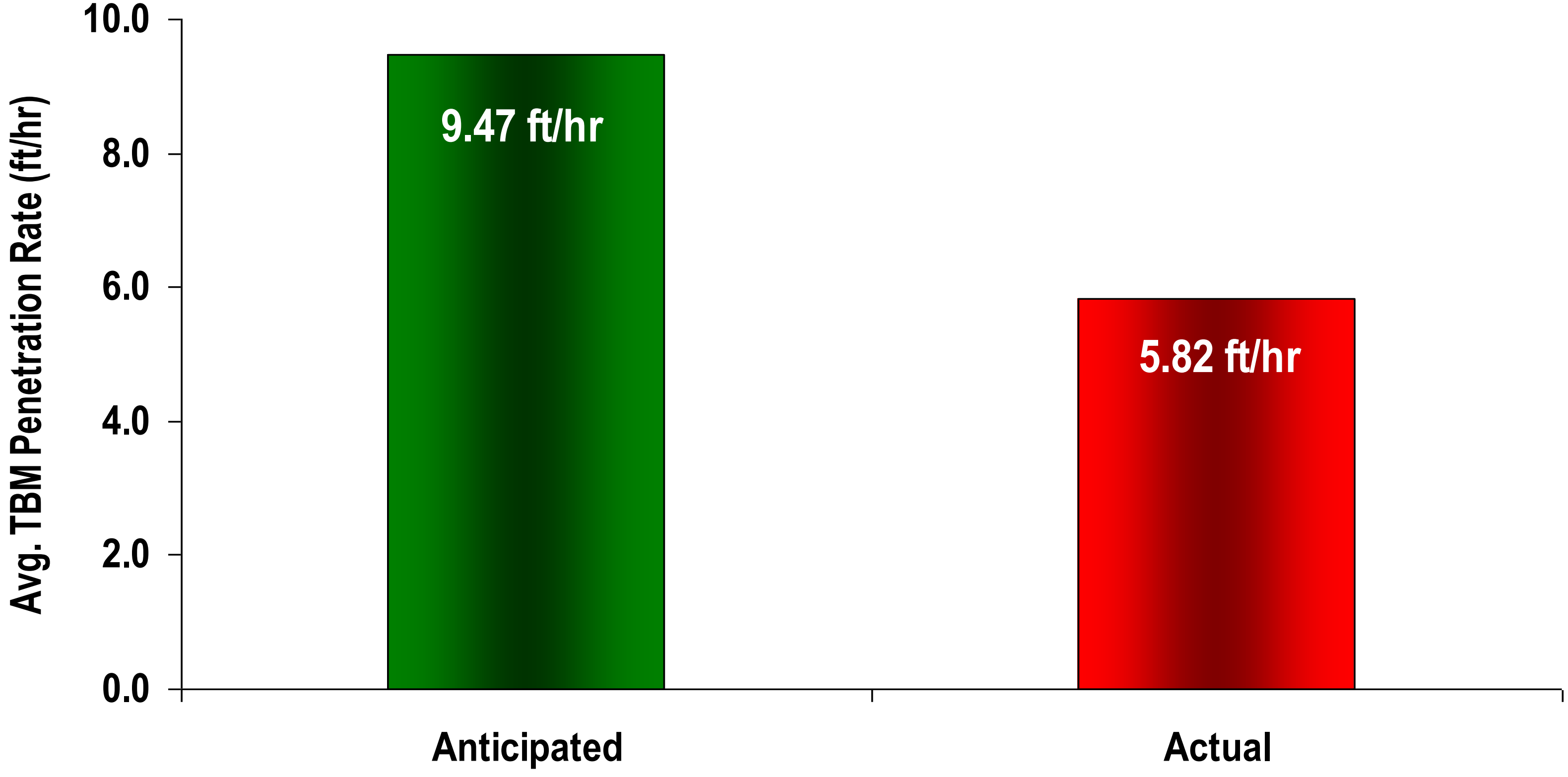
Damaged Motor

TBM Entry Port

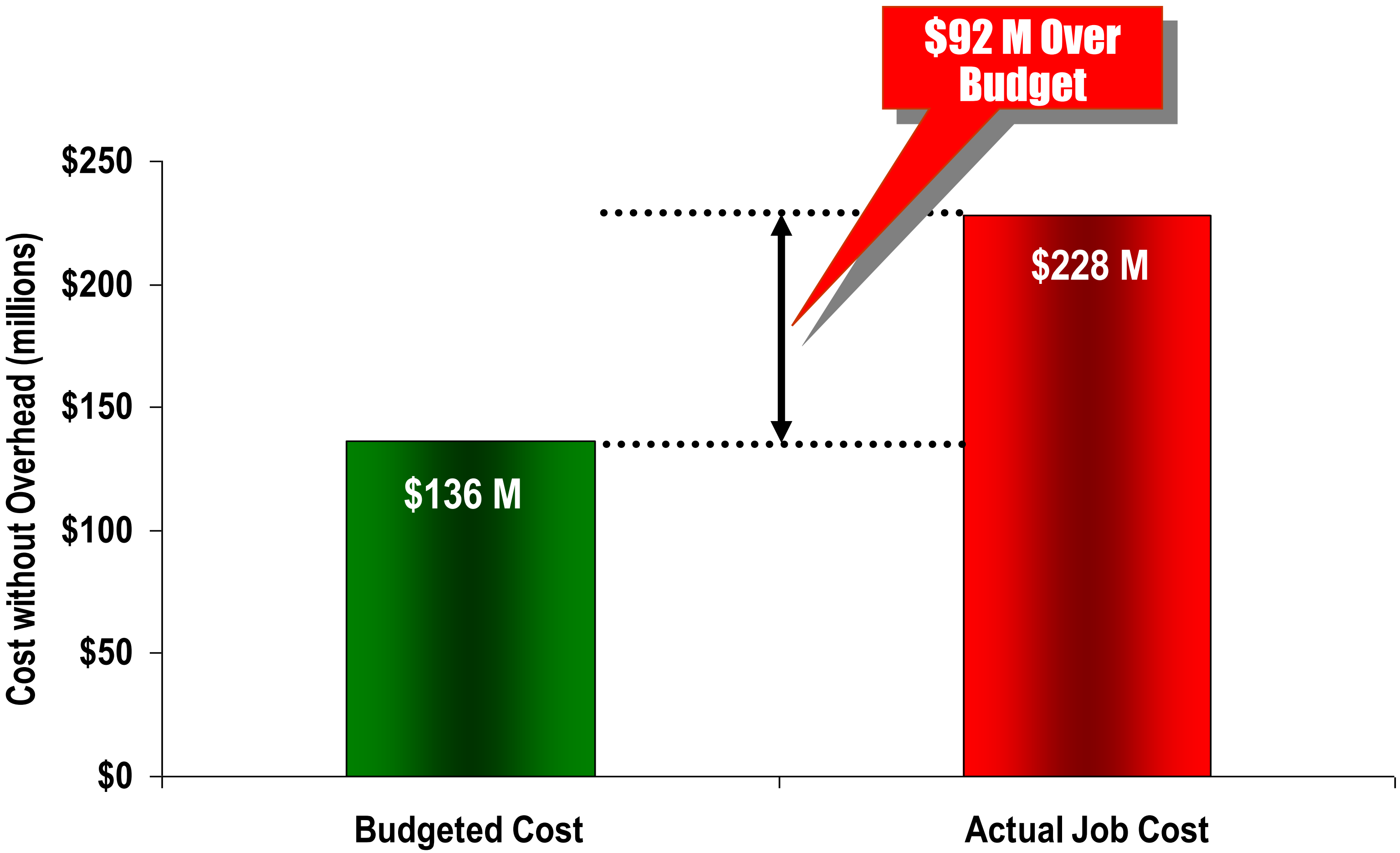
Chemical Grout in Heading

TBM Cutter Inspection

Anticipated vs. Actual Penetration Rate



Anticipated vs. Actual Cost



Excessive Fines

Blocky Ground

Modifications to Buckets Damaged by Blocky Ground


DNAG
CM
IN
mm
Damaged Cutters

Before

After


Collapsing Face
Station 130+33


Support at Collapsed Right Rib
Station 153+30

Faults - Disturbed Ground Zone 59


Rainy Conditions
Station 140+60

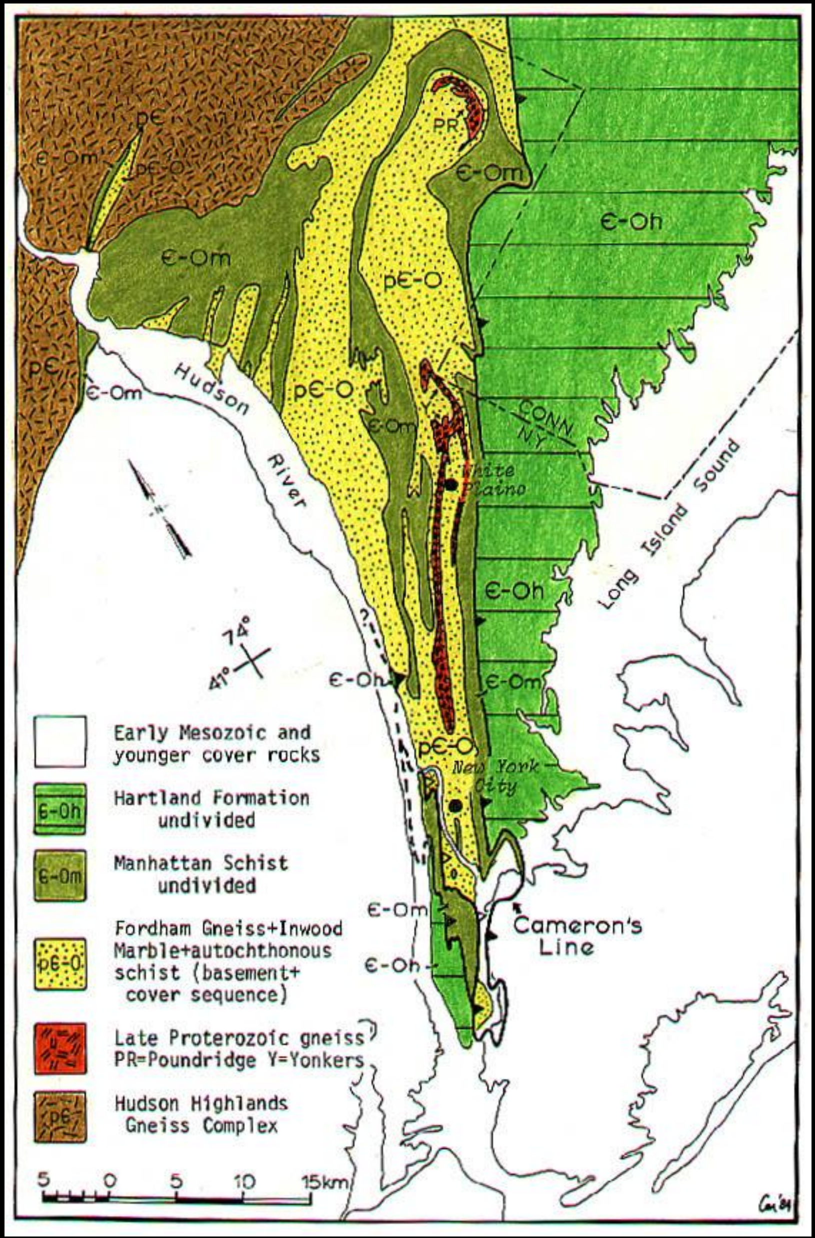

Flooding Incident

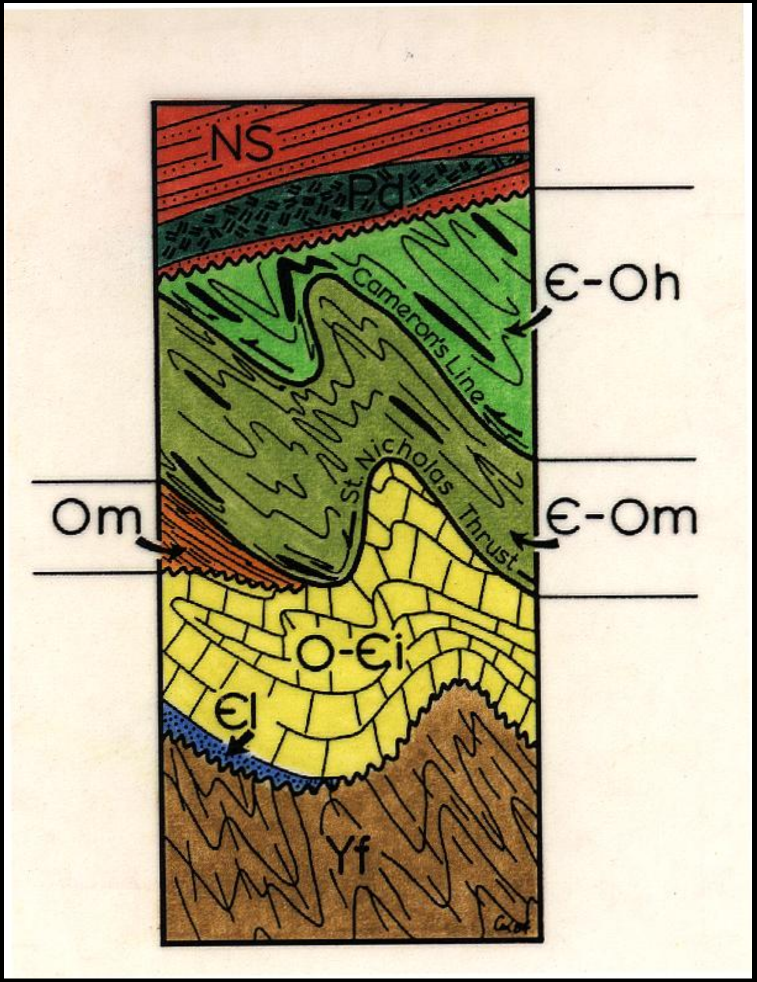
Flooding Incident

Flooding Incident

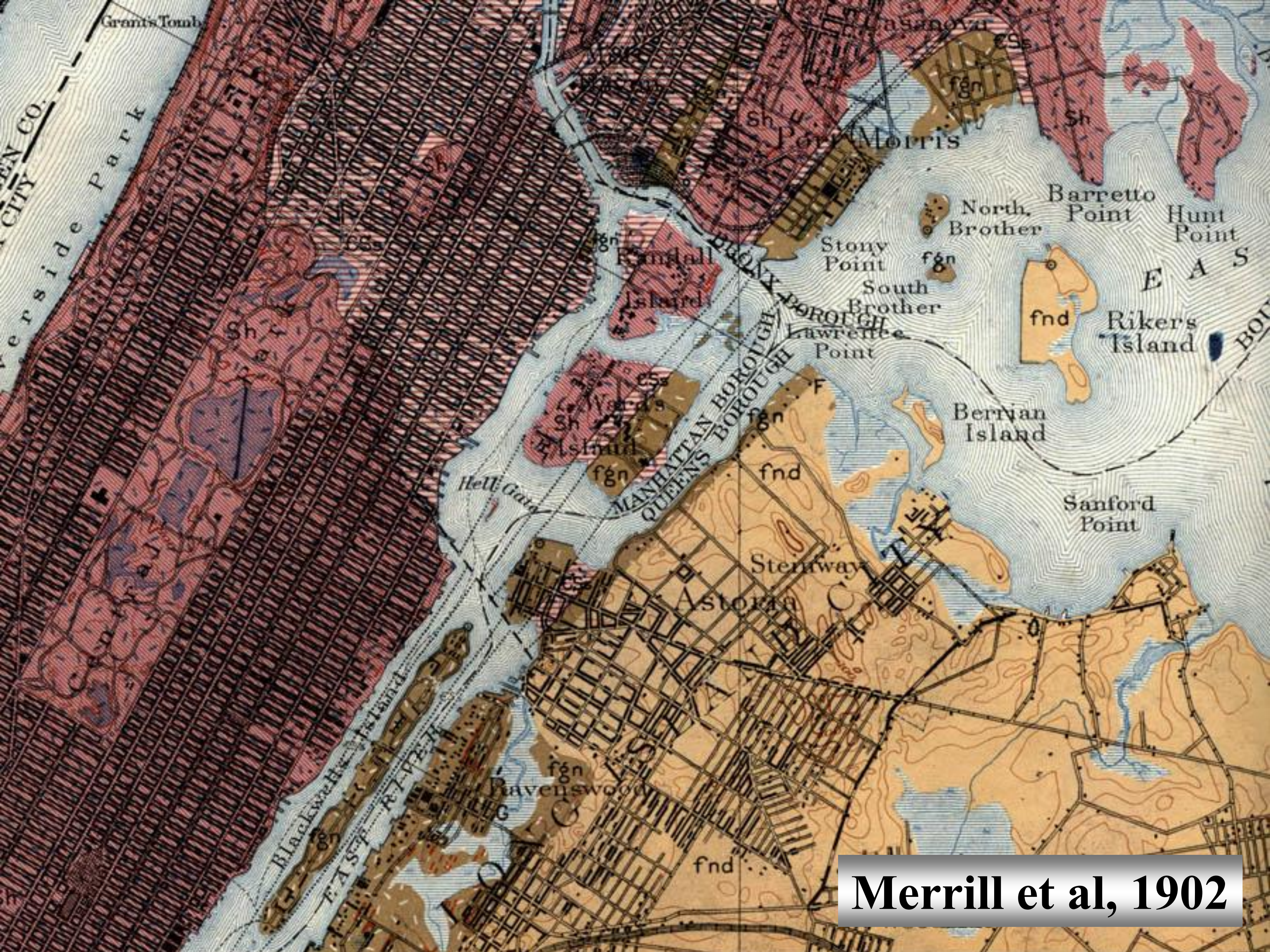
Unisex Bathroom Facility

Geology of the New York City Area



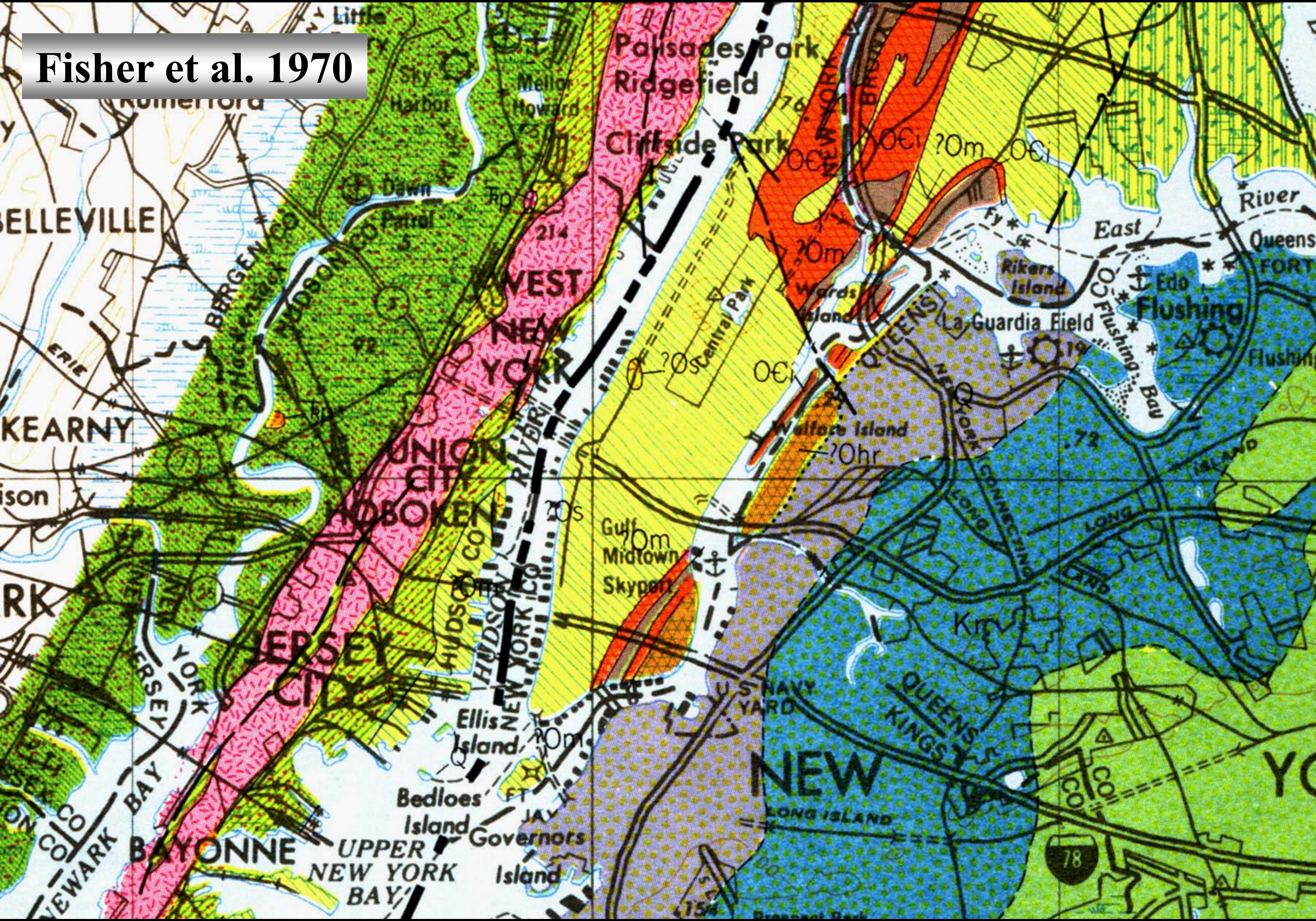


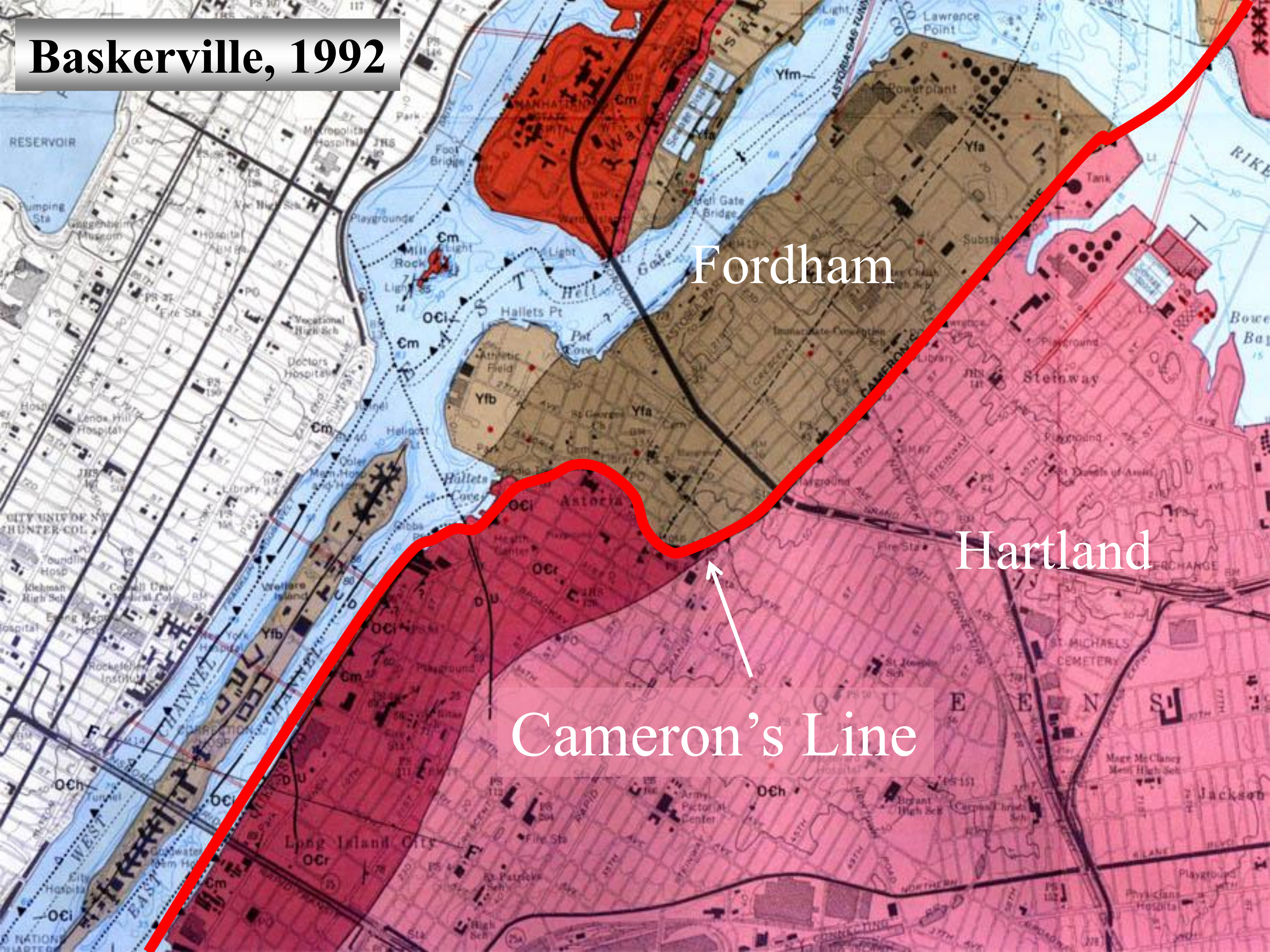
(Adapted from Mose and Merguerian, 1985, Figure 1, P. 21.)

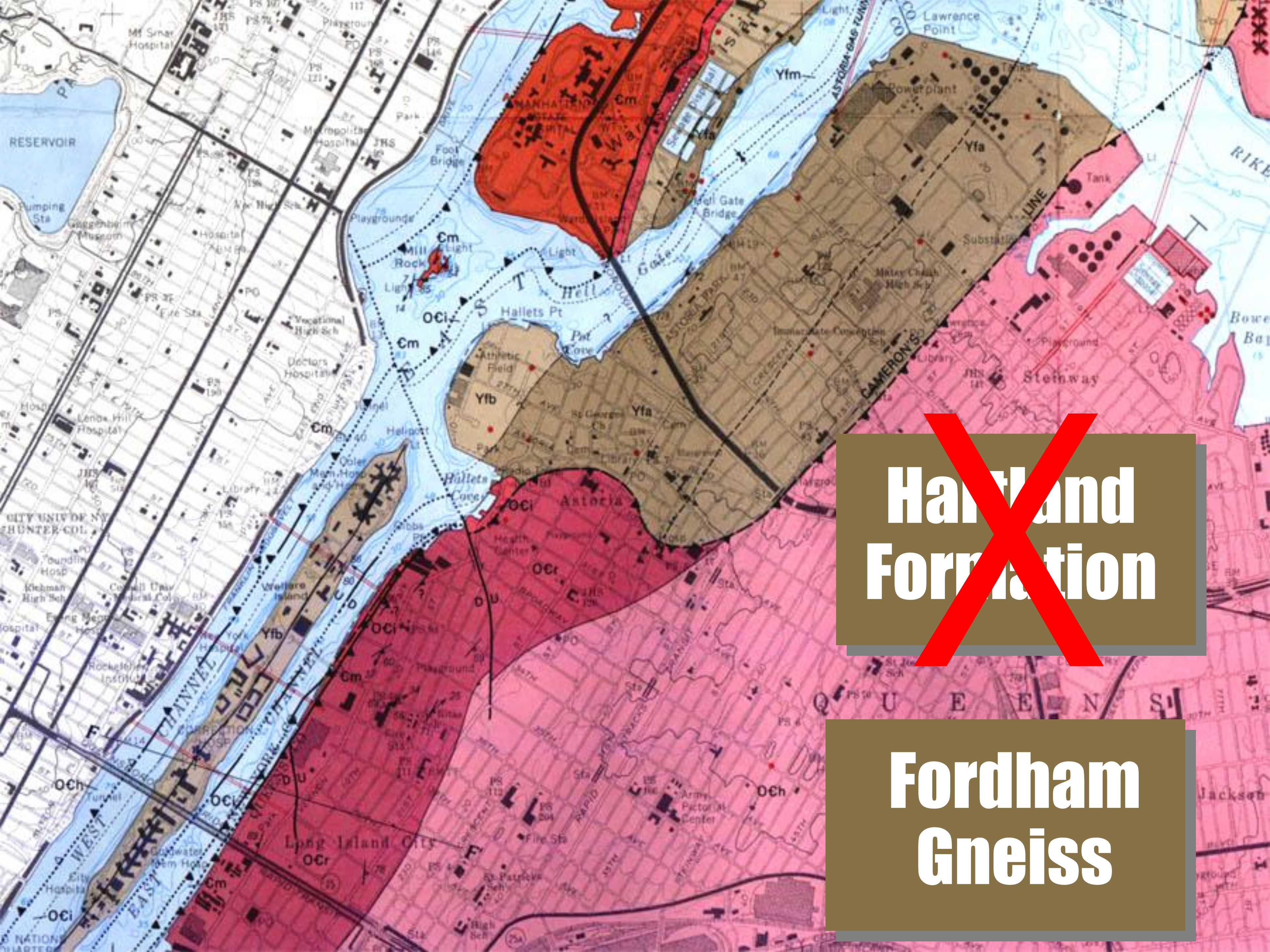


Merrill et al, 1902

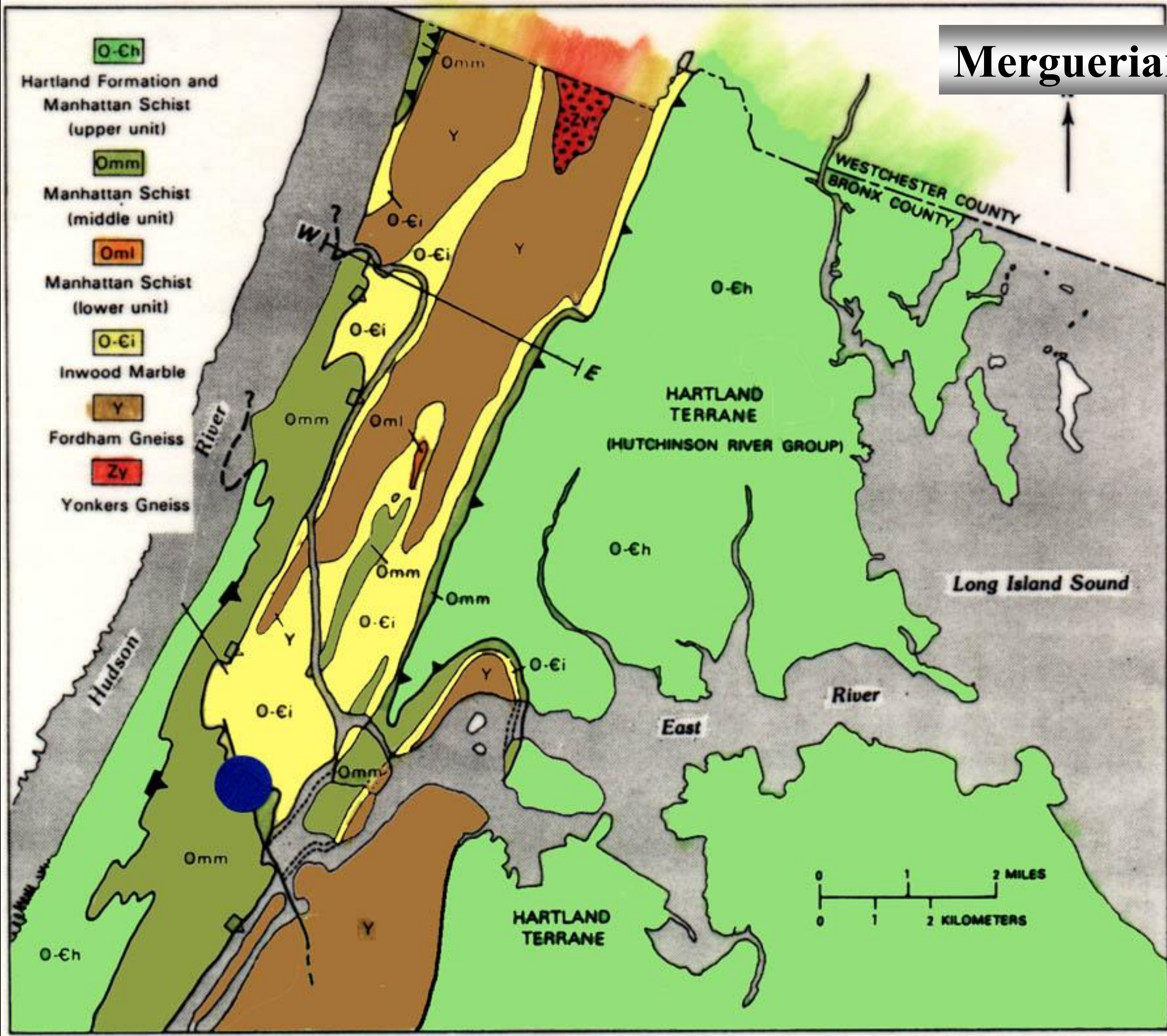
Fisher et al. 1970




Baskerville, 1992
Fordham
Hartland
Cameron's Line


Hartland Formation
Fordham Gneiss
RESERVOIR
Hallets Pt
Astoria
Long Island City
Steinway
Q U E E N S
Yfa
Yfb
Yfm
Cm
OCi
OCr
OCh

Merguerian, 2002



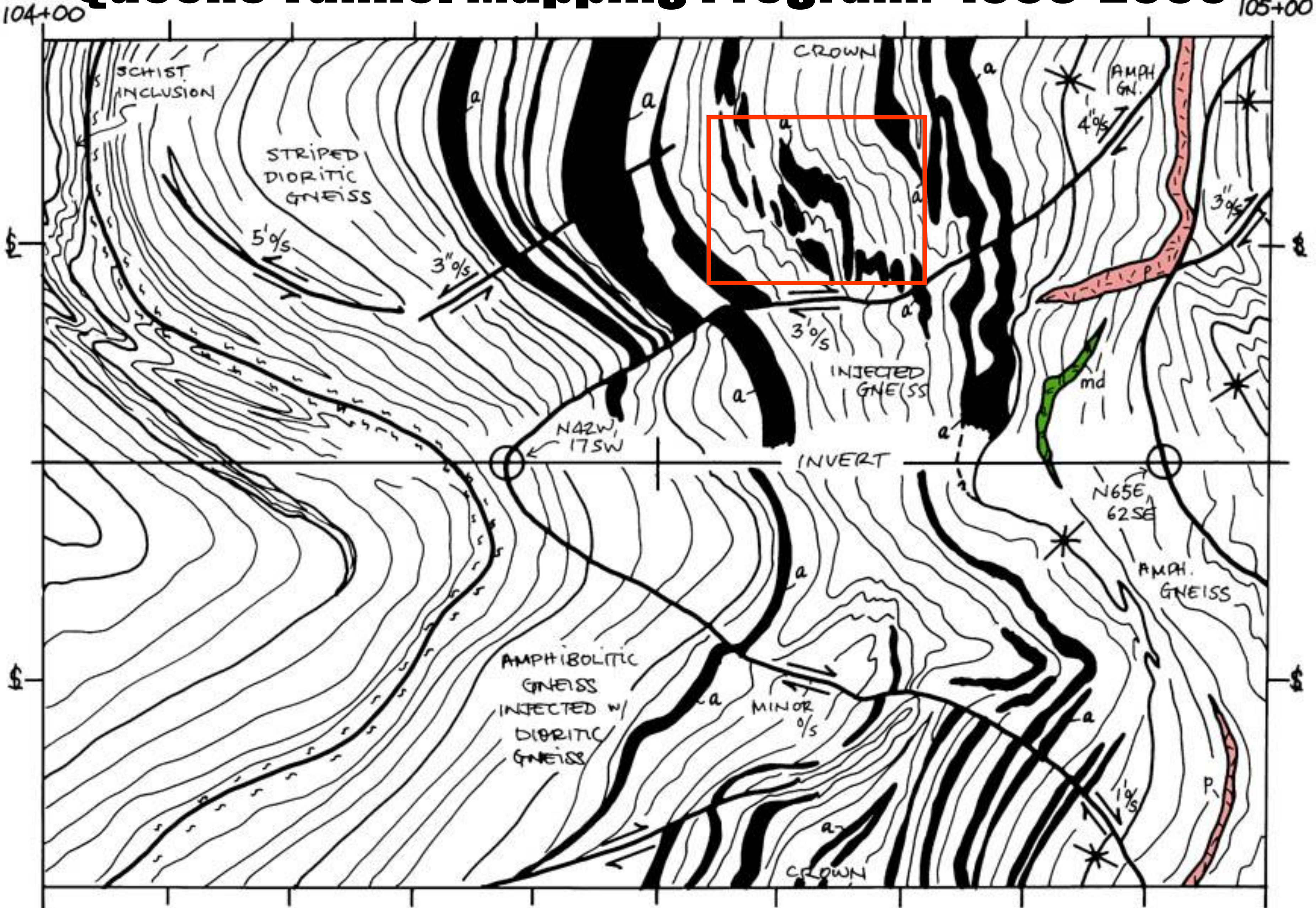
Queens Tunnel Complex

d-Schmartland
Garnet?
Pegmatite?
God, I hope they don't figure me out!
How the hell should I know?
Schist?
Hartland?
Gneiss?
Hartland ?
Fordham?

Let The Mapping Begin

Dukelabs Field Office

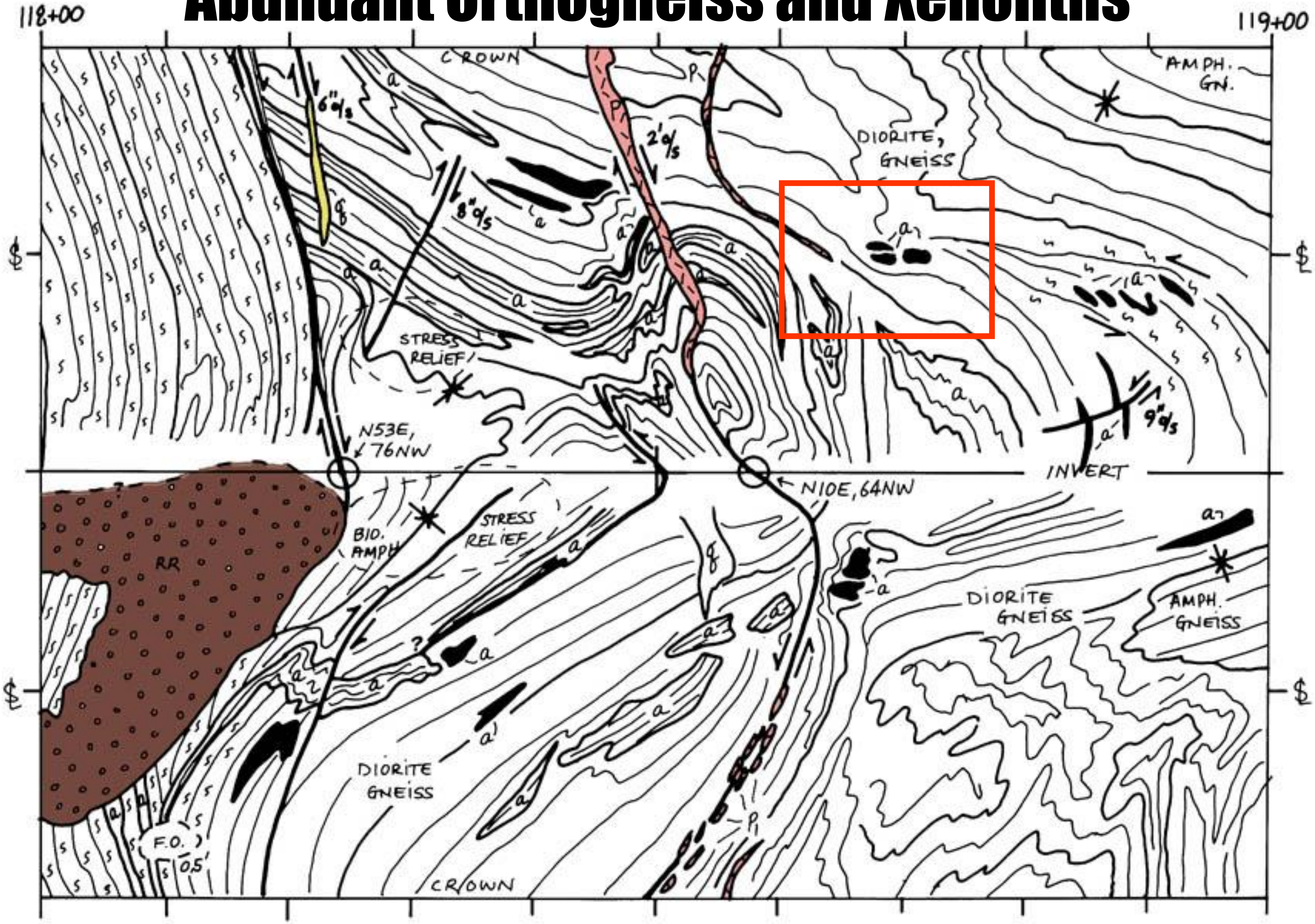
Queens Tunnel Mapping Program: 1998-2000



- Scale 1 in. = 10 ft


104+60
104+65

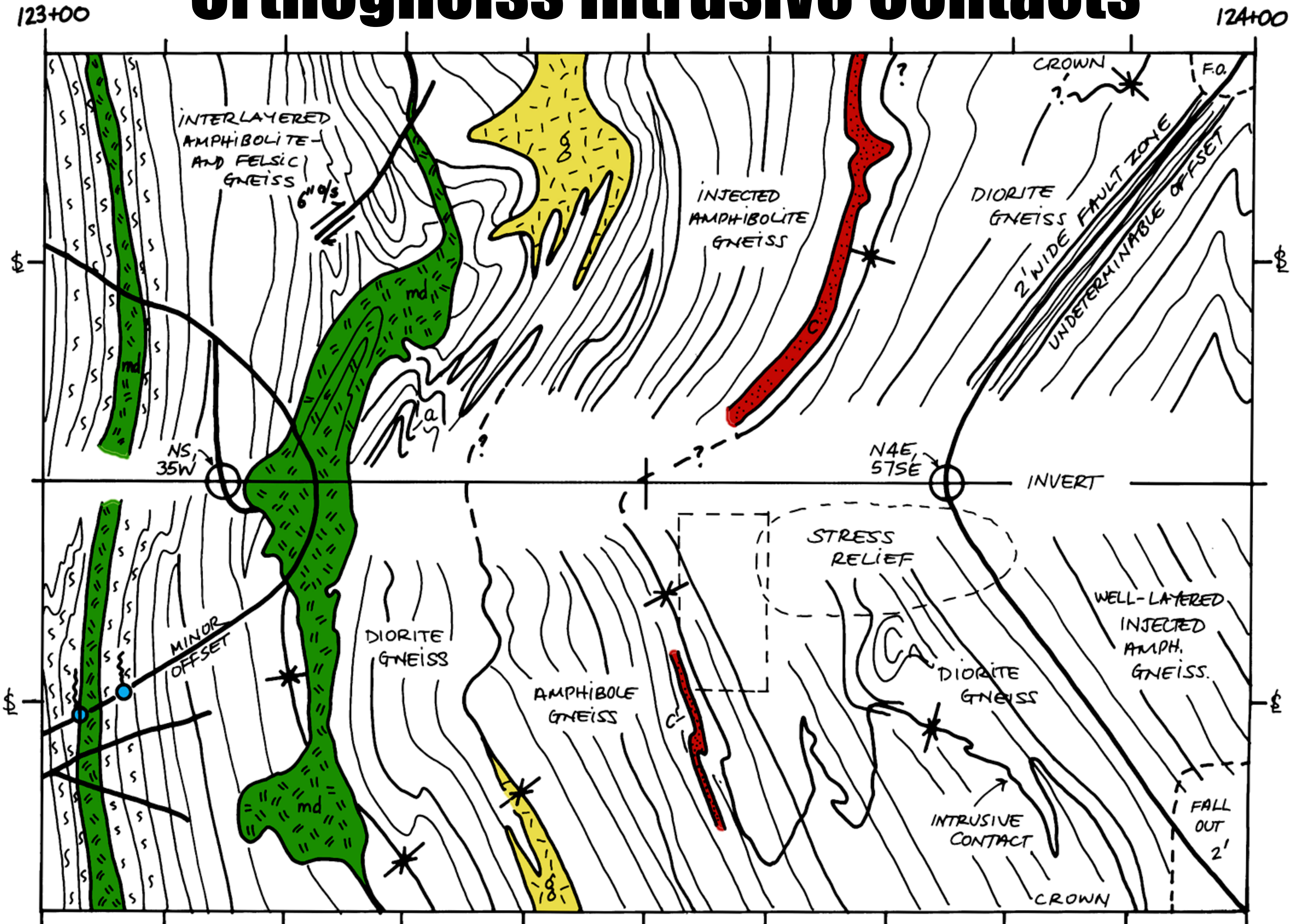
Abundant Orthogneiss and Xenoliths



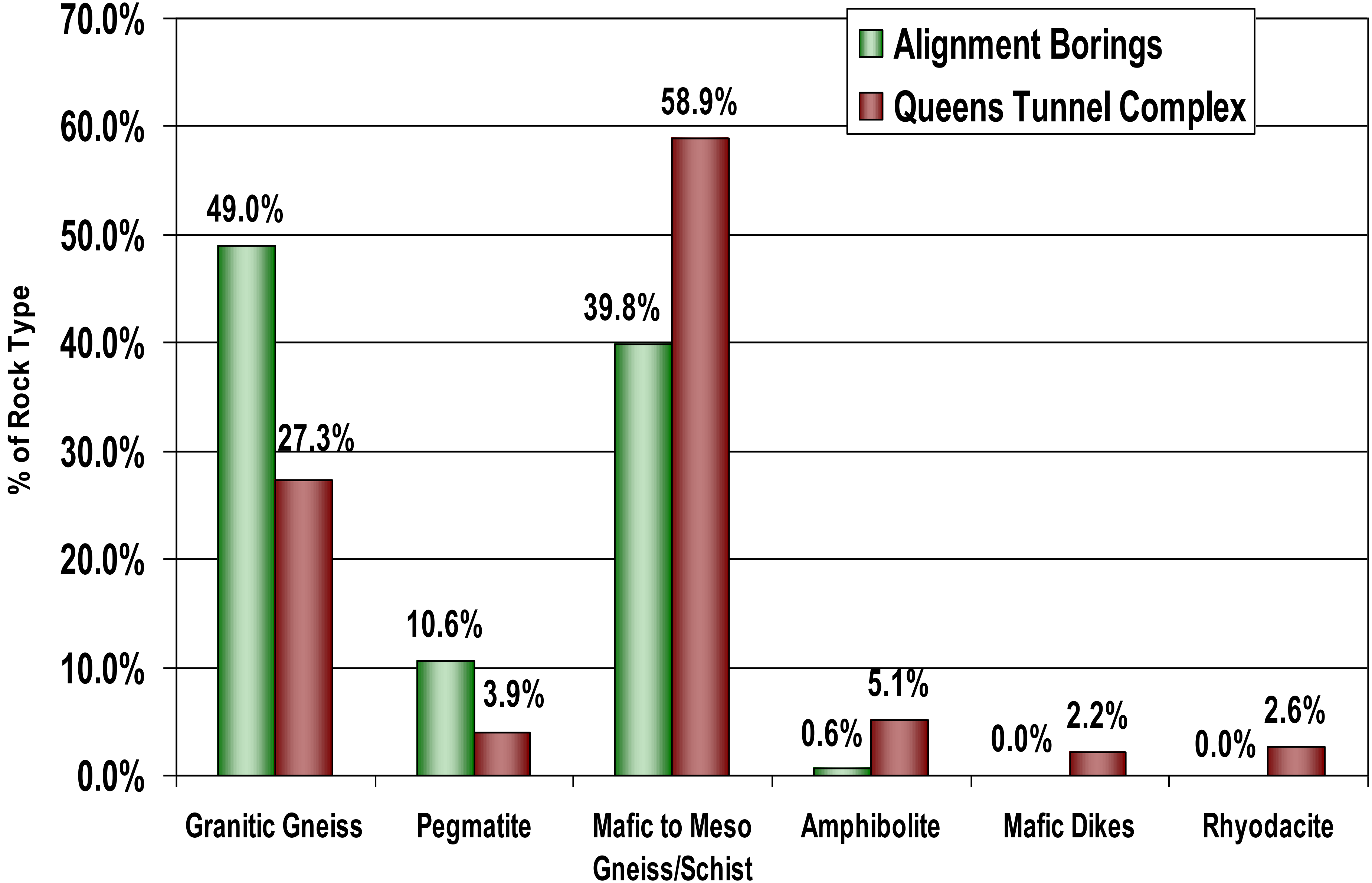
- **Scale of Mapping: 1 in. = 10 ft**

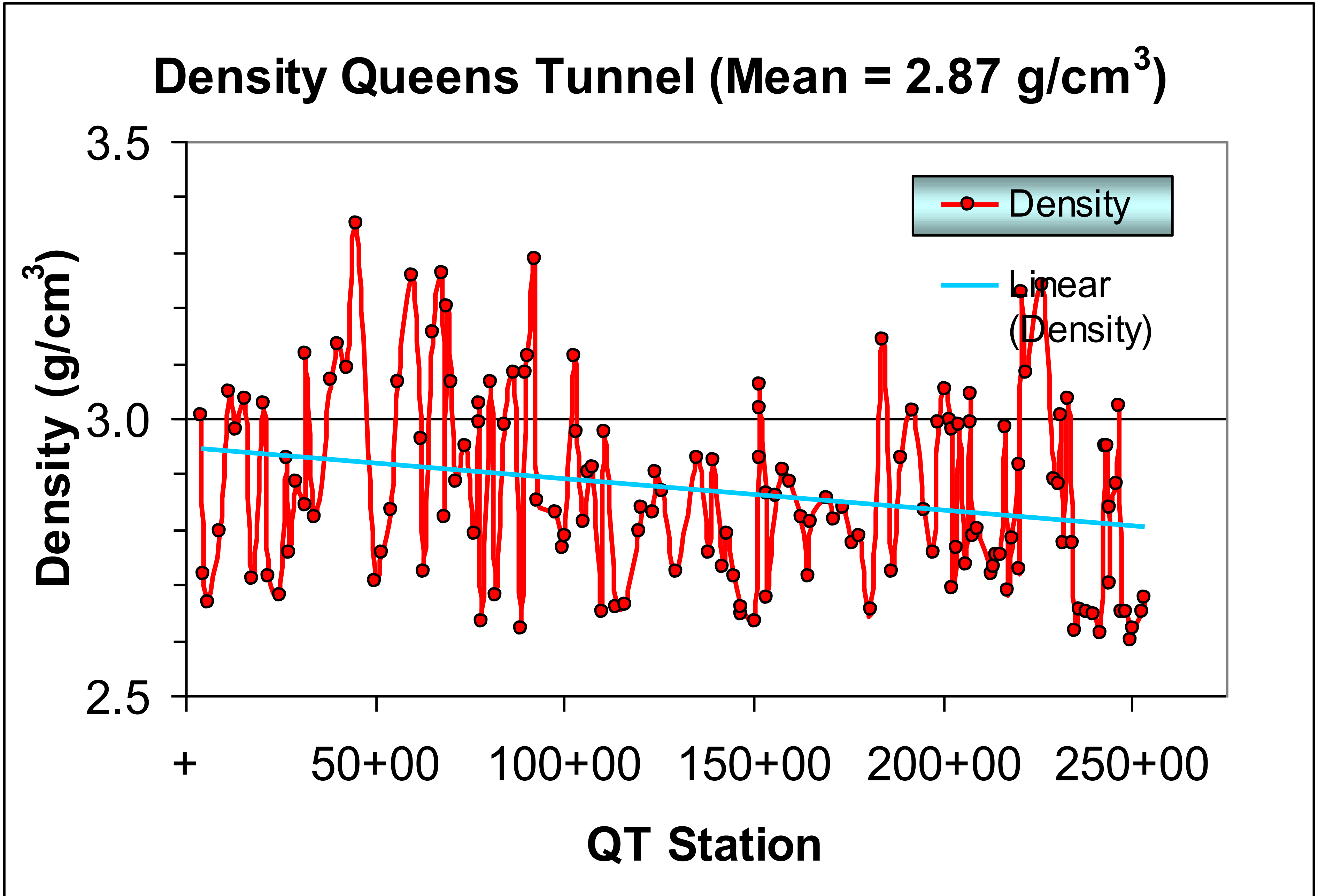

ADJ
118+70
118+
118

Orthogneiss Intrusive Contacts



Comparative Lithologic Analysis





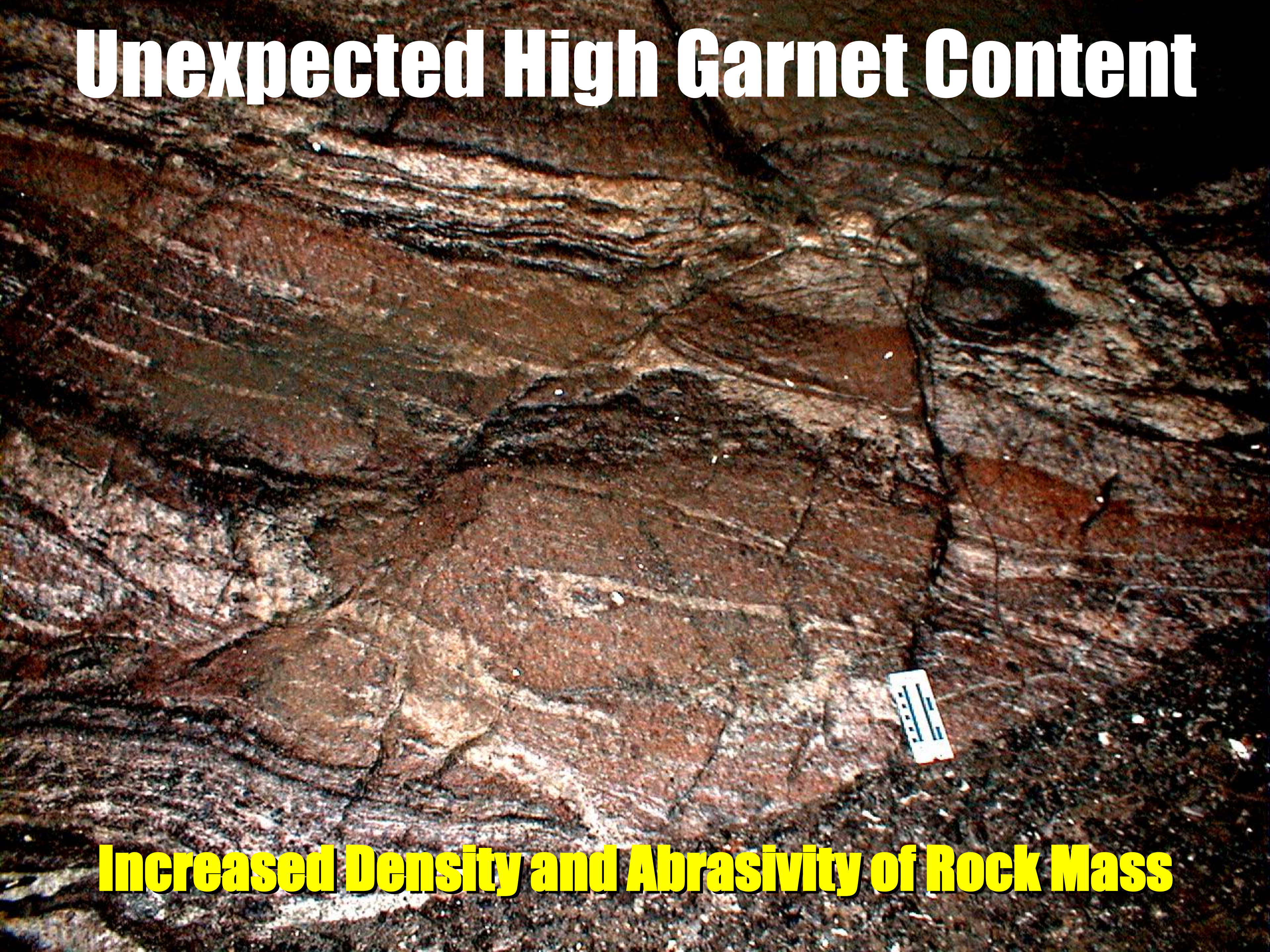
Density Queens Tunnel (Mean = 2.87 g/cm3)
3.5
3.0
2.5
Density (g/cm3)
Density
Linear (Density)
+
50+00
100+00
150+00
200+00
250+00
QT Station

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

Folded Garnet-Plagioclase Segregations in Mafic Gneiss

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 cutter abrasivity and production of excessive fines.

Granulite "Green" Coloration

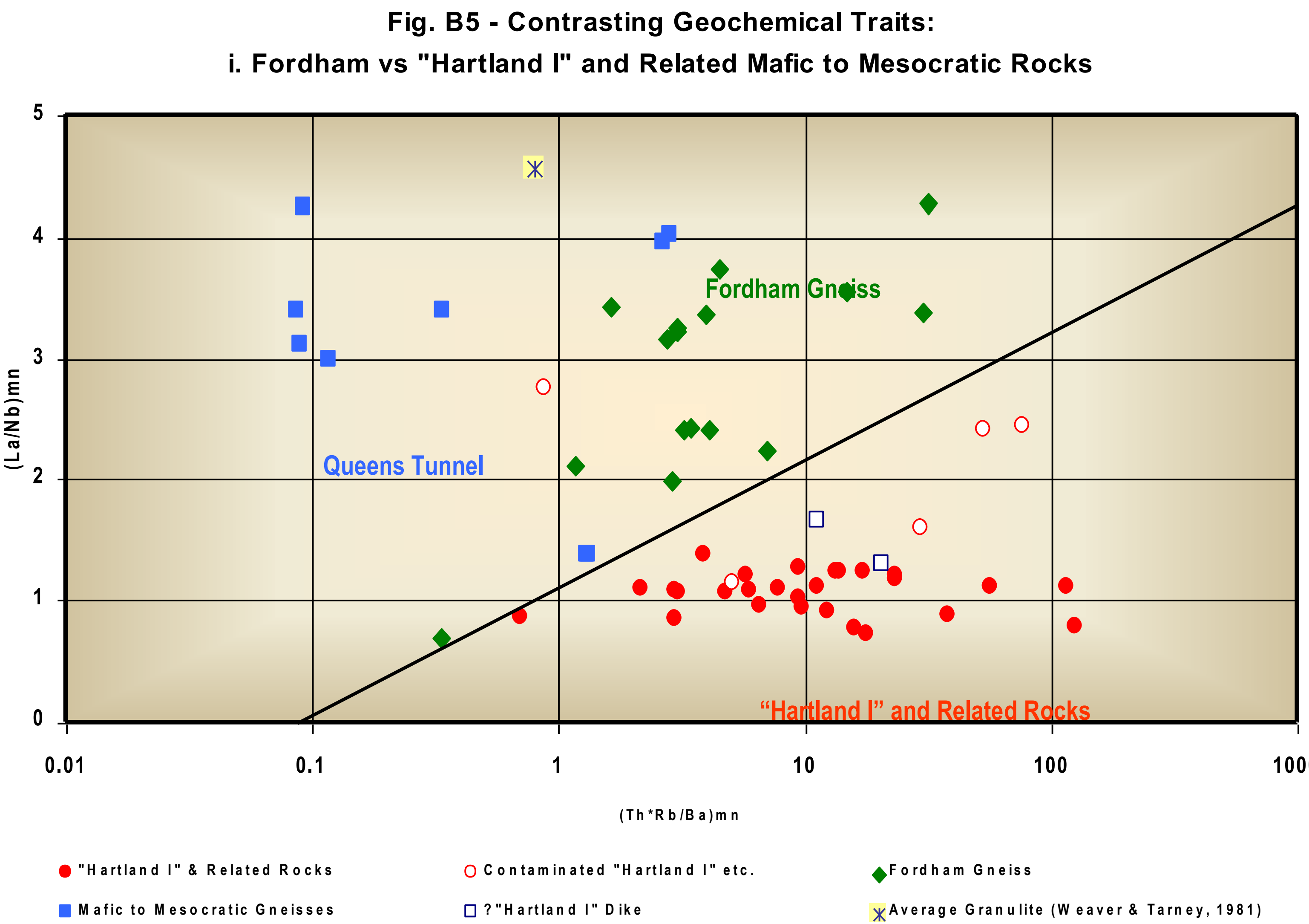
Granulites have a distinctive color and appearance, which is subtle but familiar to experienced field geologists who have mapped granulites in Canada, Africa, Europe, and elsewhere.

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"*.

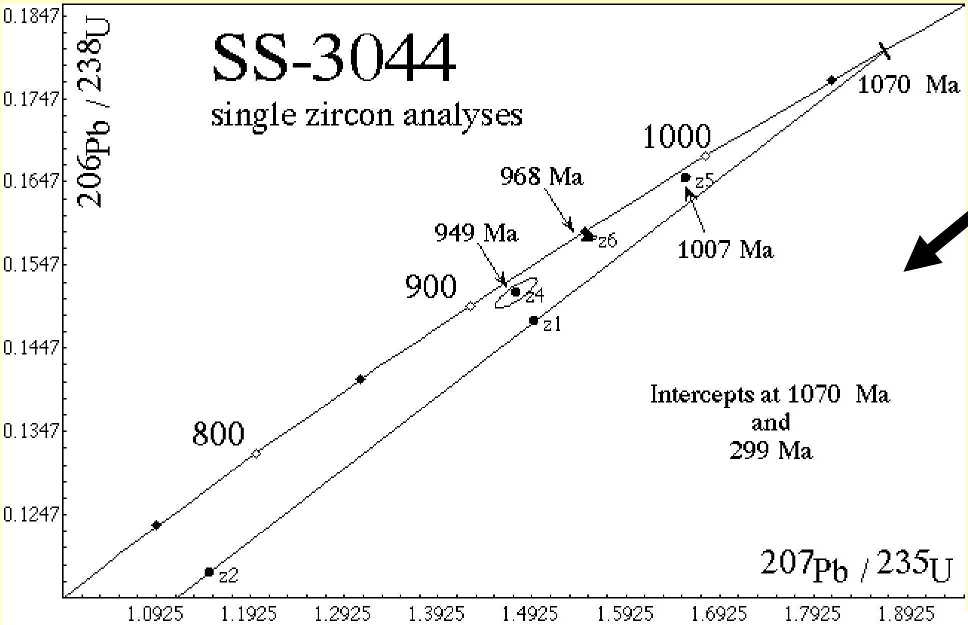
Many Queens Tunnel rocks show this characteristic; it reflects the substantial retention of their granulite-age feldspar.

Geochemical Investigations by the Brocks

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

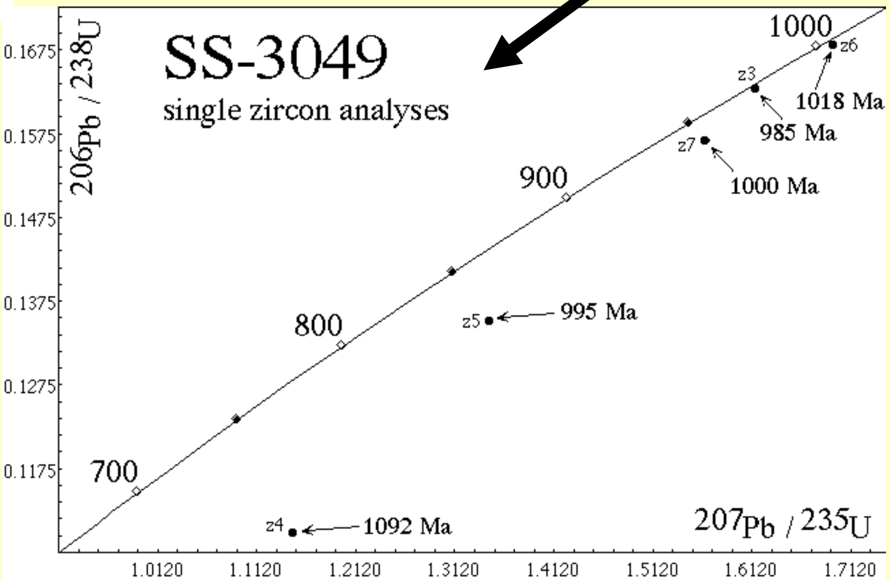


1.0 Ga U/Pb Geochronologic Analysis



Station 9+45

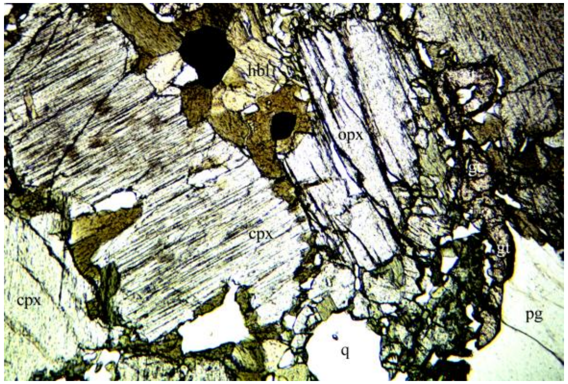
Station 68+15



Queens Tunnel Complex

Age Dating Verified
Fordham vs. Hartland

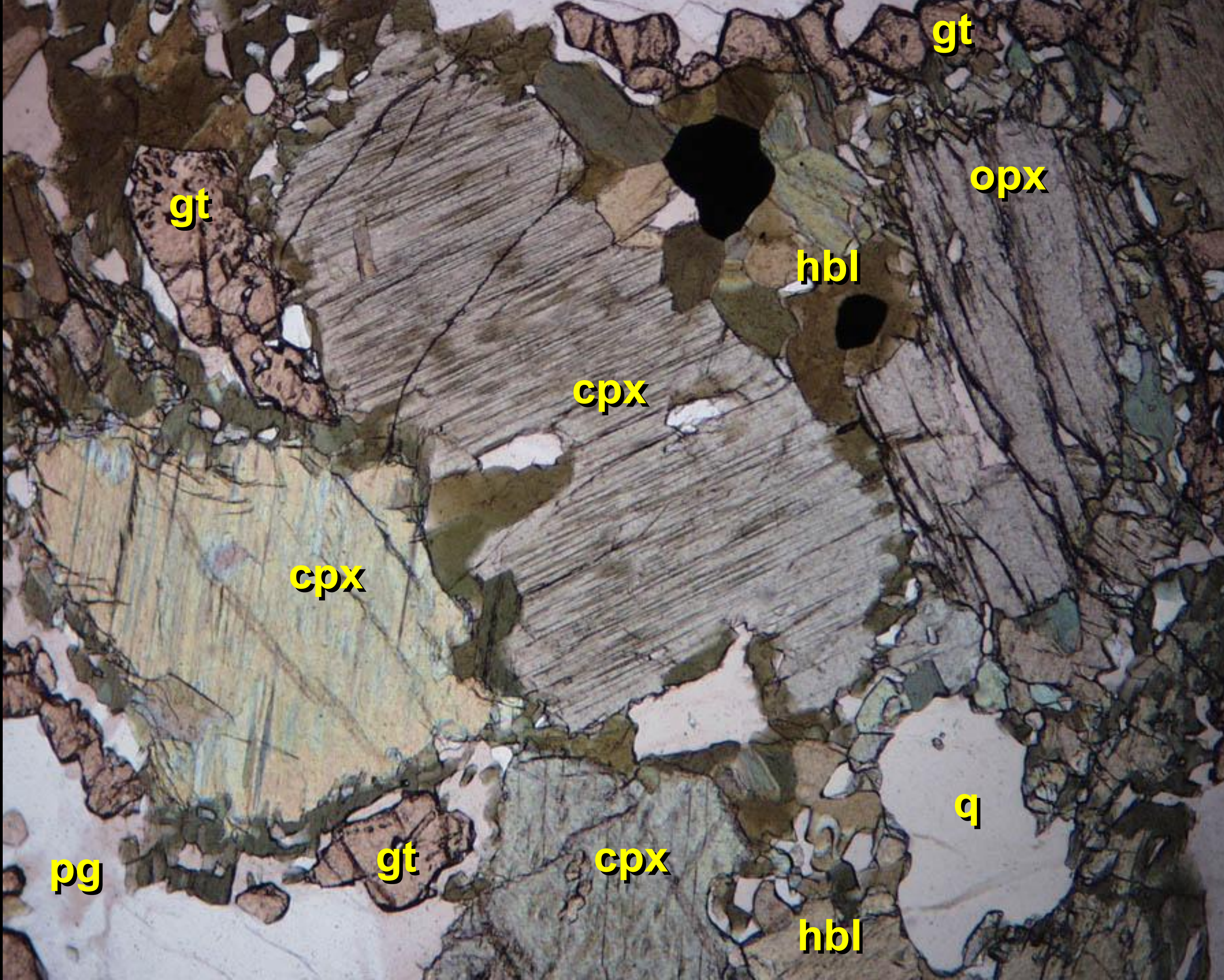
- **Petrographic Analysis (92 Samples)**
  - **Texture**
  - **Mineralogy**
  - **Internal Structure**
  - **Metamorphism**



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	53-39norm	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	10 vermi
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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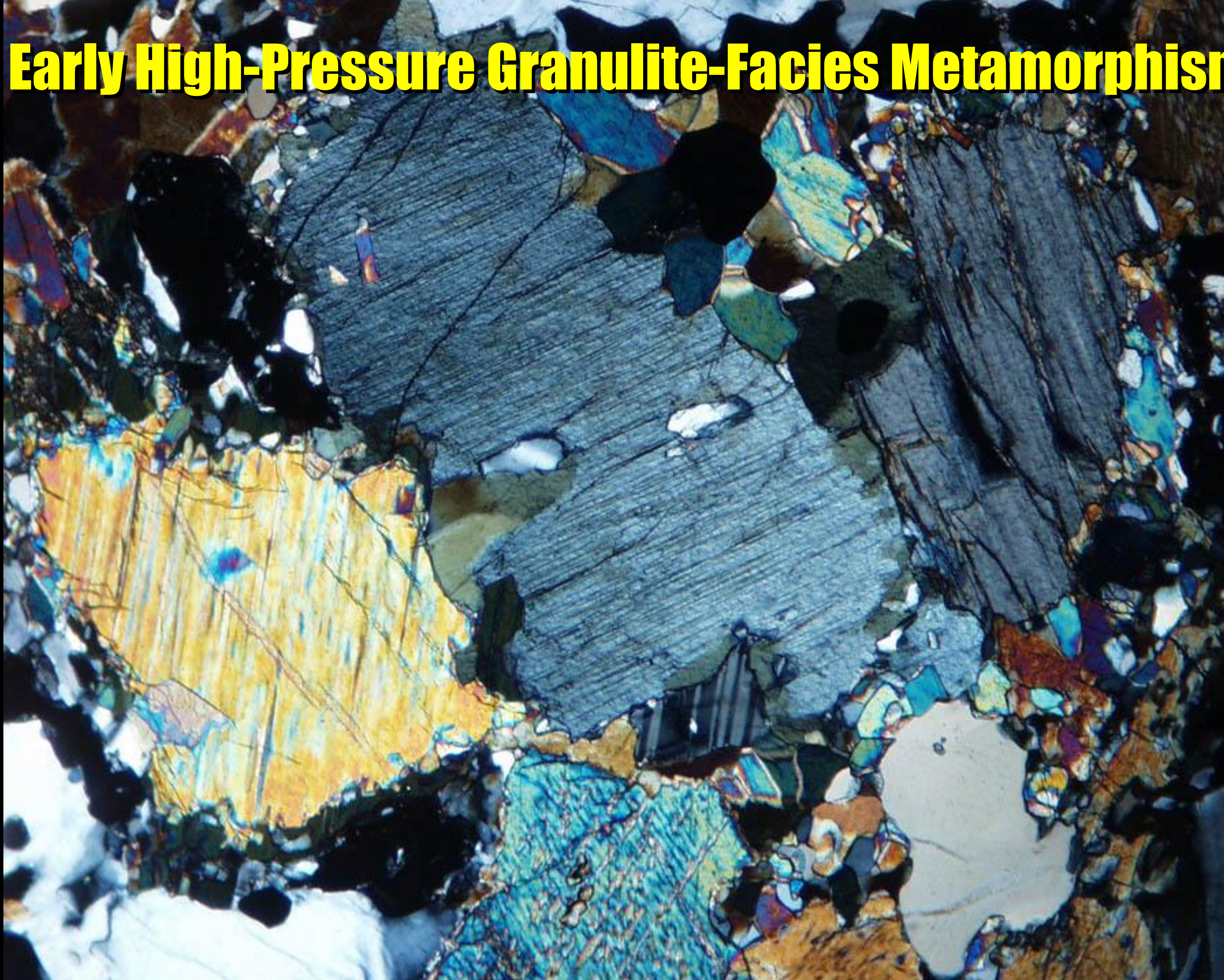
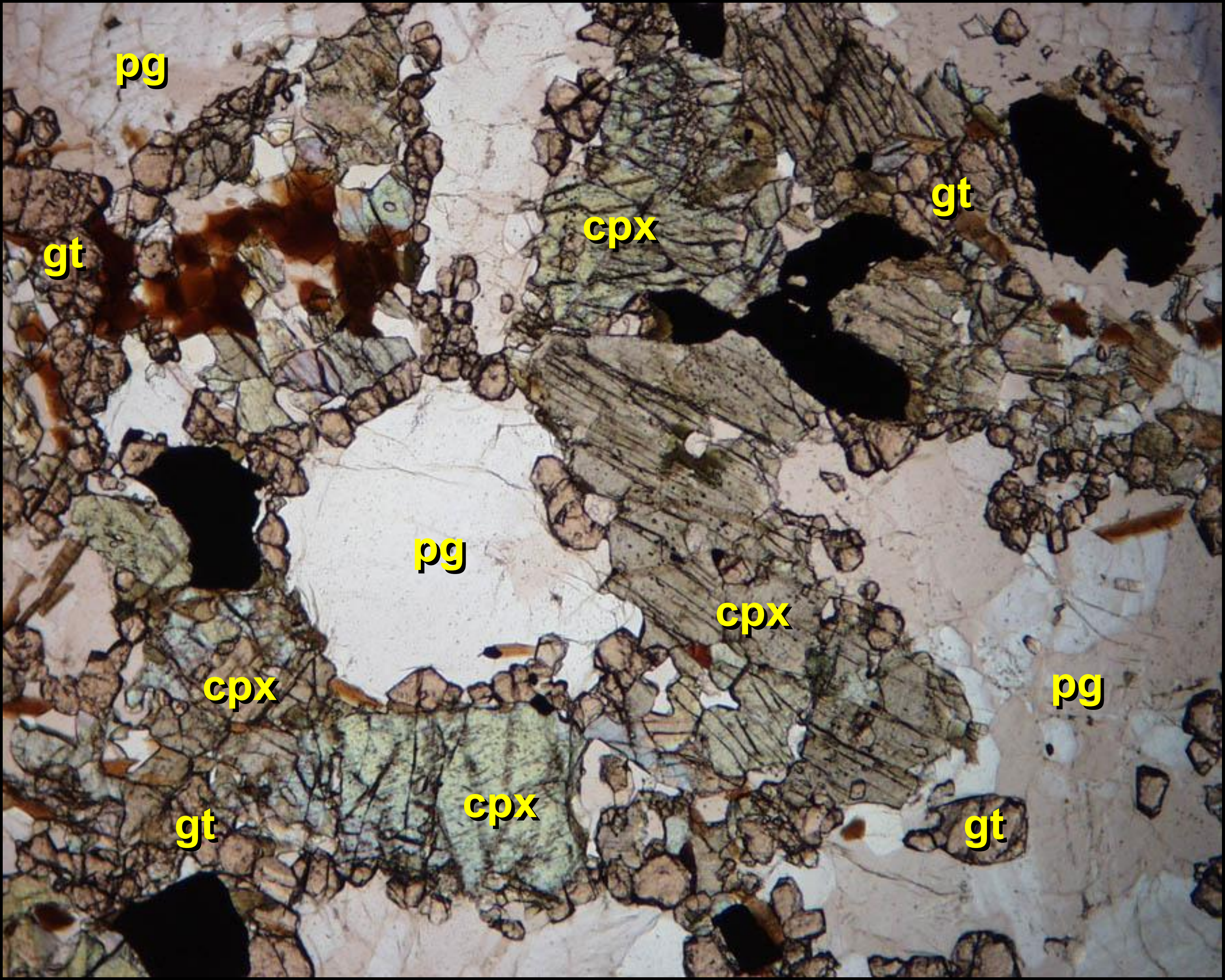
Early High-Pressure Granulite-Facies Metamorphism

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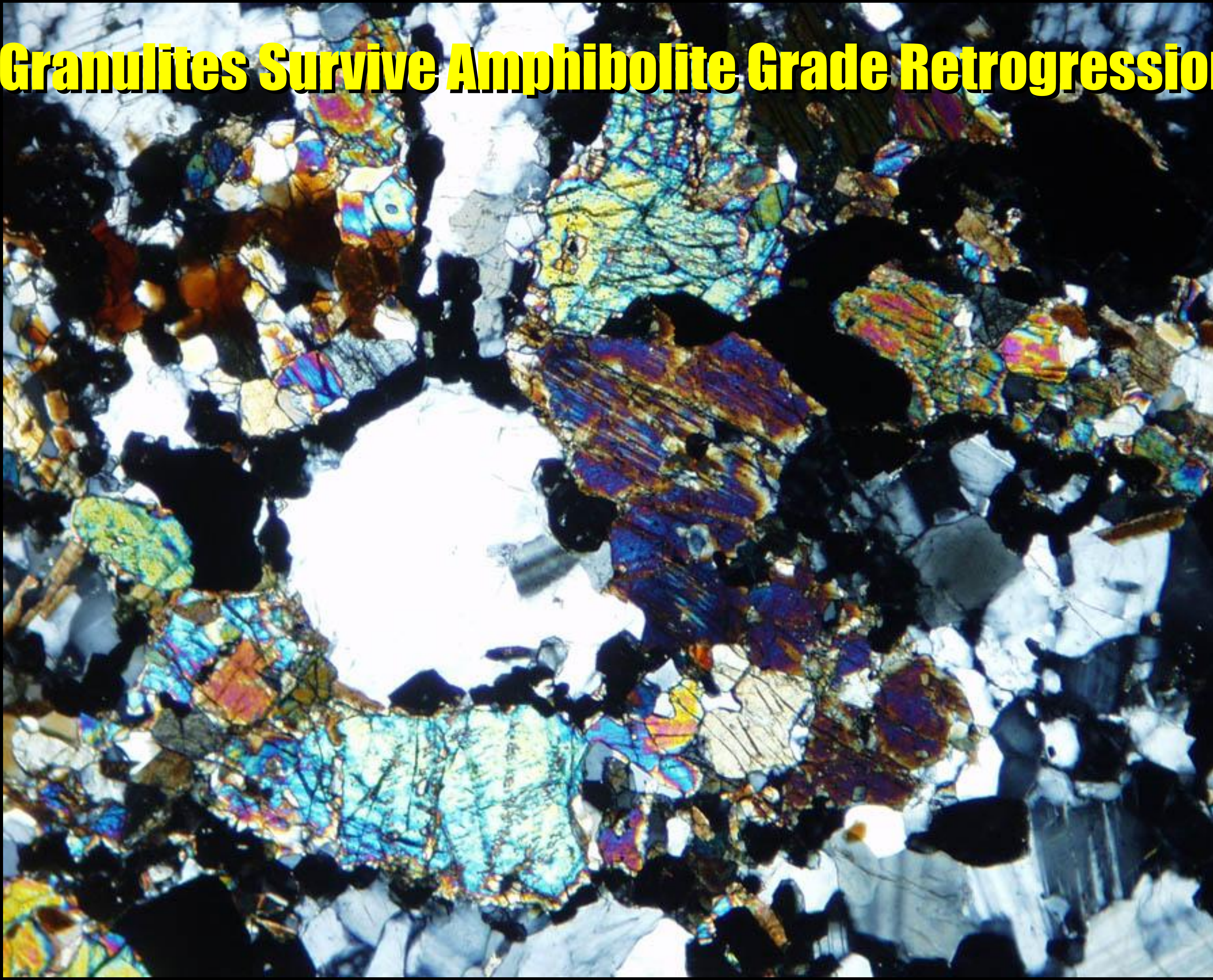
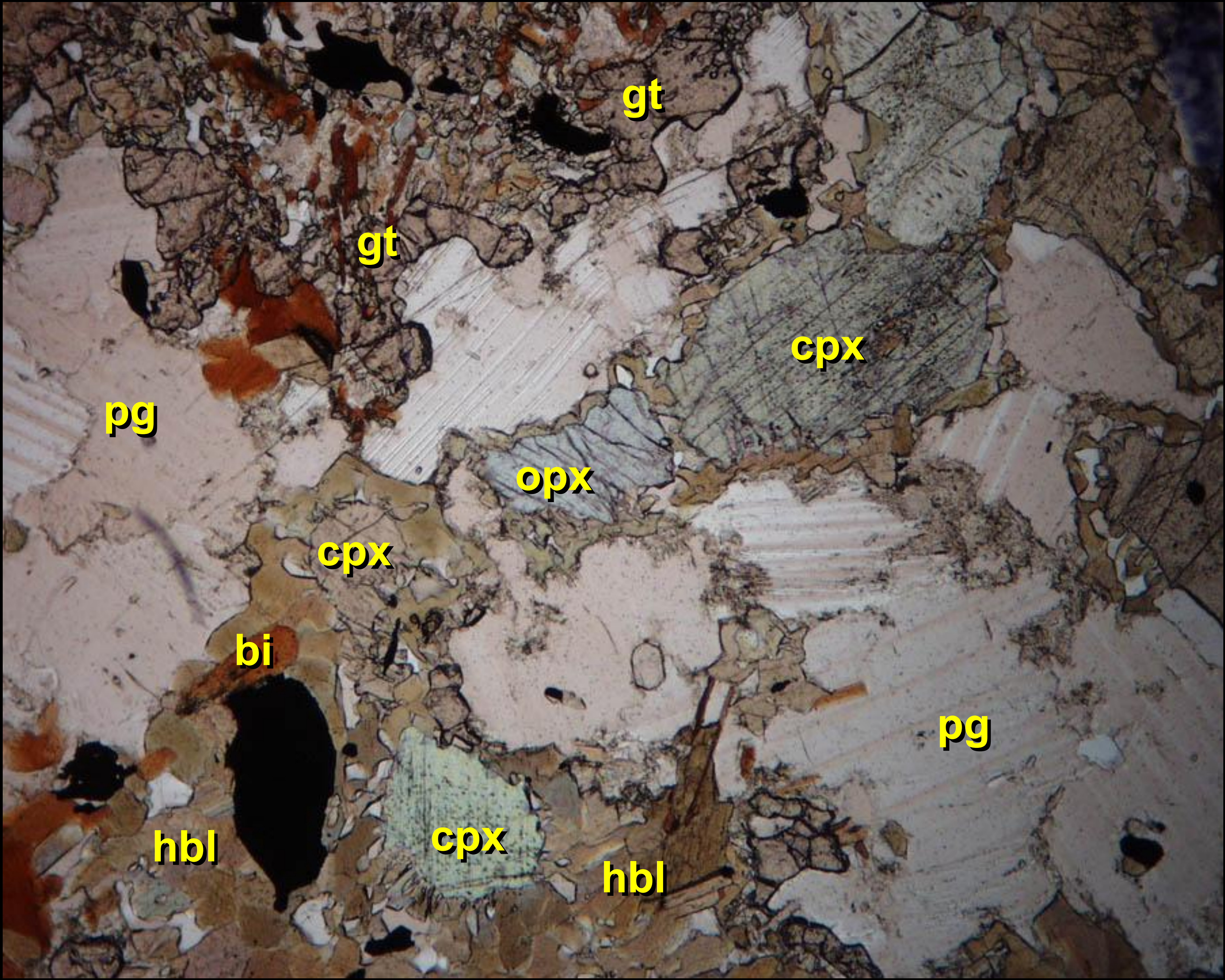
Granulites Survive Amphibolite Grade Retrogression

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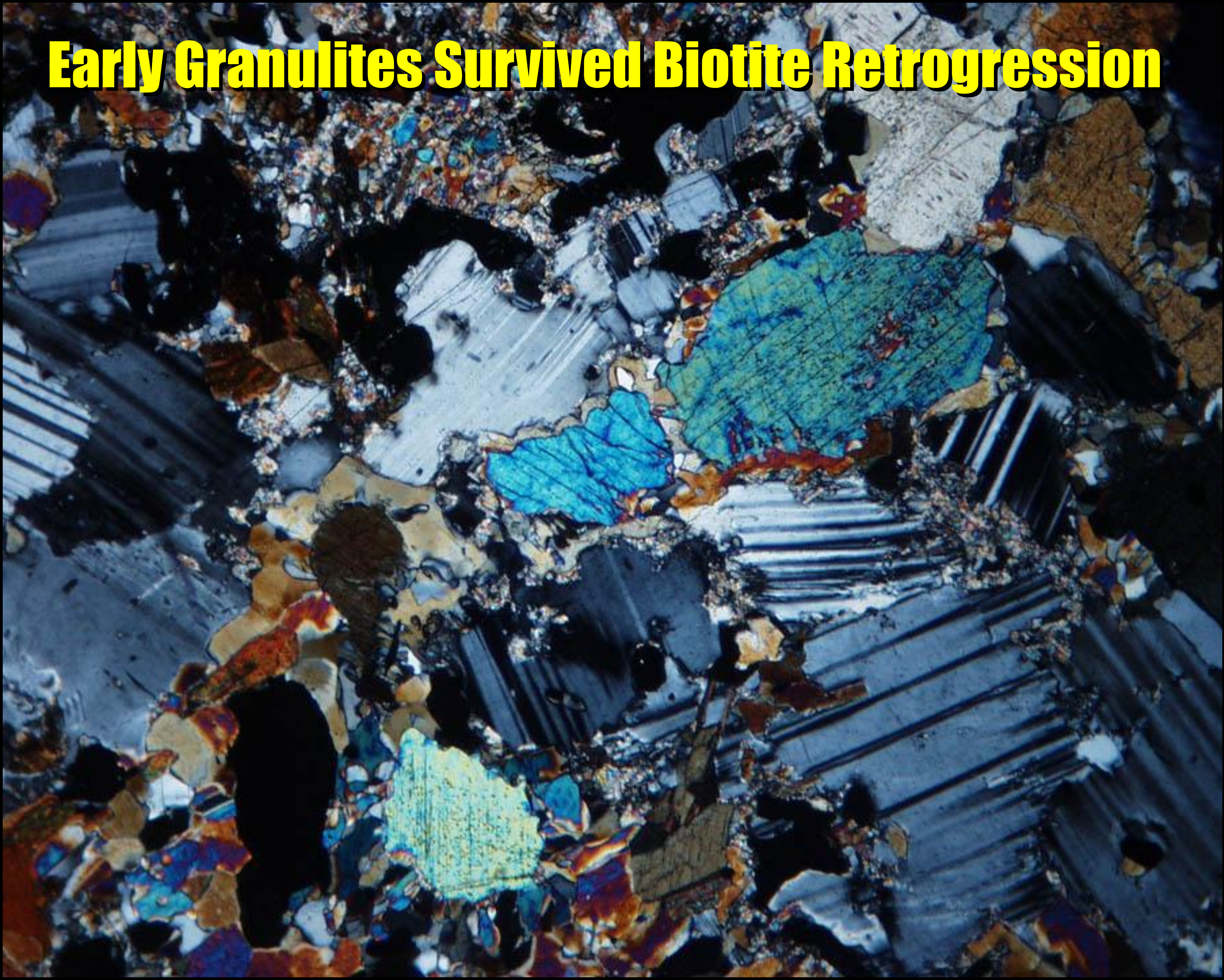
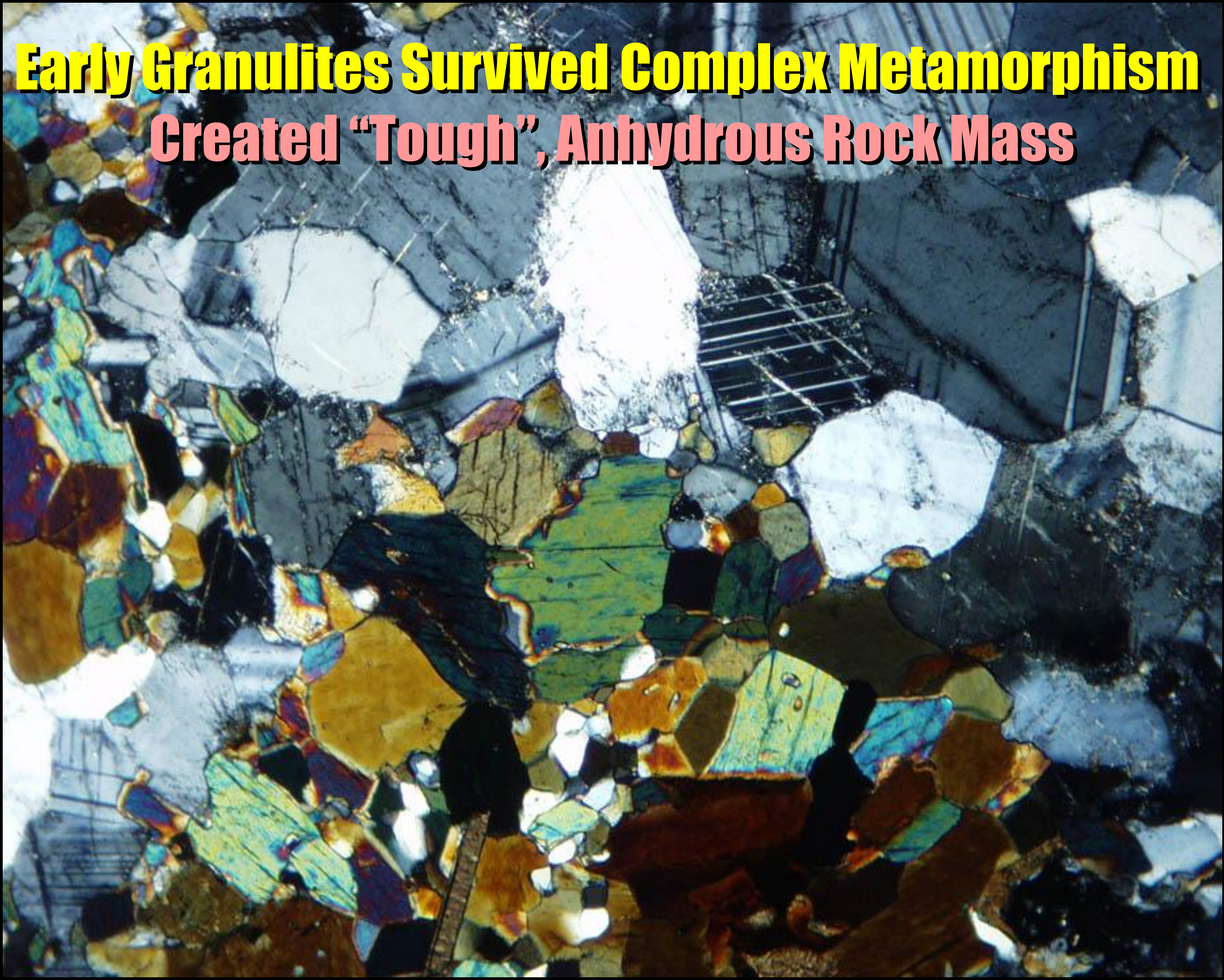
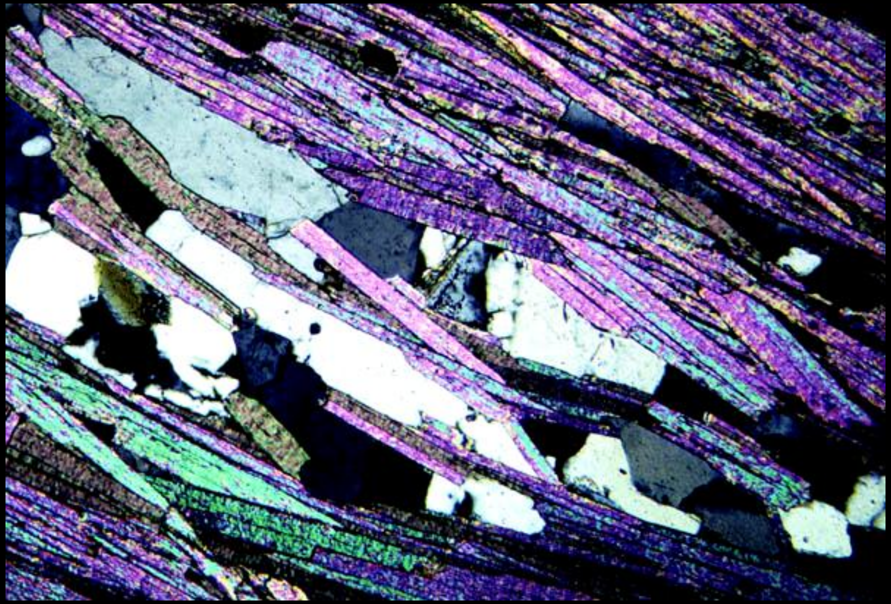
Early Granulites Survived Biotite Retrogression



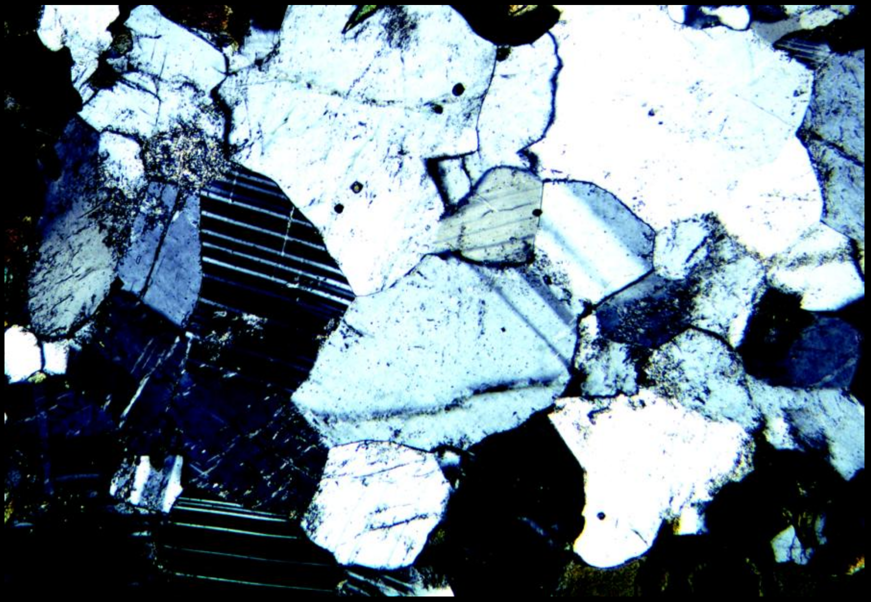

Early Granulites Survived Complex Metamorphism
Created "Tough", Anhydrous Rock Mass

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

The Queens Tunnel Complex

Fordham Lithologies

1.0 Ga mesocratic, leucocratic, and mafic gneiss
Primary granulite-facies texture and mineralogy
Granulite “green” coloration

Non-Fordham Lithologies

<465 Ma granite and pegmatite
biotite+garnet rich metasedimentary rock (Walloomsac Formation)
Metamorphosed mafic dikes
Unmetamorphosed rhyodacite dikes

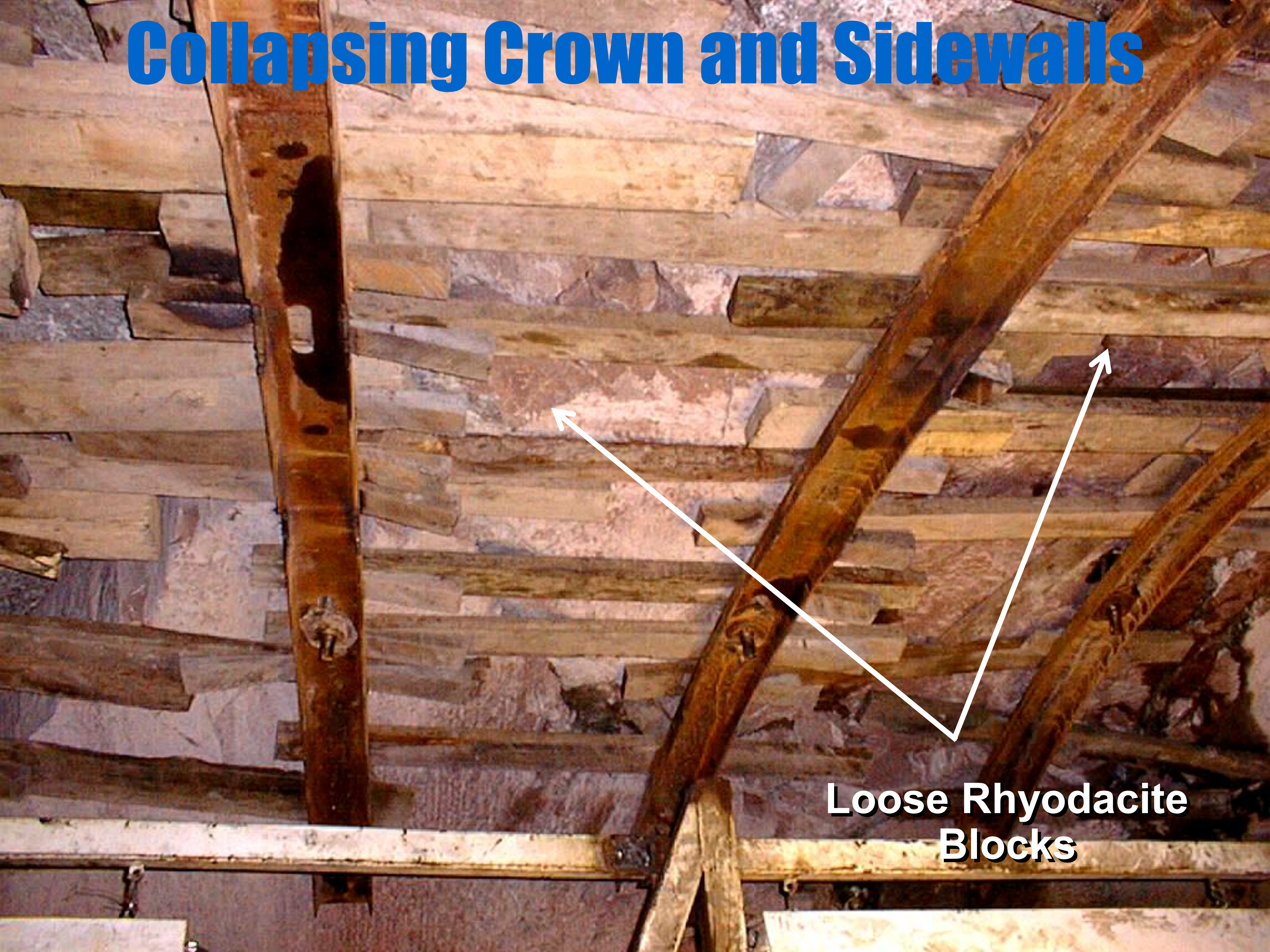

CONTRACT 543B SHEET 1
SHEETS IN SET, 19
Dikes
18B
19B
20B
21B
22B
23B
17B
16B
PROSPECT PARK
543B
EAST RIVER
ROOSEVELT IS.
MANHATTAN
GOVERNORS IS.
UPPER BAY
NEW JERSEY
N.I.C. - Not in Contract 543B
City of New York
DEPARTMENT OF ENVIRONMENTAL PROTECTION
BUREAU OF ENVIRONMENTAL ENGINEERING
CITY TUNNEL 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

Tunneling Difficulties

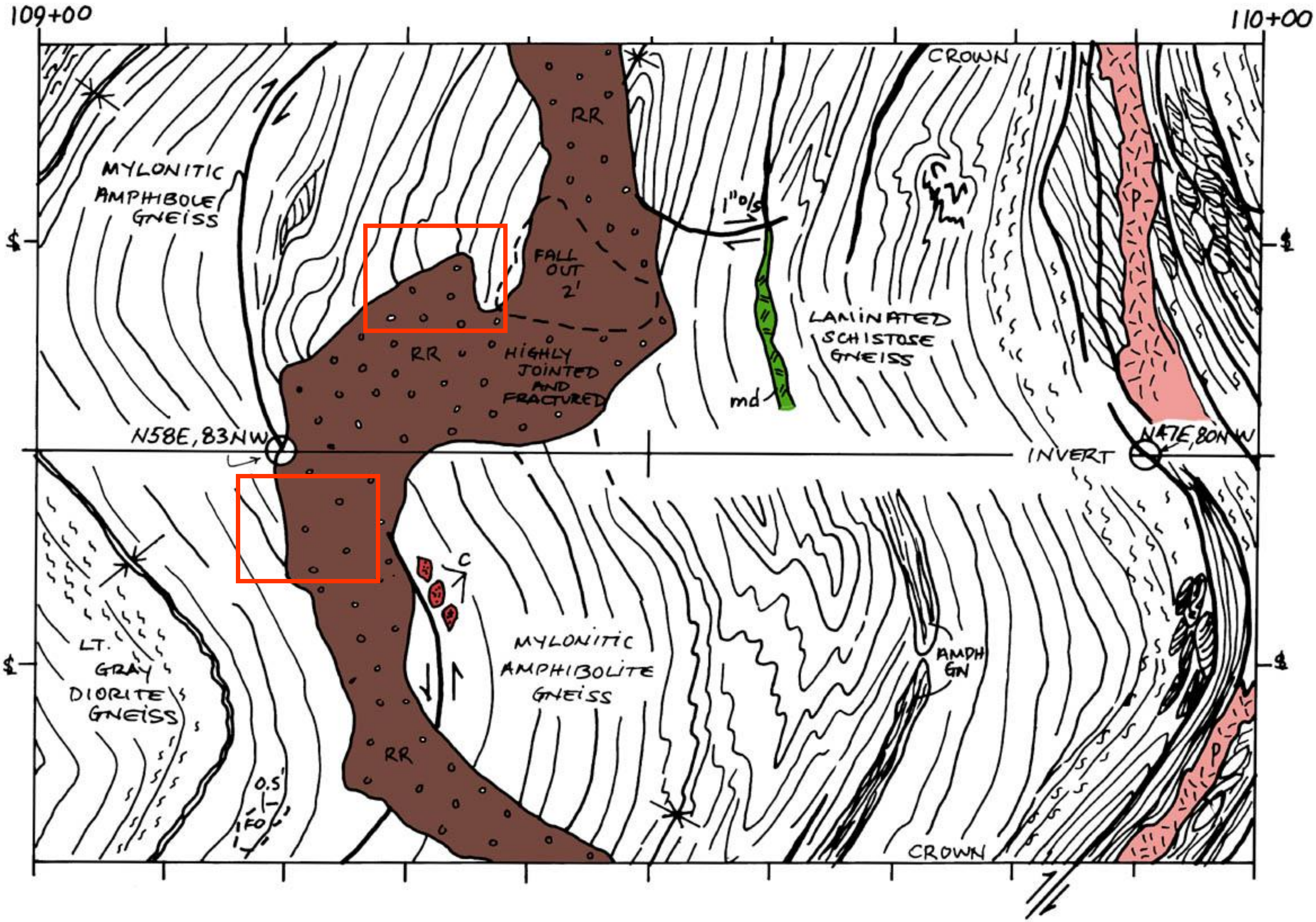
Collapsing Crown and Sidewalls



Geochemistry

Major Elements	QTR-1	Q01-B	Q02-B	QT Average	Nockolds Rhyodacite
SiO2	64.89	66.16	63.06	64.70	66.27
TiO2	0.58	0.51	0.62	0.57	0.66
Al2O3	14.54	14.83	14.78	14.72	15.39
FeO*	3.73	3.31	4.35	3.80	4.15
MnO	0.07	0.08	0.08	0.08	0.07
MgO	1.62	1.77	2.22	1.87	1.57
CaO	3.97	4.40	5.54	4.64	3.68
Na2O	4.80	5.07	4.48	4.78	4.13
K2O	4.52	3.26	4.35	4.04	3.01
P2O5	0.40	0.41	0.54	0.45	0.17
Total	99.12	99.80	100.01	99.64	99.10
LOI	0.87	3.81	2.86	2.51	0.68
*Total Iron as Fe0					

Dike 1

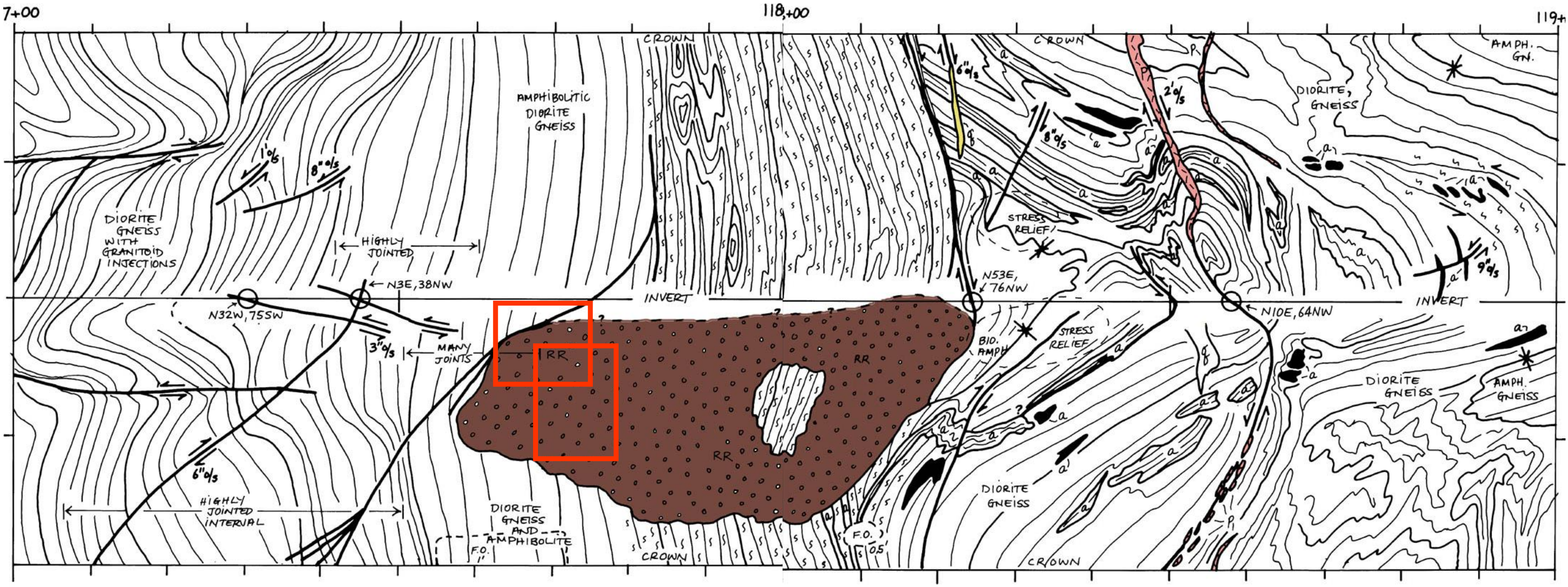


109+00
110+00
CROWN
MYLONITIC AMPHIBOLE GNEISS
RR
FALL OUT 2'
1" o/s
RR
HIGHLY JOINTED AND FRACTURED
LAMINATED SCHISTOSE GNEISS
md
P
N58E, 83NW
N47E, 80NW
INVERT
C
LT. GRAY DIORITE GNEISS
MYLONITIC AMPHIBOLITE GNEISS
AMPH GN
RR
0.5'
1FO
CROWN


109

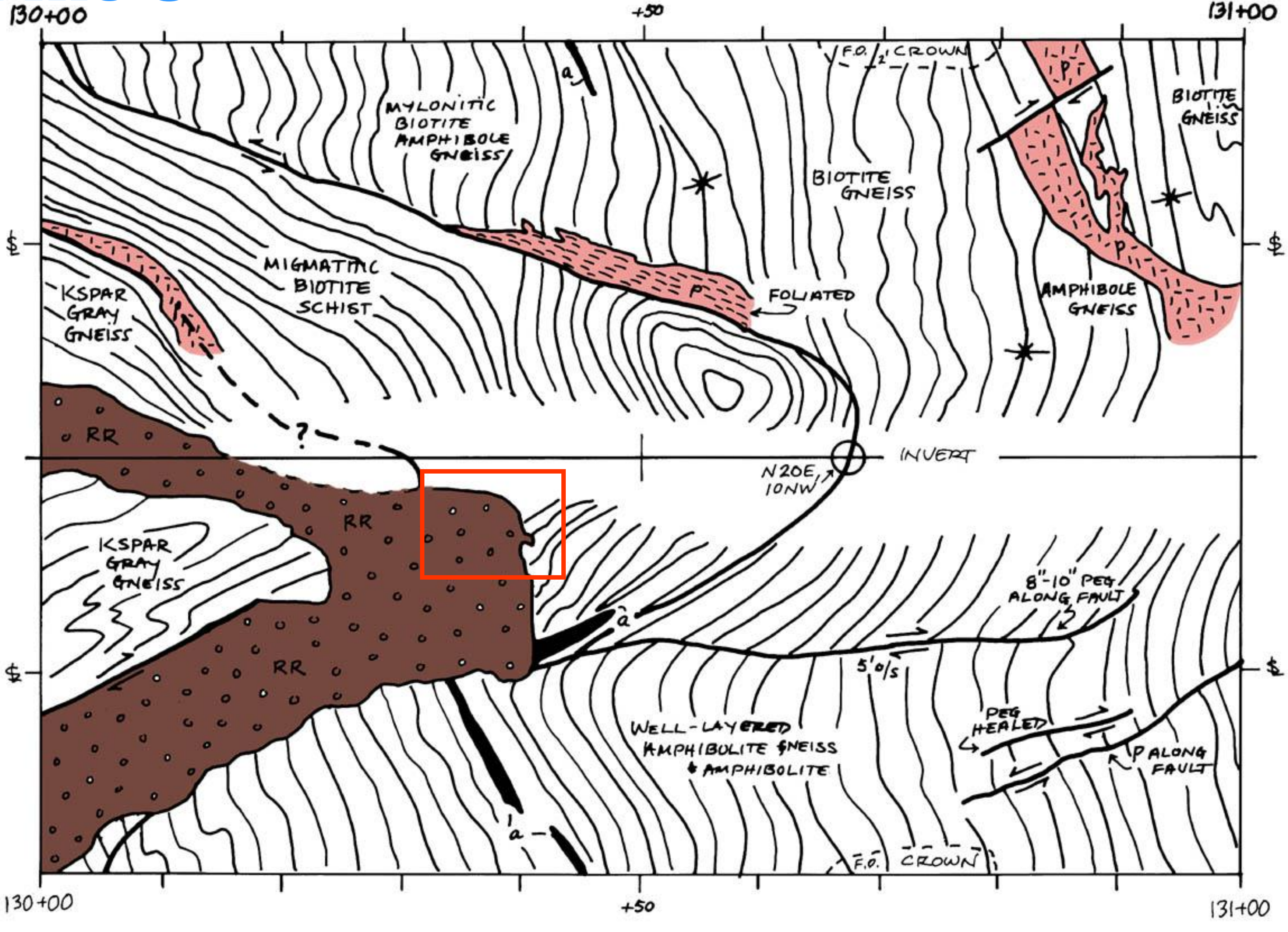

Station 109+20, Right Wall
Cooling joints extend 10' into country rock

Dike 2



7+00
118+00
119+
CROWN
AMPHIBOLITIC DIORITE GNEISS
DIORITE GNEISS WITH GRANITOID INJECTIONS
HIGHLY JOINTED
N3E, 38NW
N32W, 75SW
INVERT
3"o/s
MANY JOINTS
RR
HIGHLY JOINTED INTERVAL
DIORITE GNEISS AND AMPHIBOLITE
F.O.
N53E, 76NW
STRESS RELIEF
BIO. AMPH
DIORITE, GNEISS
AMPH. GN.
N10E, 64NW
DIORITE GNEISS
AMPH. GNEISS
F.O. 05'

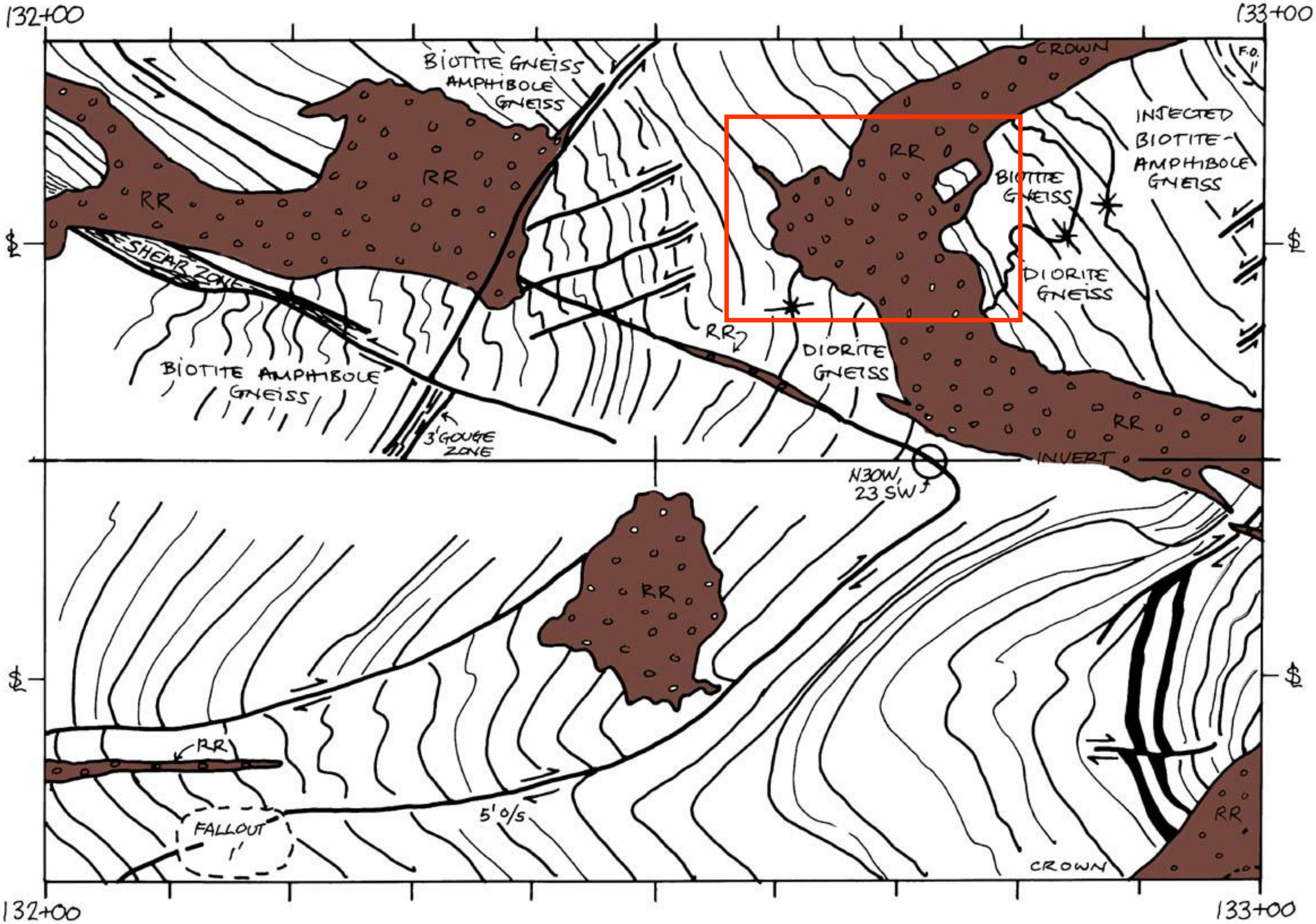
Dike 3



130+00
+50
131+00
F.O. 1/2' CROWN
MYLONITIC BIOTITE AMPHIBOLE GNEISS
BIOTITE GNEISS
BIOTITE GNEISS
MIGMATITIC BIOTITE SCHIST
KSPAR GRAY GNEISS
FOLIATED
AMPHIBOLE GNEISS
P
P
P
RR
RR
RR
?
INVERT
N20E, 10NW
KSPAR GRAY GNEISS
8"-10" PEG ALONG FAULT
5' o/s
WELL-LAYERED AMPHIBOLITE GNEISS & AMPHIBOLITE
PEG HEALED
P ALONG FAULT
F.O. CROWN
130+00
+50
131+00


Station 130+40, Right Wall
Multidirectional cooling
joints in rhyodacite

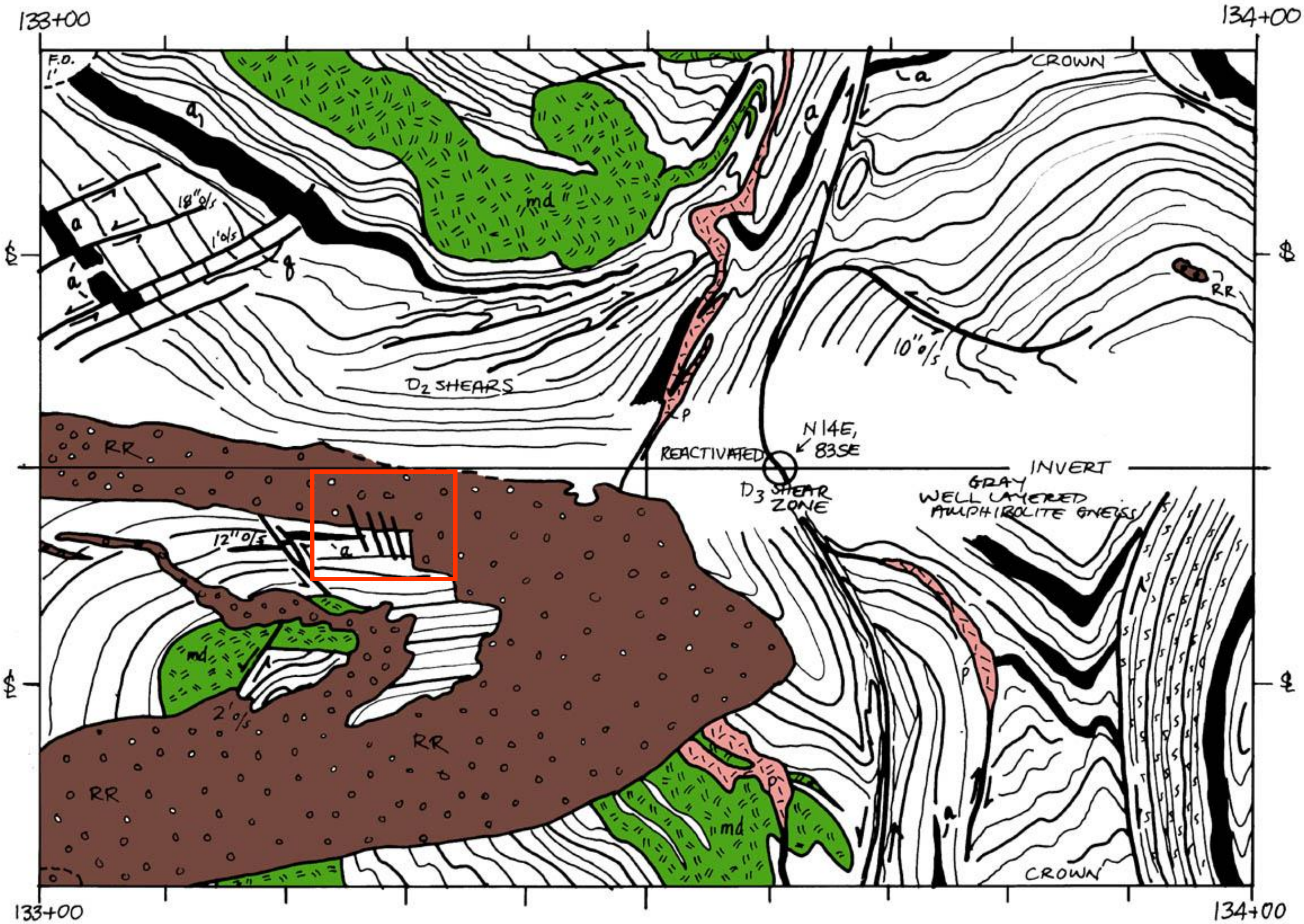
Dike 4



132+00
133+00
BIOTITE GNEISS
AMPHIBOLE GNEISS
CROWN
F.O. 1'
RR
INJECTED BIOTITE-AMPHIBOLE GNEISS
BIOTITE GNEISS
DIORITE GNEISS
SHEAR ZONE
RR?
BIOTITE AMPHIBOLE GNEISS
3' GOUGE ZONE
DIORITE GNEISS
INVERT
N30W, 23 SW
5' O/S
FALLOUT 1'
CROWN

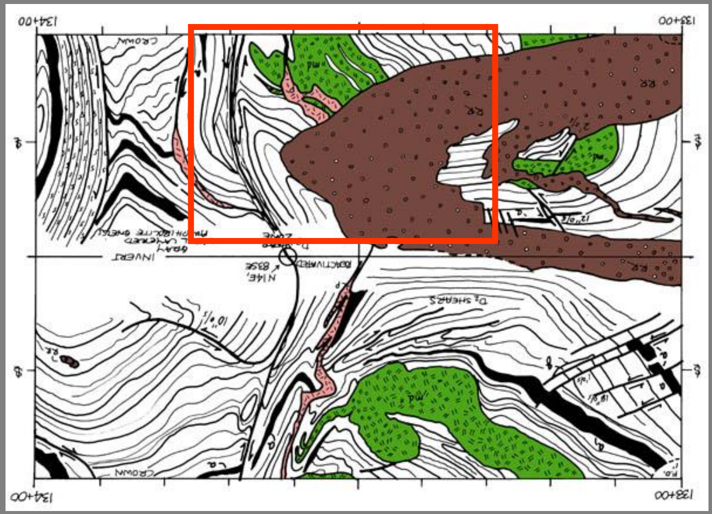

132+60
132+65
132+70

Dike 4

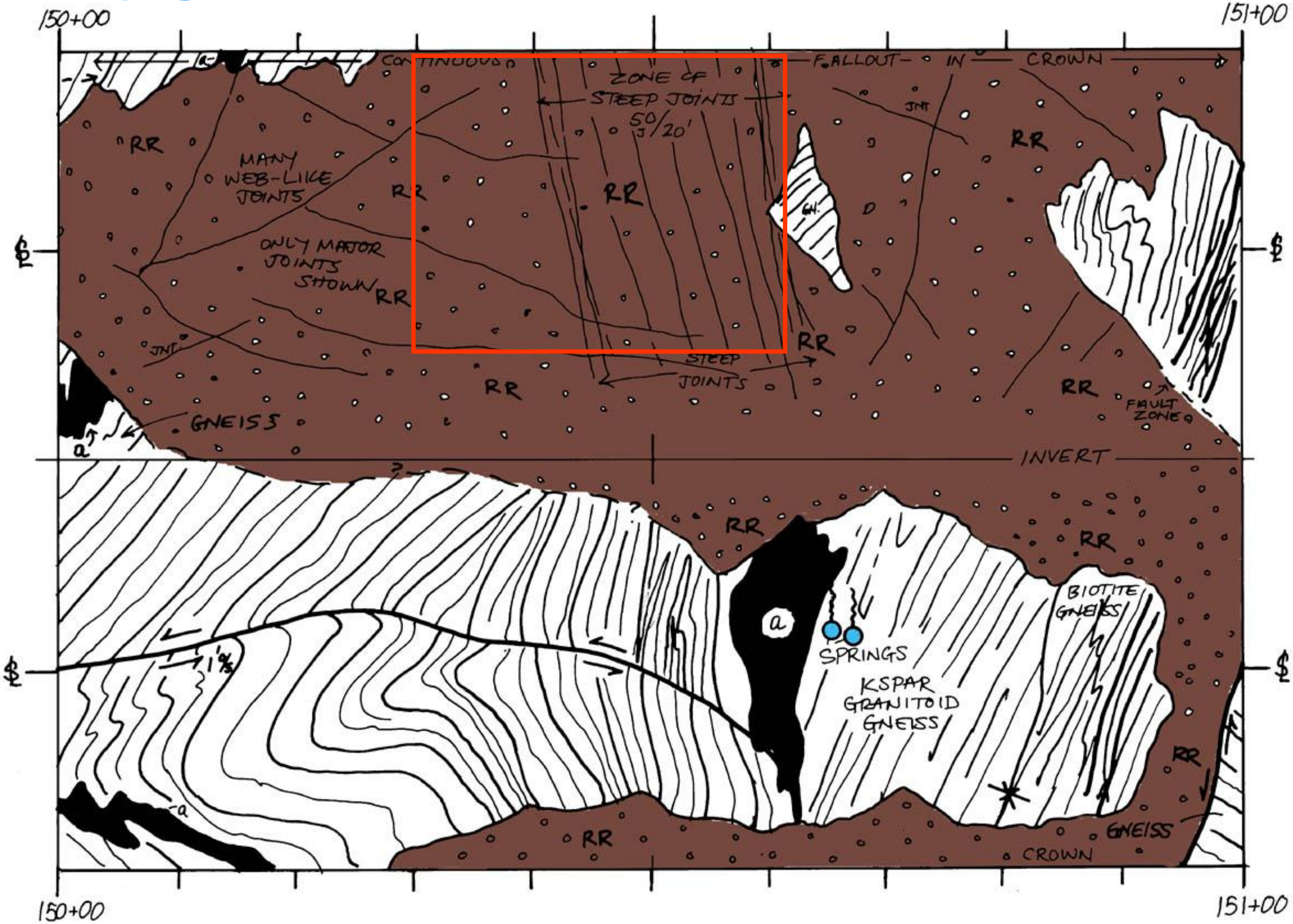


133+00
134+00
F.O. 1'
a
18" o/s
1' o/s
g
md
CROWN
RR
10" o/s
D2 SHEARS
P
N14E, 83SE
REACTIVATED
INVERT
D3 SHEAR ZONE
GRAY WELL LAYERED AMPHIBOLITE GNEISS
12" o/s
2' o/s
133+00
134+00

Dike 4

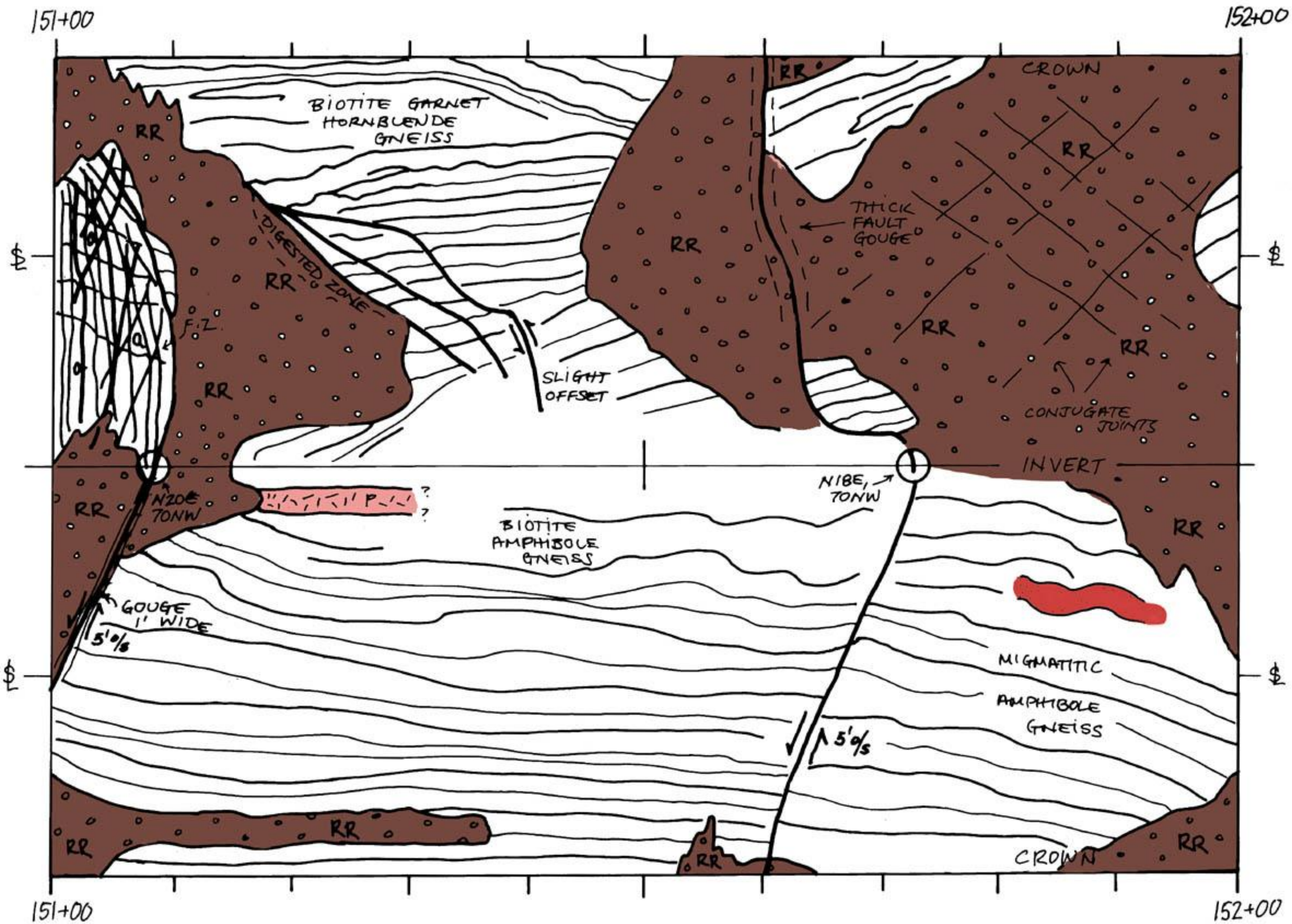


Dike 5



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
a
SPRINGS
KSPAR GRANITOID GNEISS
BIOTITE GNEISS
CROWN
150+00
151+00

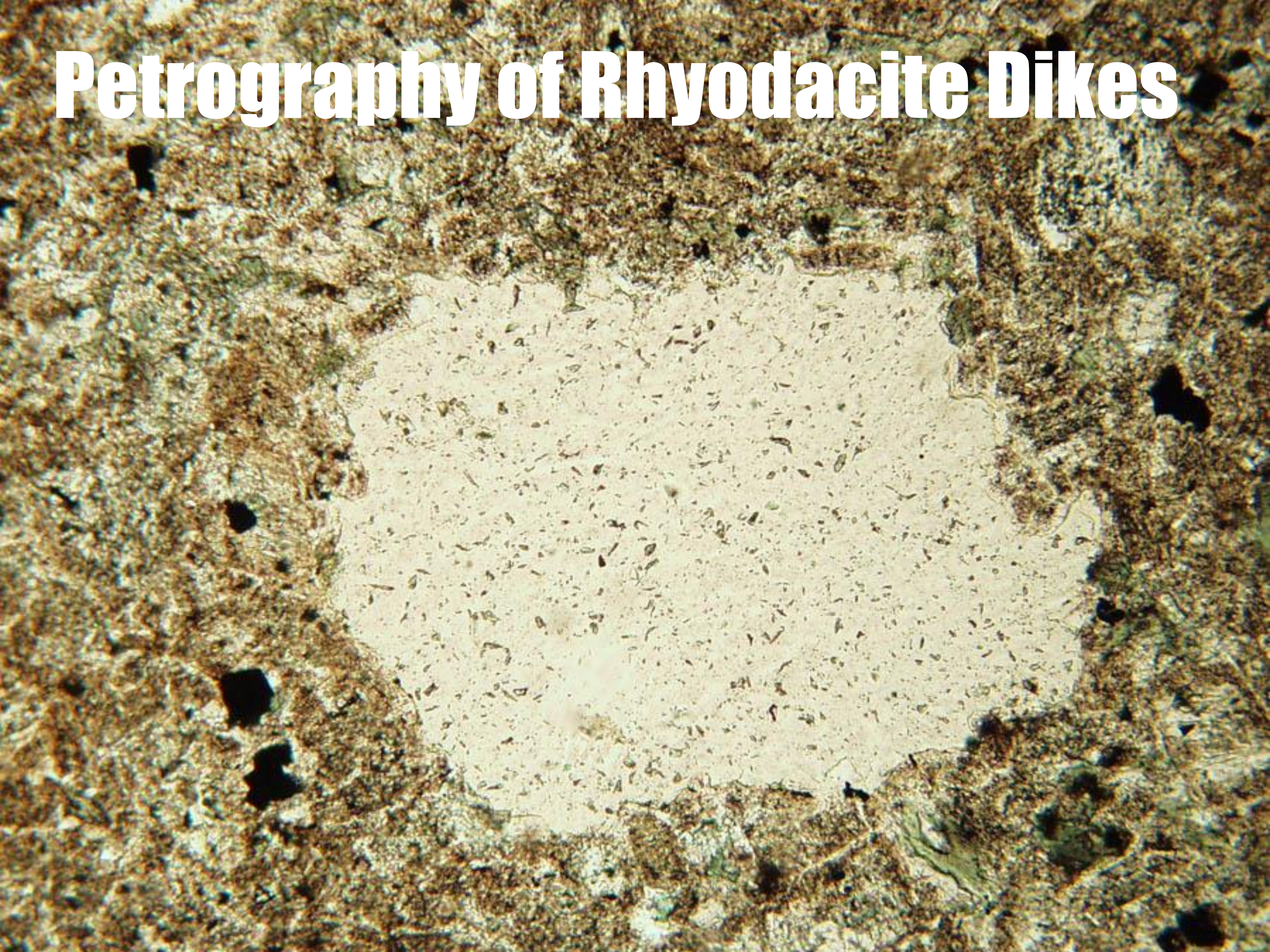
Dike 5

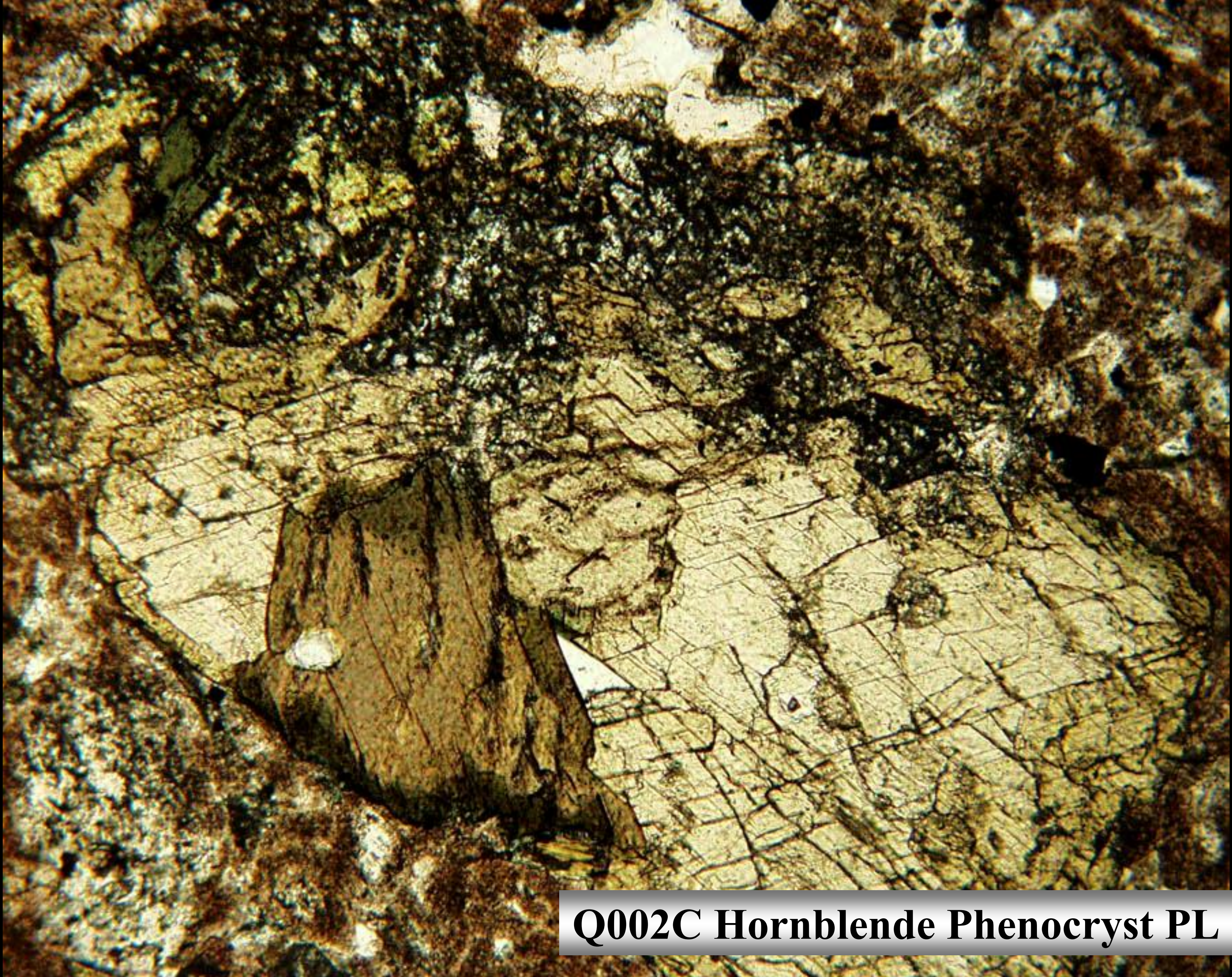


151+00
152+00
BIOTITE GARNET HORNBLENDE GNEISS
RR
DIGESTED ZONE
F.Z.
SLIGHT OFFSET
THICK FAULT GOUGE
CROWN
CONJUGATE JOINTS
INVERT
N20E 70NW
N1BE, 70NW
P
BIOTITE AMPHIBOLE GNEISS
GOUGE 1' WIDE
5' o/s
MIGMATITIC AMPHIBOLE GNEISS
CROWN
151+00
152+00

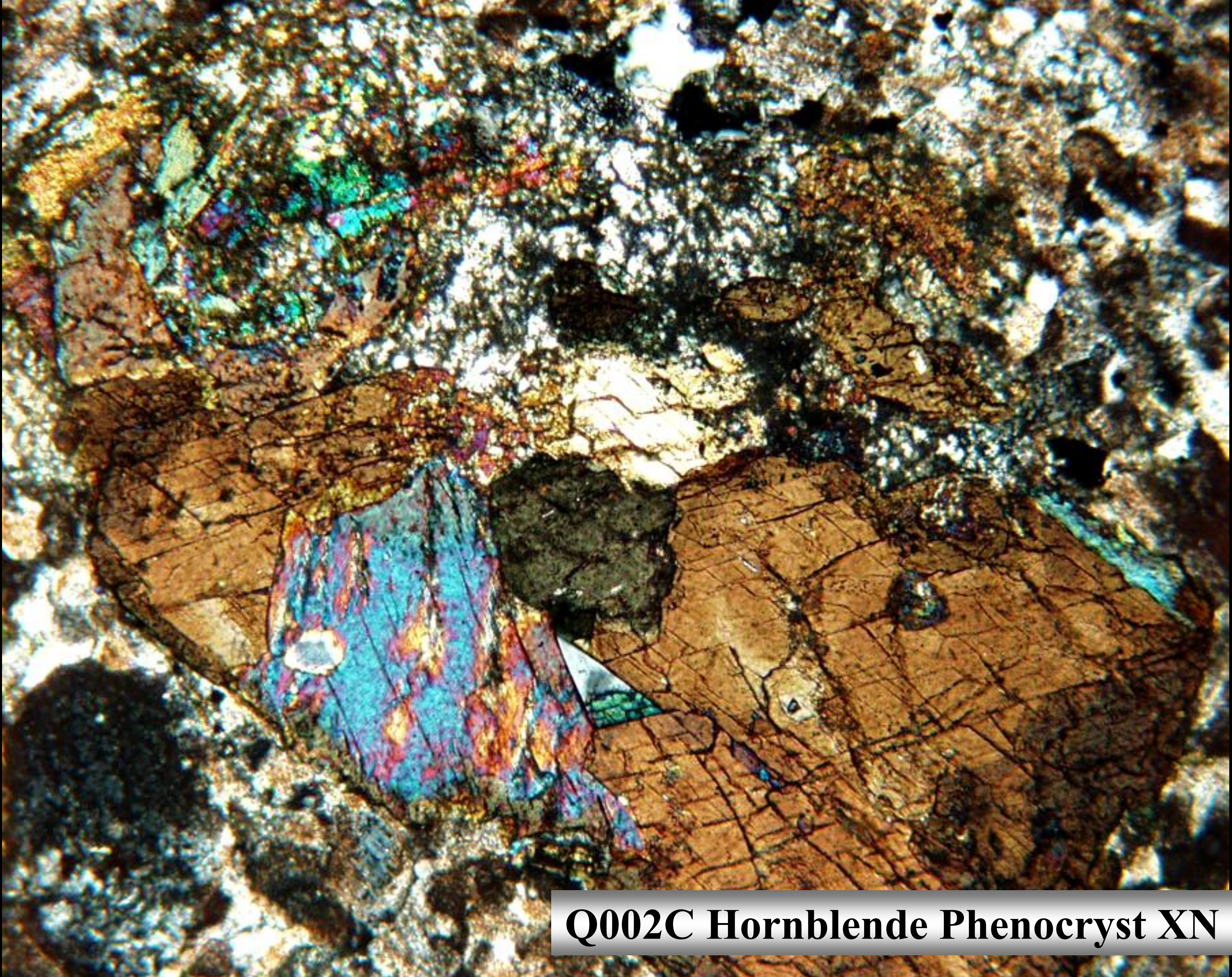

12:05PM
5/15/1998

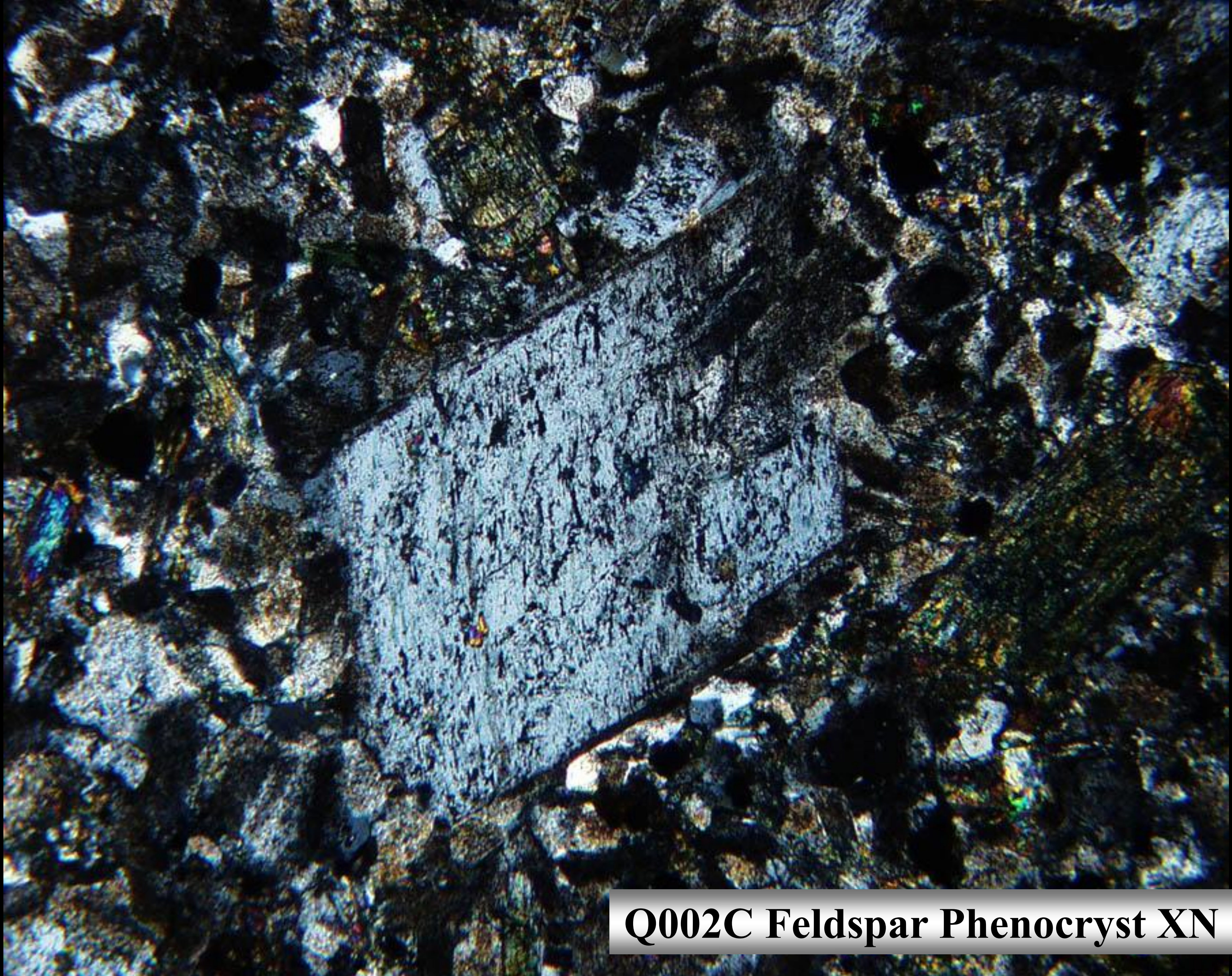
Petrography of Rhyodacite Dikes





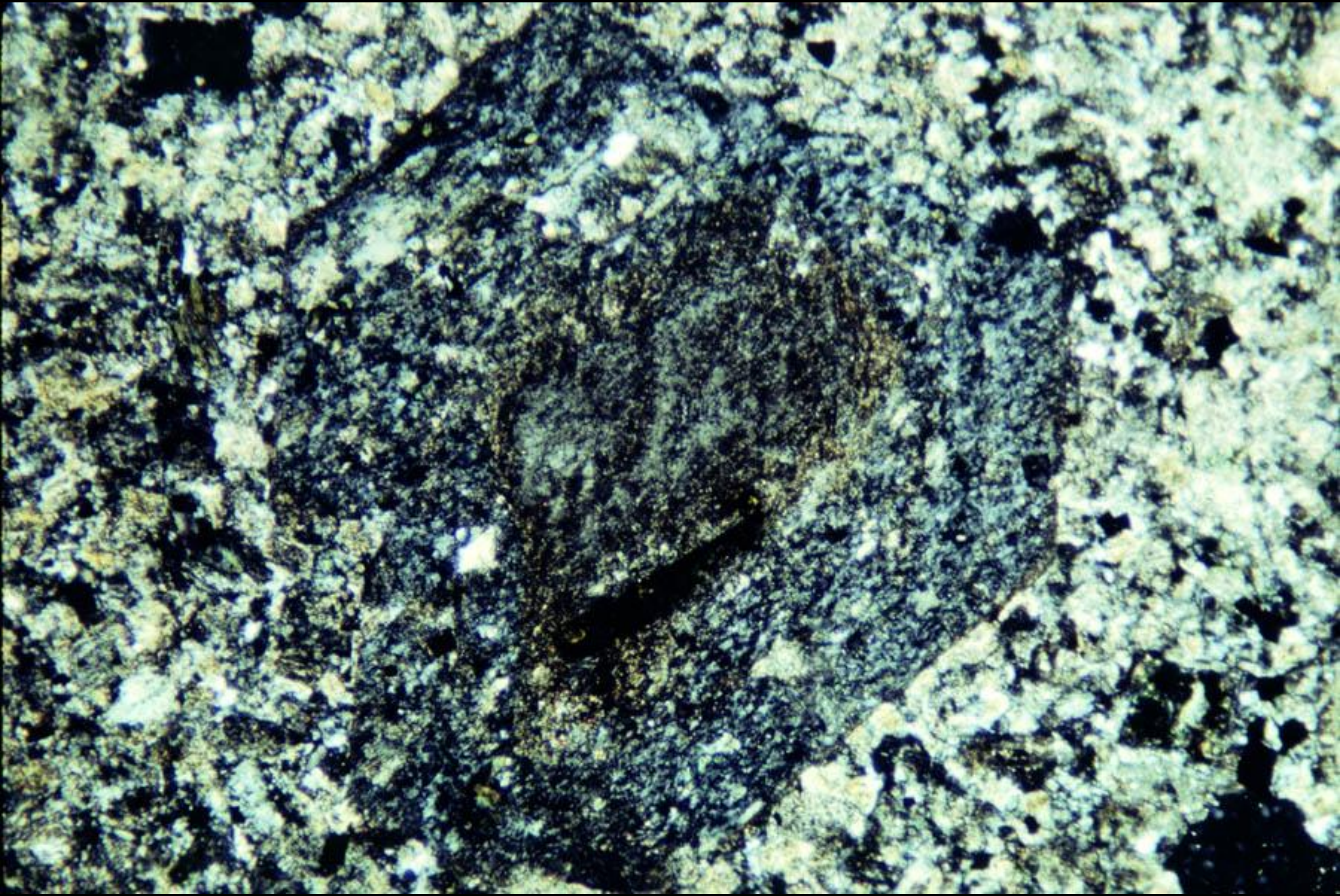
Q002C Hornblende Phenocryst PL

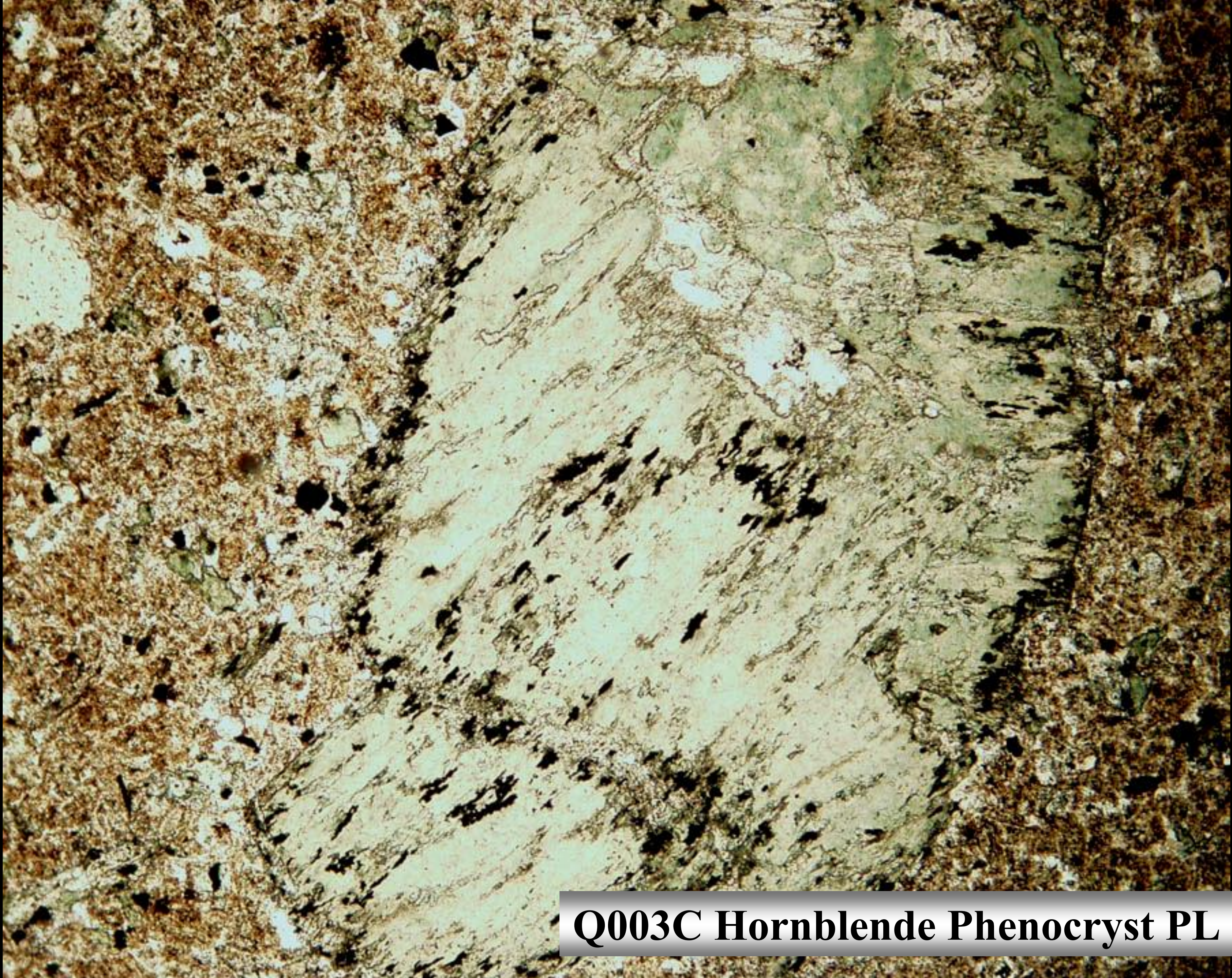

Q002C Hornblende Phenocryst XN



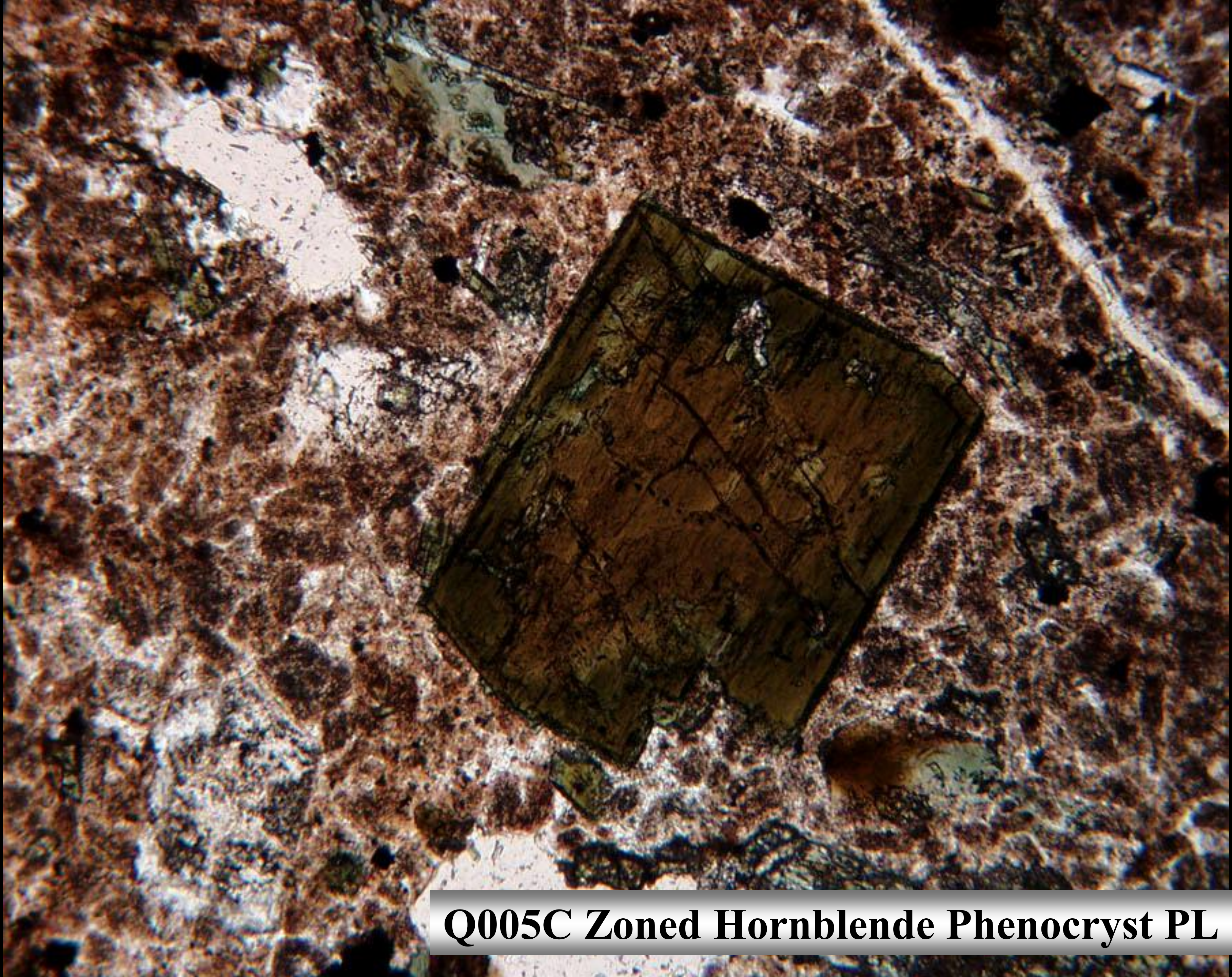
Q002C Feldspar Phenocryst XN

Q006C Oscillatory Zoned Plagioclase Phenocryst XN



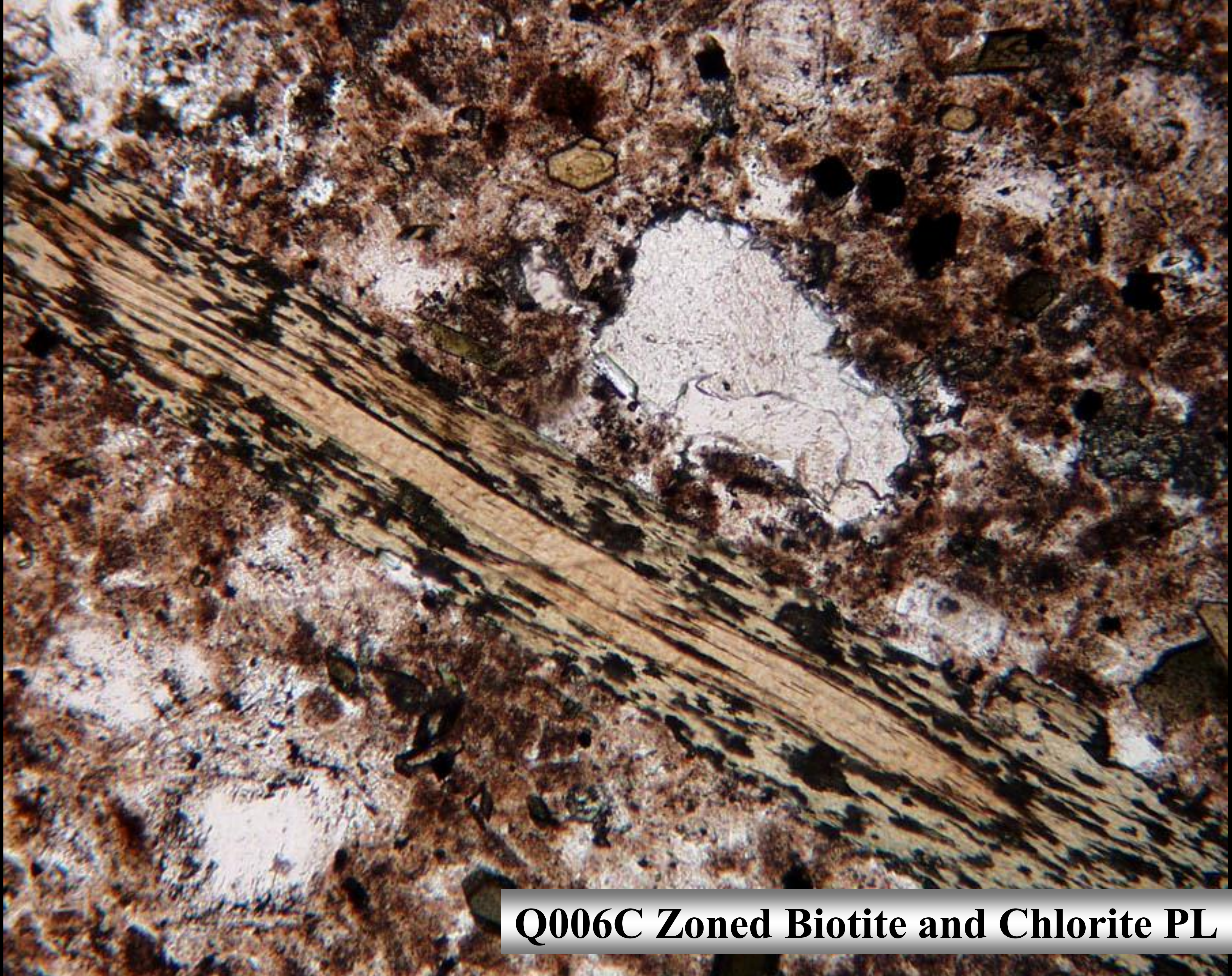


Q003C Hornblende Phenocryst PL

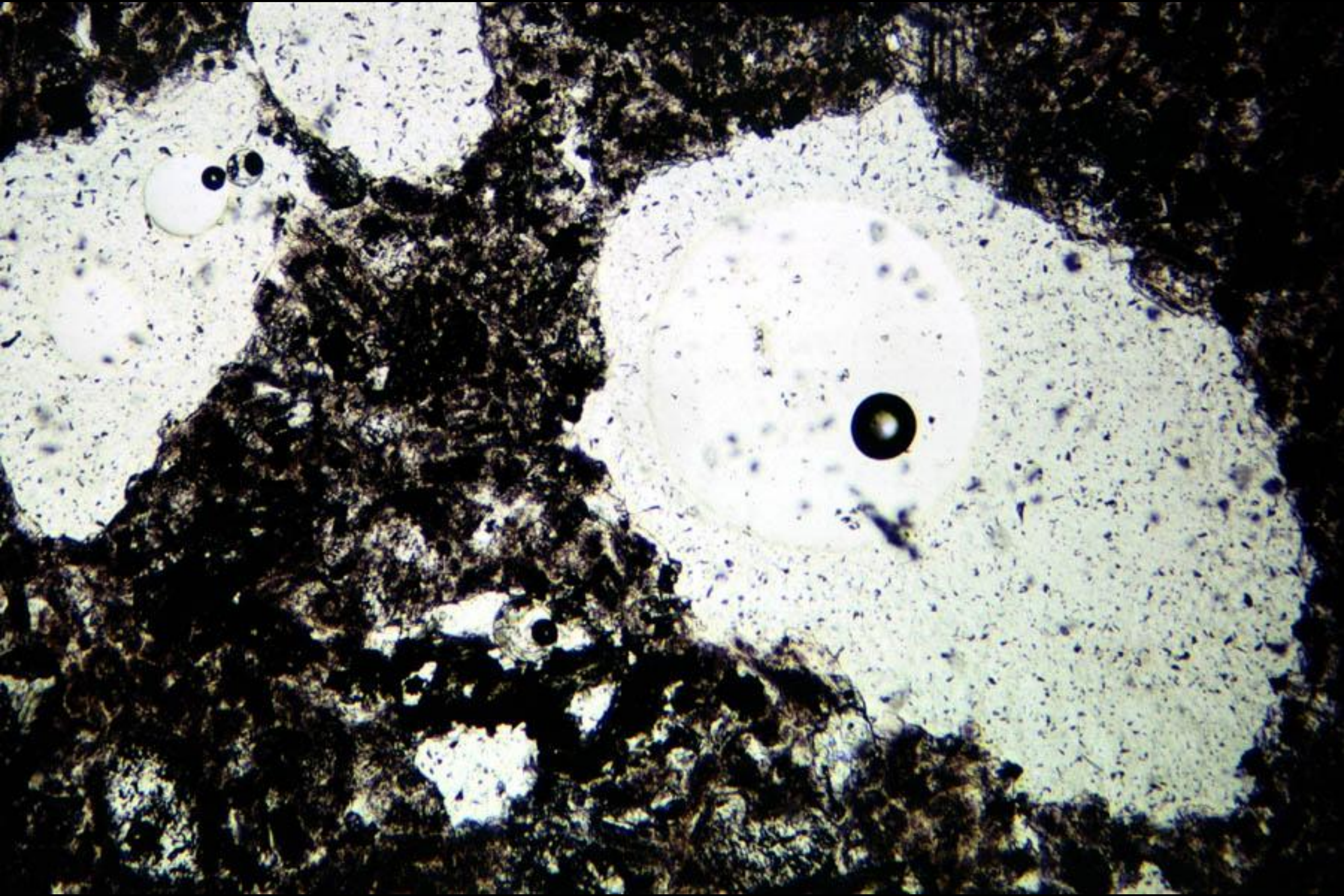


Q005C Zoned Hornblende Phenocryst PL

Q006C Zoned Hornblende Phenocryst PL



Q006C Zoned Biotite and Chlorite PL



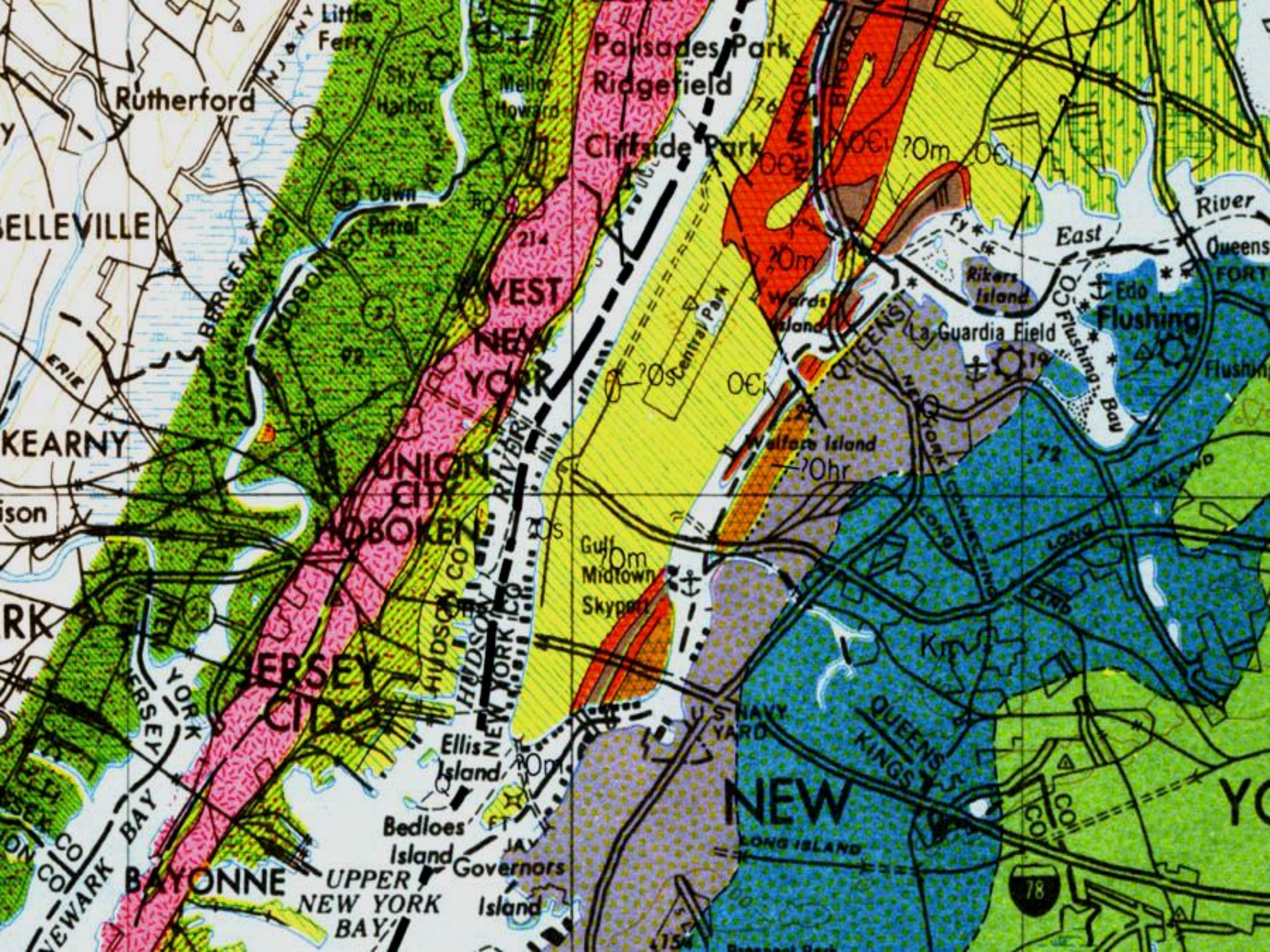
Major Lithologic Contrast

DEP Borings – QTL-13

Lava Flows in Woodside?

Queens Tunnel Complex

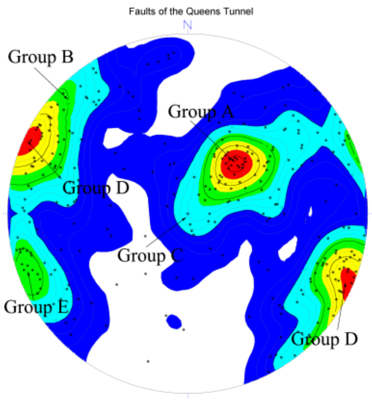
Brittle Faults



Little Ferry
Rutherford
Palisades Park
Ridgefield
Cliffside Park
Sky Harbor
Mellor
Howard
Dawn Patrol
BELLEVILLE
BERGEN CO
HUDSON CO
WEST NEW YORK
UNION CITY
HOBOKEN
KEARNY
JERSEY CITY
HUDSON CO
NEW YORK CO
HUDSON RIVER
Central Park
Wards Island
Welfare Island
Rikers Island
La Guardia Field
East River
Flushing
Flushing Bay
Queens
QUEENS
Gulf
Midtown
Skyport
U S NAVY YARD
Ellis Island
Bedloes Island
FT JAY
Governors Island
UPPER NEW YORK BAY
BAYONNE
NEWARK BAY
NEW
LONG ISLAND
QUEENS
KINGS
78

Brittle Faults

- Hundreds of faults mapped in five major groups
- From oldest to youngest:



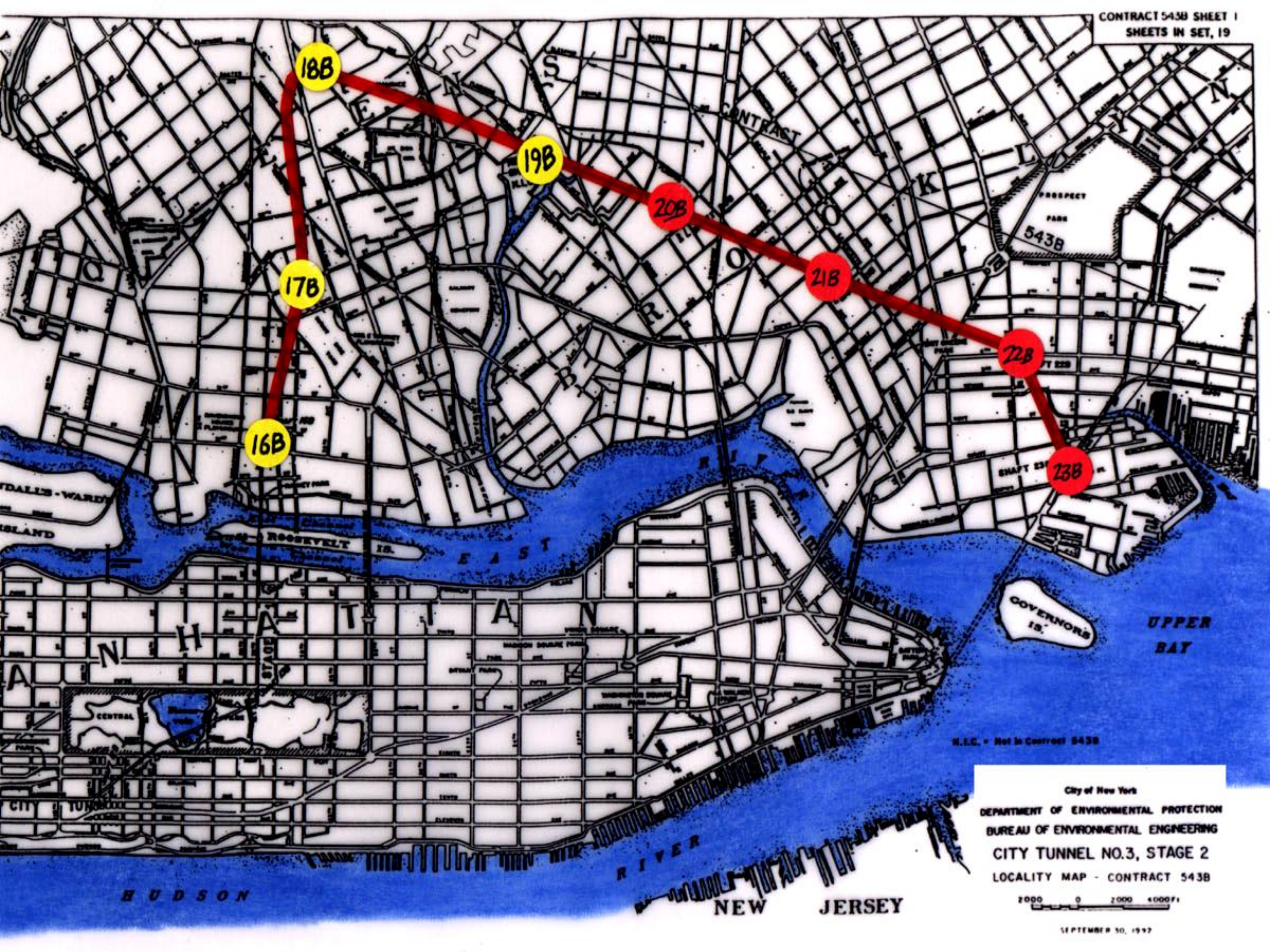
Group A = NW strike and gentle SW dip

Group B = ENE strike and steep dips

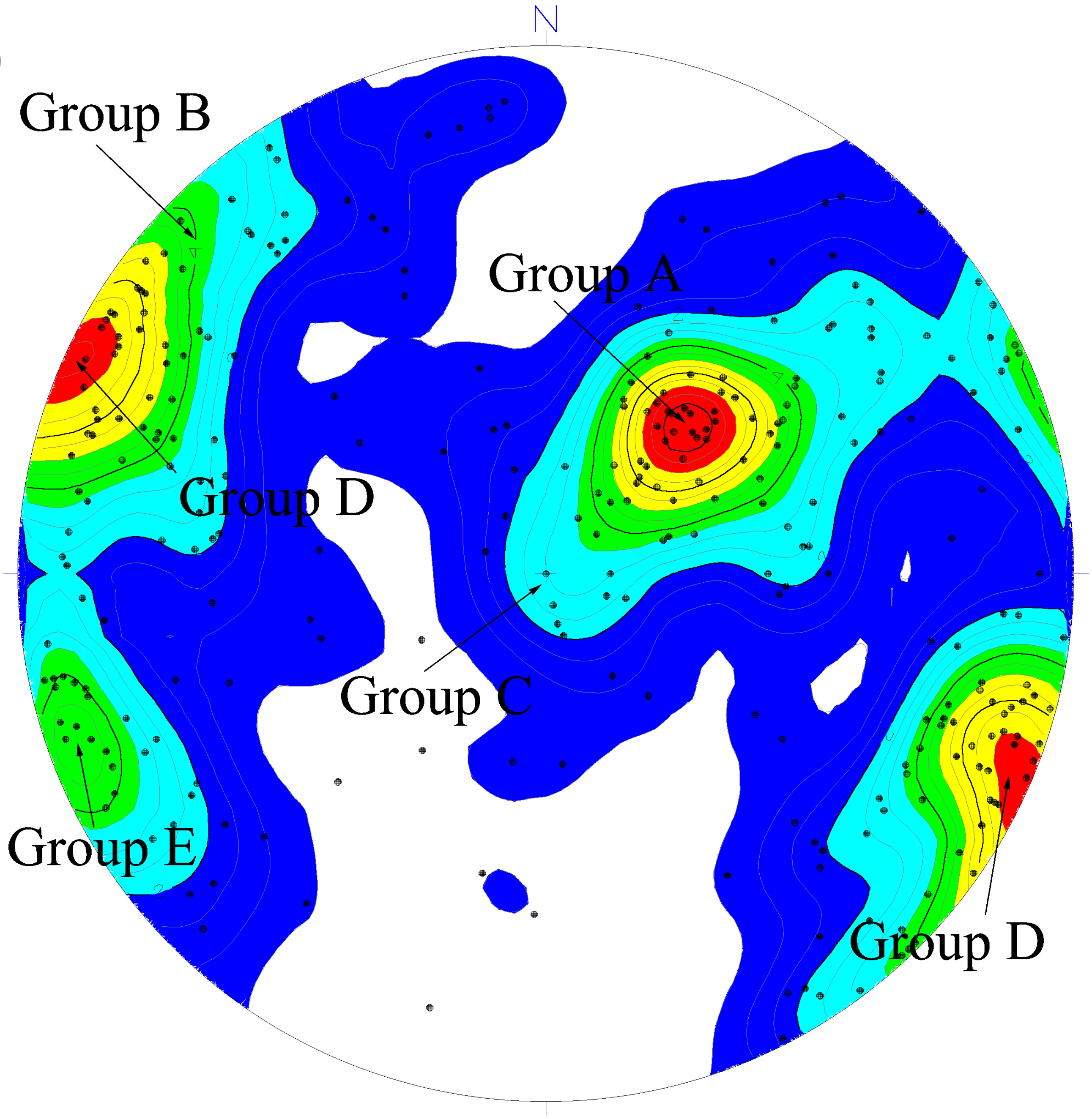
Group C = Subhorizontal fractures, faults, and shears

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

Group E = NNW-trending "Manhattanville" fault system


CONTRACT 543B SHEET 1
SHEETS IN SET, 19
16B
17B
18B
19B
20B
21B
22B
23B
543B
PROSPECT PARK
CONTRACT
ROOSEVELT IS.
EAST
RIVER
GOVERNORS IS.
UPPER BAY
HUDSON
RIVER
NEW JERSEY
CENTRAL
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
SEPTEMBER 30, 1997

QT Faults

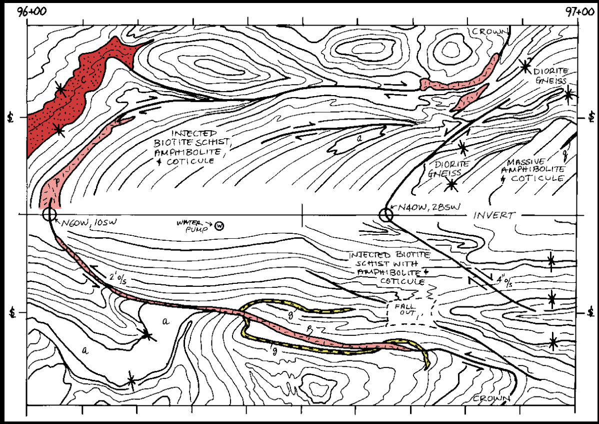


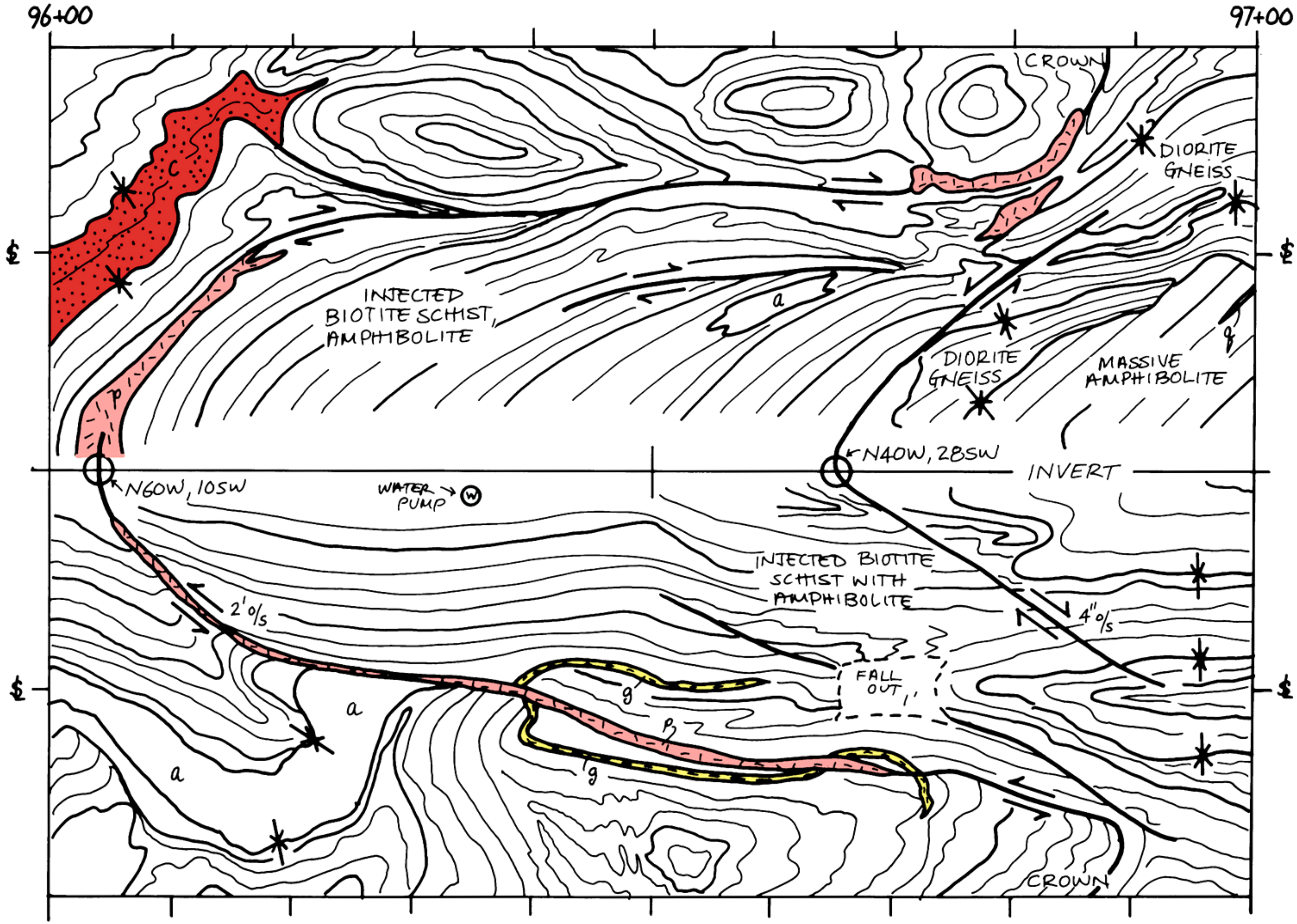
Ring Steel – Intersecting Faults

Zone 067b - Ring steel in sheared and highly faulted zones

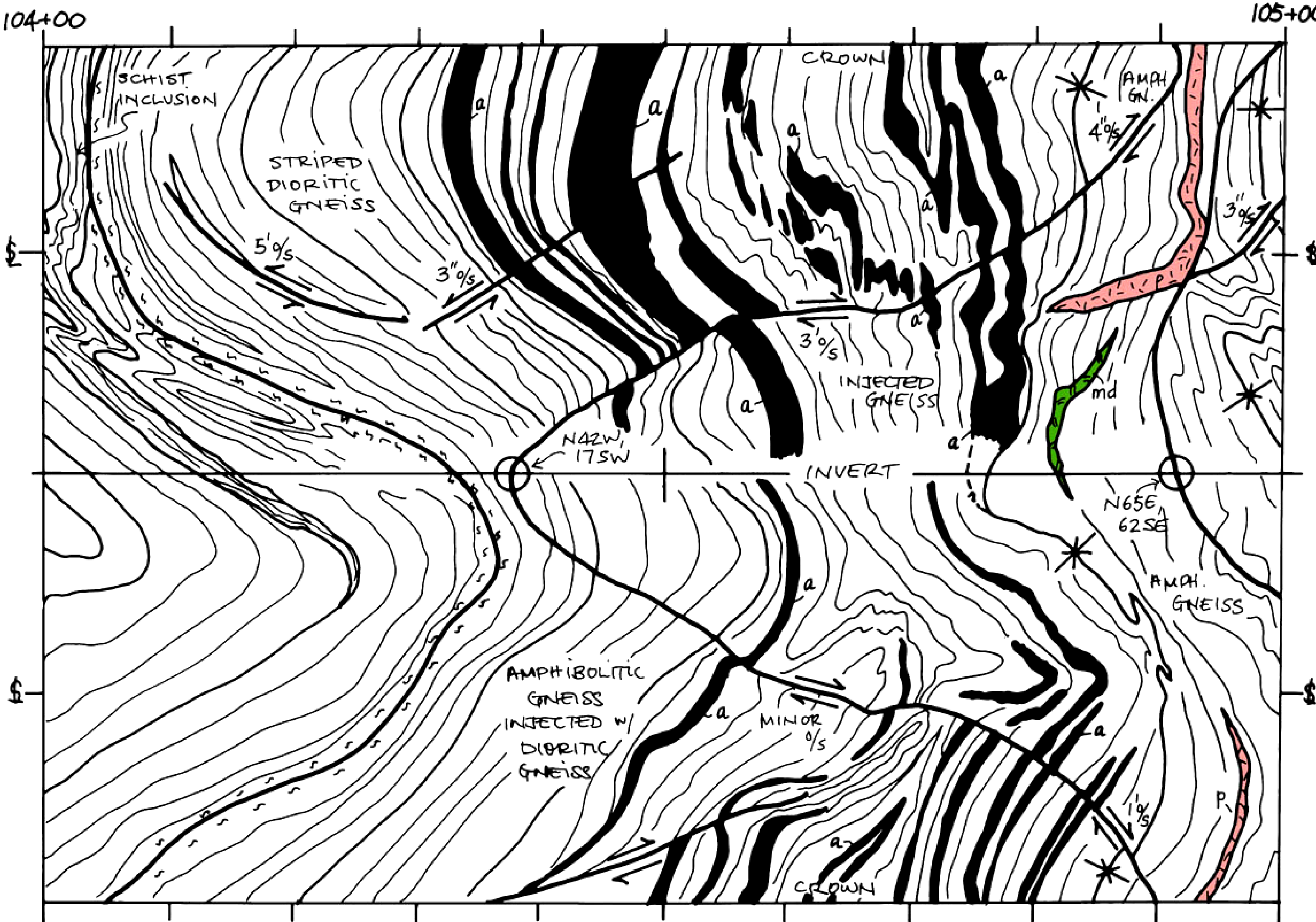
Gently-dipping Shear Zones of Group A

- NW strike and gentle SW dip
- Typically reactivate older ductile shears
- Thin zones of fault breccia and crush zones
- Commonly associated with sheared pegmatite intrusives
- Laterally extensive features that persist for 100s of feet
- Terminate by ramping steeply into crown and invert
- Wet features that resulted in collapsed tunnel heading





96+00
97+00
CROWN
DIORITE GNEISS
c
INJECTED BIOTITE SCHIST, AMPHIBOLITE
a
p
DIORITE GNEISS
MASSIVE AMPHIBOLITE
q
N40W, 28SW
INVERT
N60W, 10SW
WATER PUMP
W
INJECTED BIOTITE SCHIST WITH AMPHIBOLITE
2' o/s
4" o/s
FALL OUT
g
a
p
a
g
CROWN



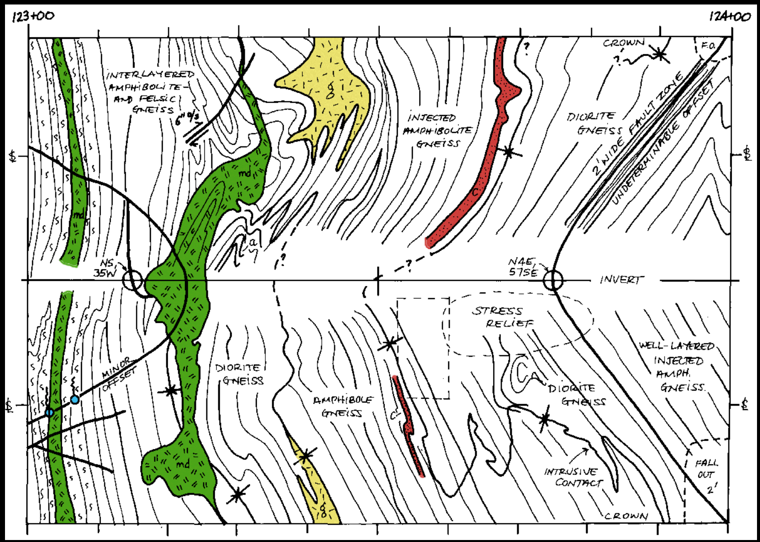
104+00
105+00
SCHIST INCLUSION
STRIPED DIORITIC GNEISS
5' o/s
3" o/s
CROWN
AMPH GN.
4" o/s
3" o/s
3' o/s
INJECTED GNEISS
md
N42W, 17SW
INVERT
N65E, 62SE
AMPH. GNEISS
AMPHIBOLITIC GNEISS INJECTED w/ DIORITIC GNEISS
MINOR o/s
1' o/s
P
CROWN

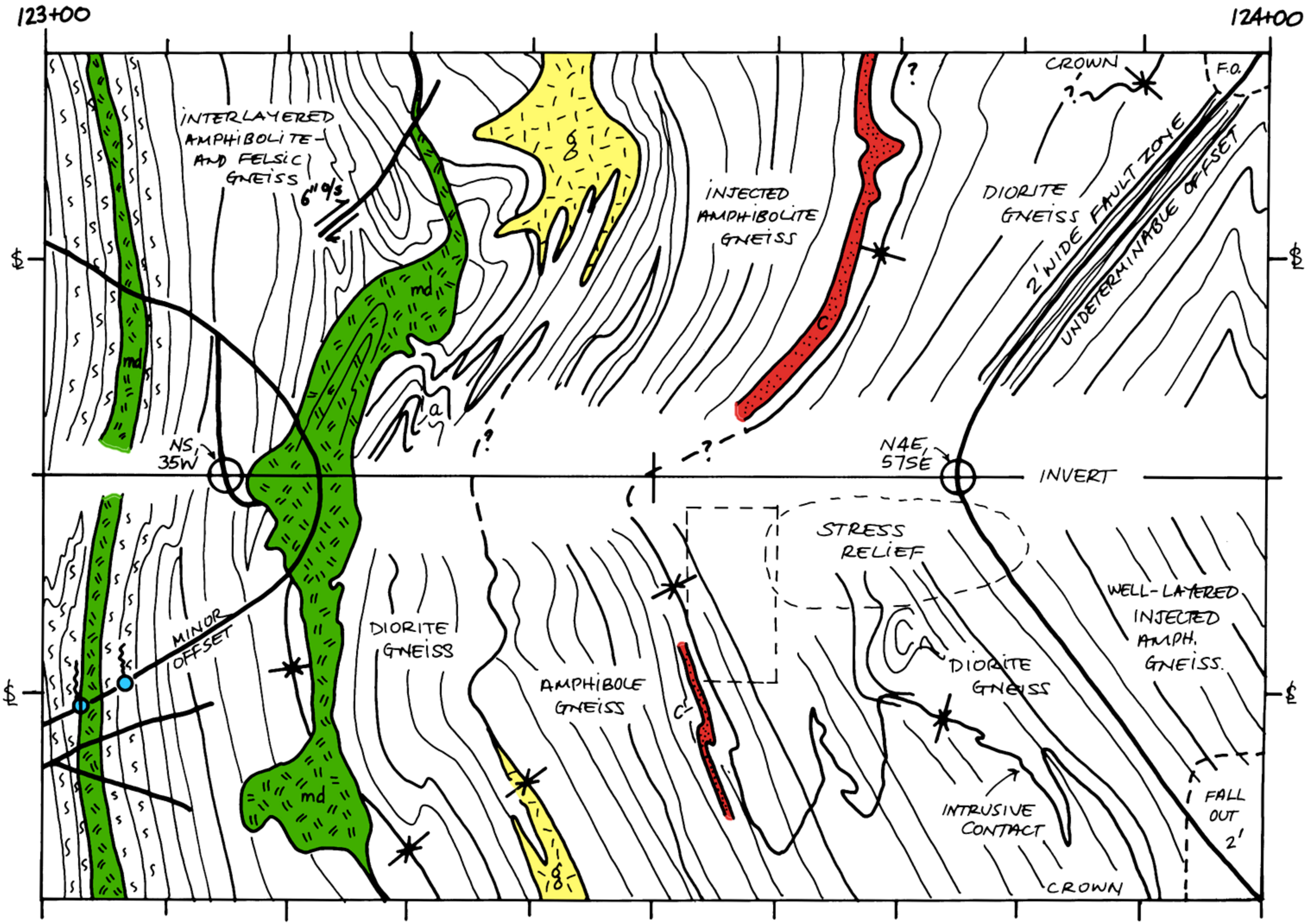
Gently Dipping NW-Trending Fault

Queens Tunnel Sta. 196+85

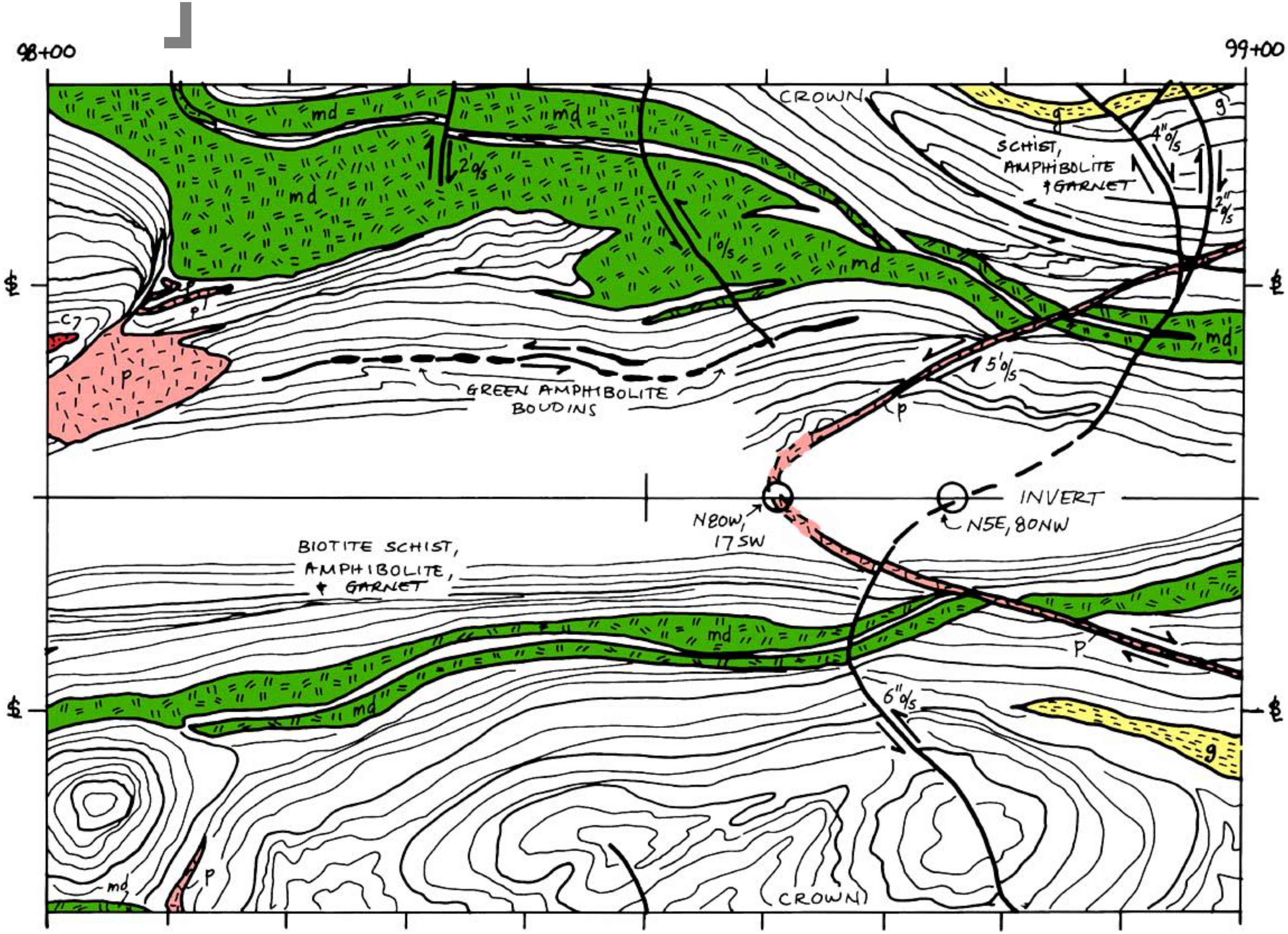
NNE-Trending Fault System of Group D

- NNE strike and steep dips; dip-slip mechanisms
- Thick zones of fault gouge and breccia
- Clay- and zeolite-rich gouge zones
- Relatively young – they cut 295 Ma rhyodacite dikes
- Reactivated by Group E "Manhattanville" faults
- Locally wet features in zones of fault convergence




123+00
124+00
INTERLAYERED AMPHIBOLITE- AND FELSIC GNEISS
6" o/s
g
md
a
INJECTED AMPHIBOLITE GNEISS
c
DIORITE GNEISS
2' WIDE FAULT ZONE
UNDETERMINABLE OFFSET
CROWN
F.O.
NS, 35W
N4E, 57SE
INVERT
STRESS RELIEF
MINOR OFFSET
DIORITE GNEISS
AMPHIBOLE GNEISS
WELL-LAYERED INJECTED AMPH. GNEISS.
INTRUSIVE CONTACT
FALL OUT 2'
CROWN

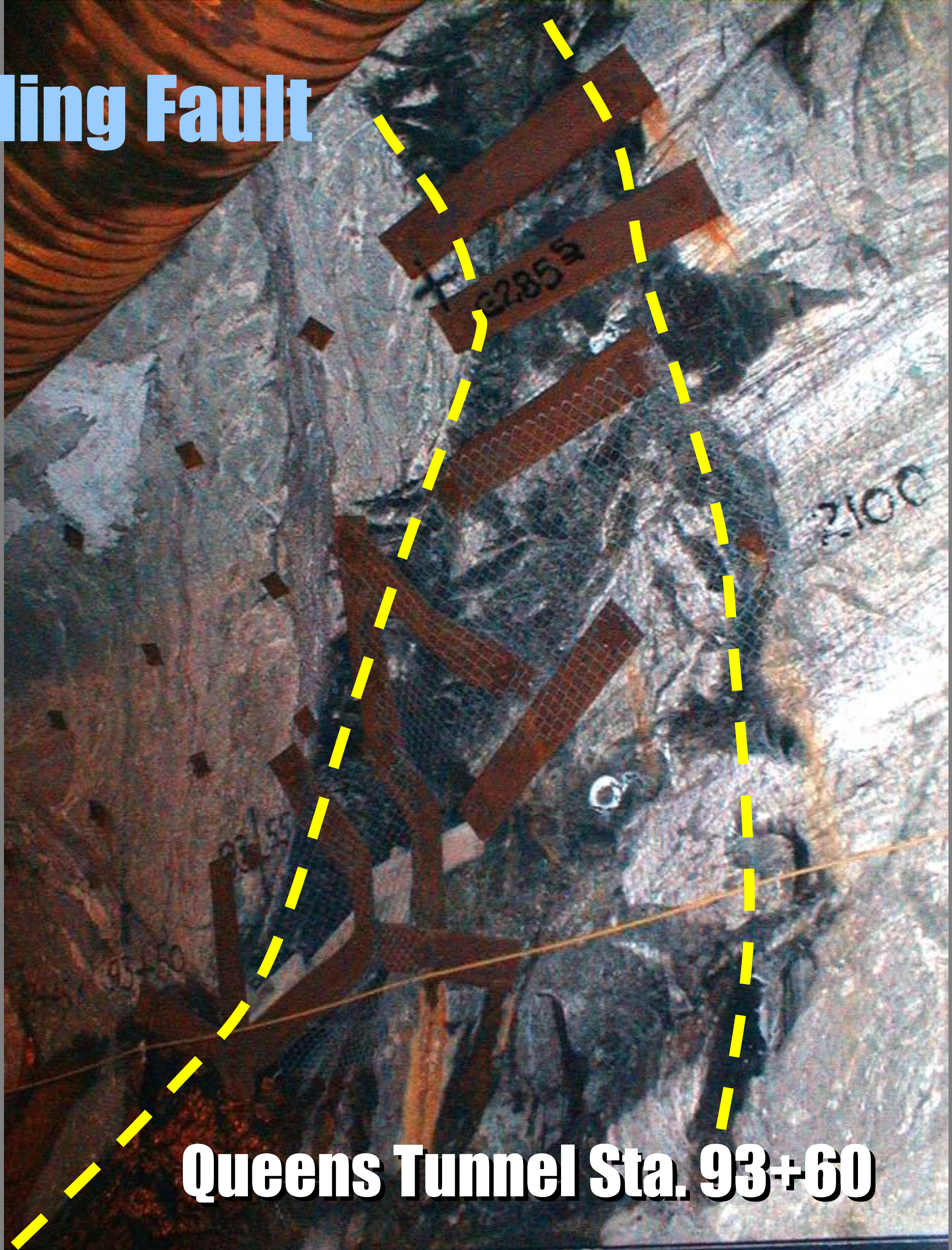
Zone 046b - Support required because of intersecting faults and joints.



98+00
99+00
CROWN
md
md
md
md
md
2'o/s
1'o/s
SCHIST,
AMPHIBOLITE
& GARNET
g
g
4"o/s
2"o/s
5'o/s
c
p
p
p
GREEN AMPHIBOLITE
BOUDINS
INVERT
N80W,
17SW
N5E, 80NW
BIOTITE SCHIST,
AMPHIBOLITE,
& GARNET
md
md
P
6"o/s
g
md
p
CROWN

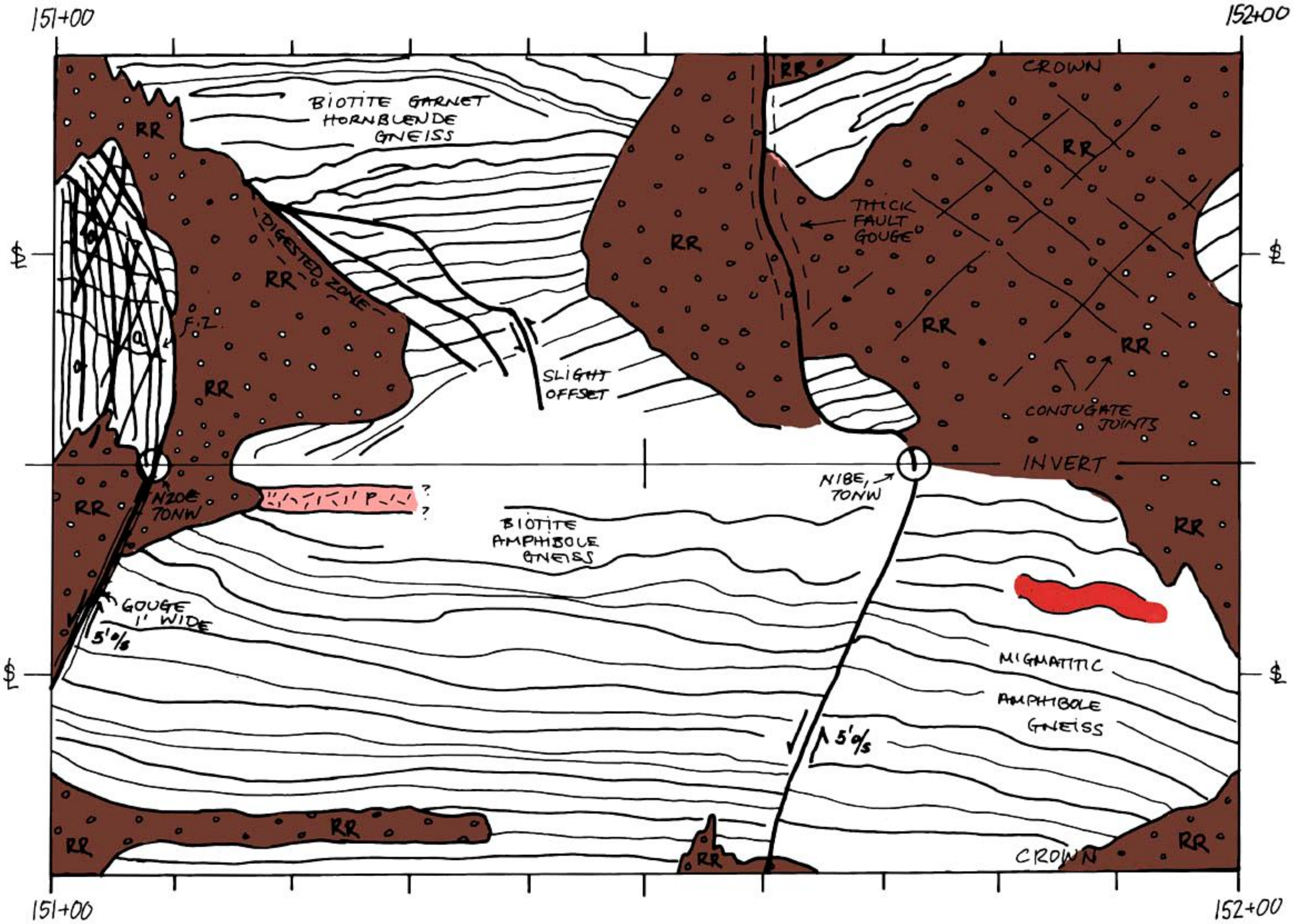

NW-Trending Fault Cut by NNE Fault
8’ Gouge
214+30
214+40
Queens Tunnel Sta. 214+25

NNE-Trending Fault



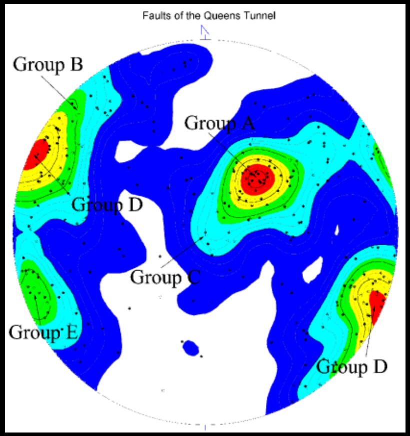
Queens Tunnel Sta. 93+60

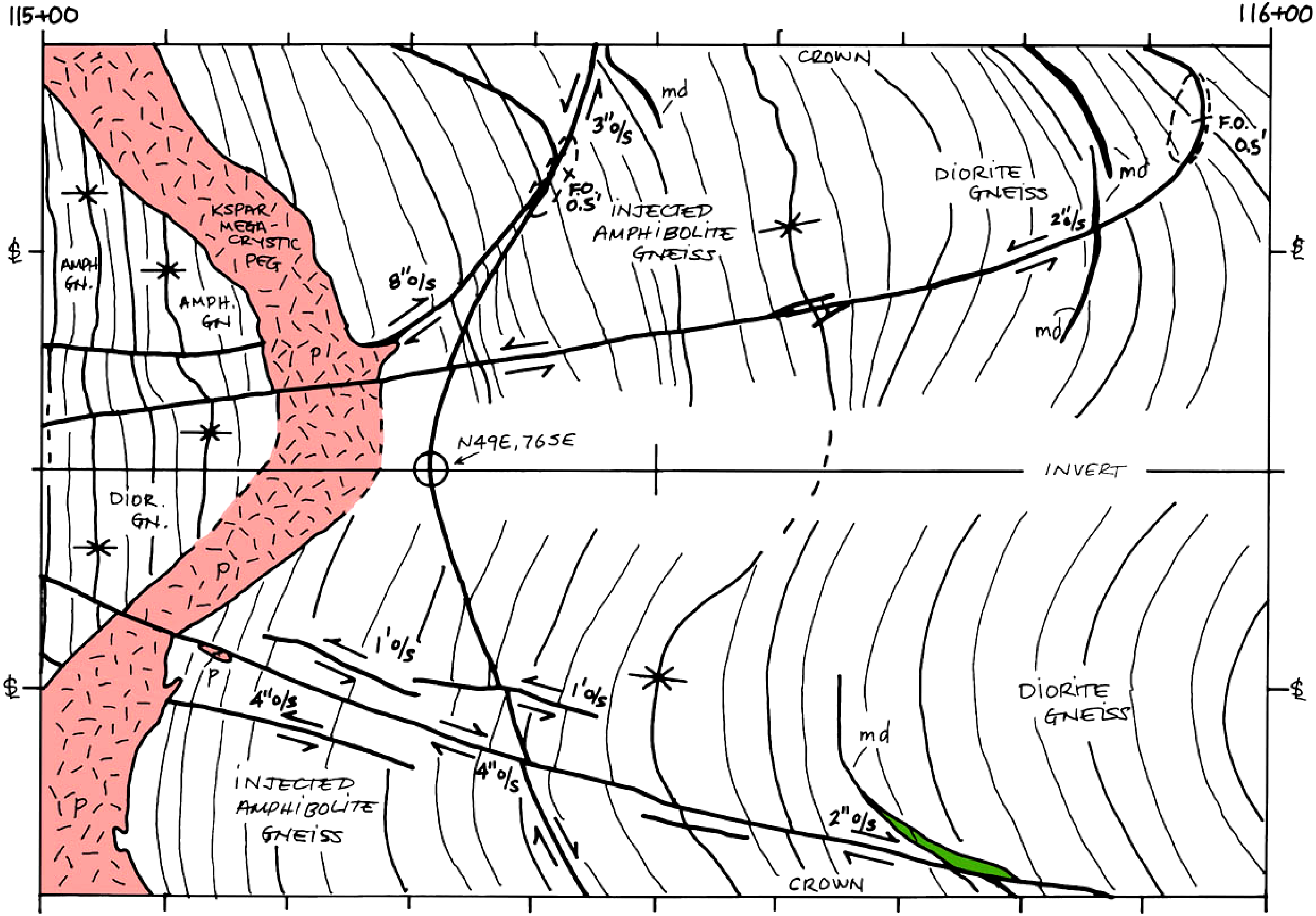

Station 130+40, Right Wall
Multidirectional cooling joints in rhyodacite


151+00
152+00
BIOTITE GARNET
HORNBLENDE
GNEISS
CROWN
RR
THICK
FAULT
GOUGE
DIGESTED ZONE
F.Z.
SLIGHT
OFFSET
CONJUGATE
JOINTS
INVERT
N20E
70NW
N18E
70NW
P
BIOTITE
AMPHIBOLE
GNEISS
GOUGE
1' WIDE
5' o/s
MIGMATITIC
AMPHIBOLE
GNEISS
CROWN
151+00
152+00

NNW-Trending Fault System of Group E

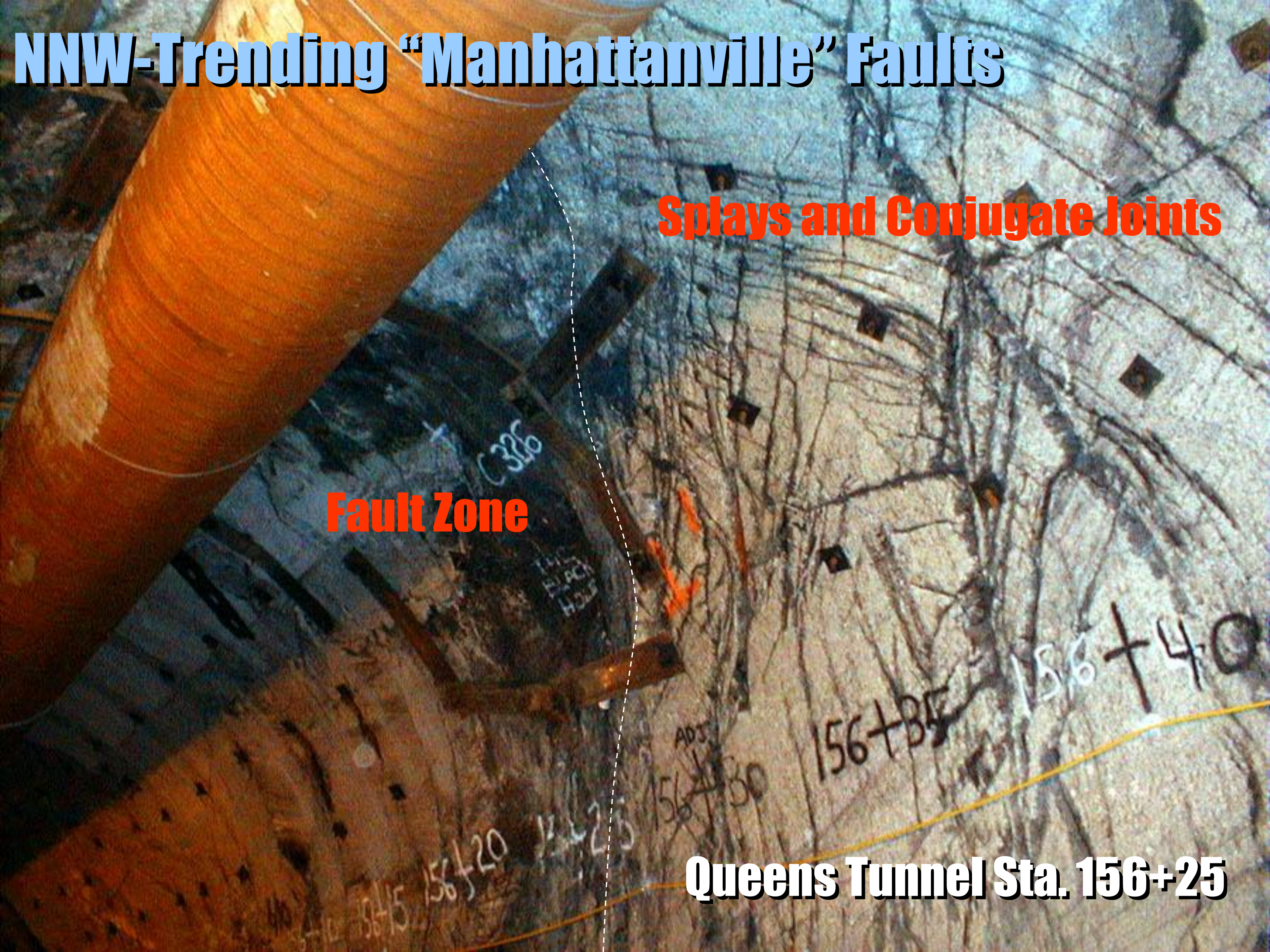
- NNW strike and steep dips; strike-slip offset
- Highly fractured zones with quartz veining and pyrite
- Youngest fault group – they cut all tunnel structures
- Persistent features in NW-leg of tunnel
- Reactivate many older faults
- Overprint dip-slip slickensides
- Associated with areas of stress relief
- Produce wet zones in areas of fault convergence





115+00
116+00
CROWN
md
3" o/s
F.O. 0.5'
F.O. 0.5'
md
DIORITE GNEISS
KSPAR MEGA CRYSTIC PEG
INJECTED AMPHIBOLITE GNEISS
2" o/s
AMPH GN.
AMPH. GN
8" o/s
p
md
N49E, 76SE
INVERT
DIOR. GN.
p
1' o/s
1' o/s
p
4" o/s
DIORITE GNEISS
md
4" o/s
INJECTED AMPHIBOLITE GNEISS
p
2" o/s
CROWN

NNW-Trending "Manhattanville" Faults




Stress Relief Adjacent to "Manhattanville" Fault
Queens Tunnel Sta. 249+50
CM

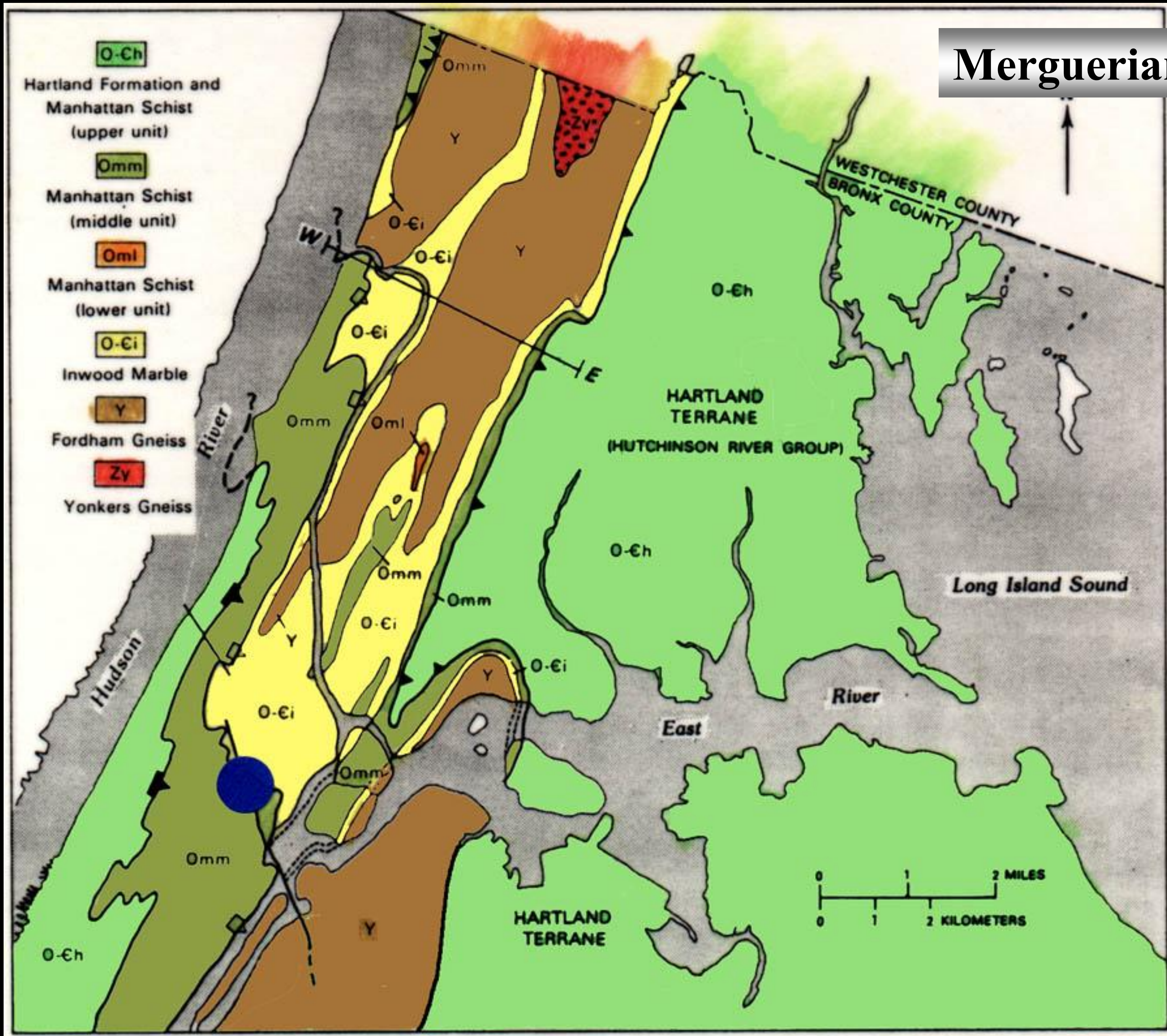

Crown Failure in Overstressed Rock
Queens Tunnel Sta. 253+40

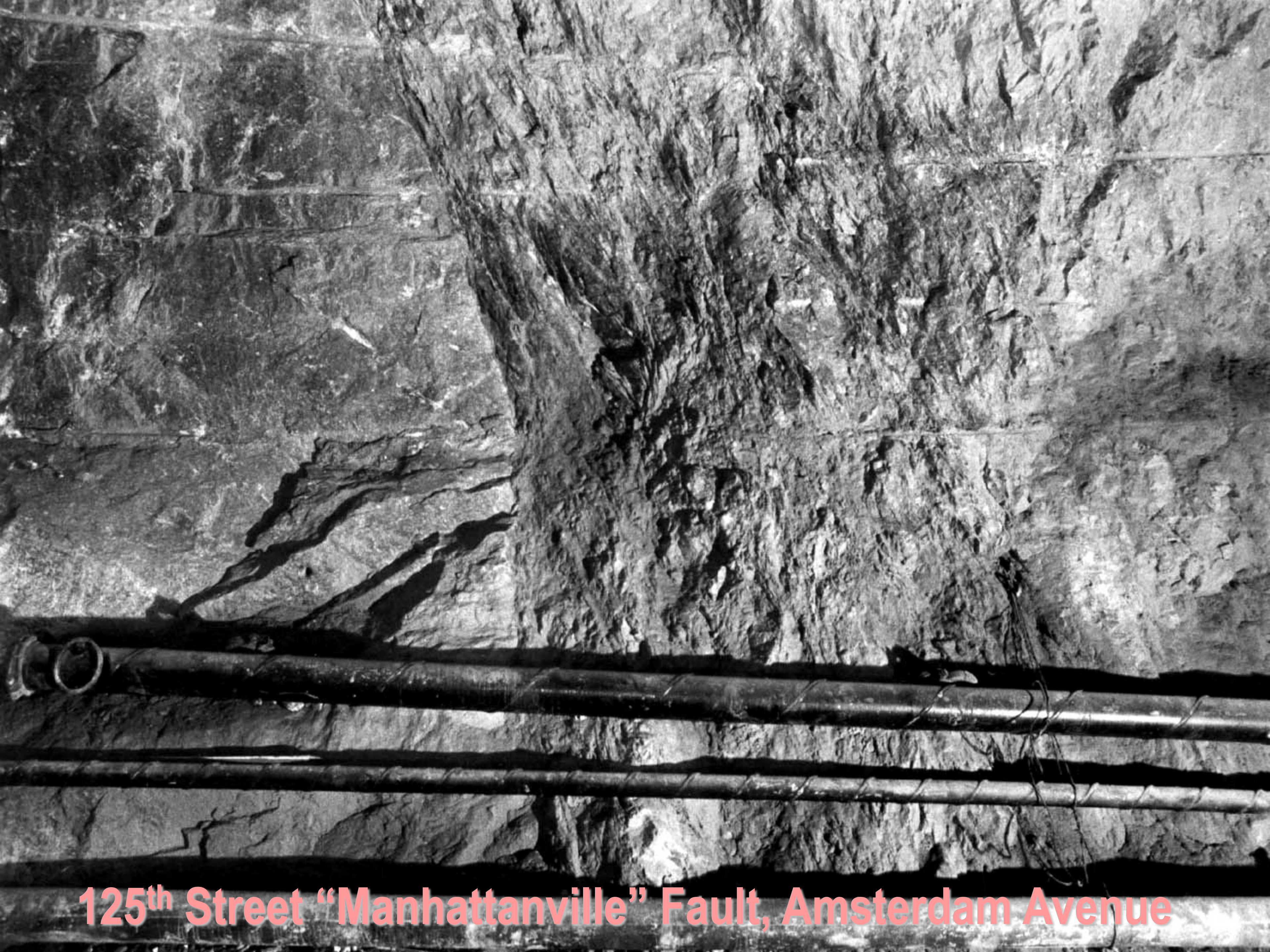
Zone 067b - Ring steel in sheared and highly faulted zones


It’s Not My Fault! He put me up to this!

Summary – QT Low Penetration

- **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
- **Collapsing face, crown, and sidewalls forced installation of additional support because of:**
  - Massive ground cut by >300 fractured (faulted) zones
  - Rhyodacite cooling fracture pattern and contact effects
  - Broad zones of subhorizontal fabrics and shear zones


Merguerian, 2002
O-Ꞓh
Hartland Formation and Manhattan Schist (upper unit)
Omm
Manhattan Schist (middle unit)
Oml
Manhattan Schist (lower unit)
O-Ꞓi
Inwood Marble
Y
Fordham Gneiss
Zy
Yonkers Gneiss
WESTCHESTER COUNTY
BRONX COUNTY
HARTLAND TERRANE
(HUTCHINSON RIVER GROUP)
Long Island Sound
East River
Hudson River
HARTLAND TERRANE
0 1 2 MILES
0 1 2 KILOMETERS
W
E

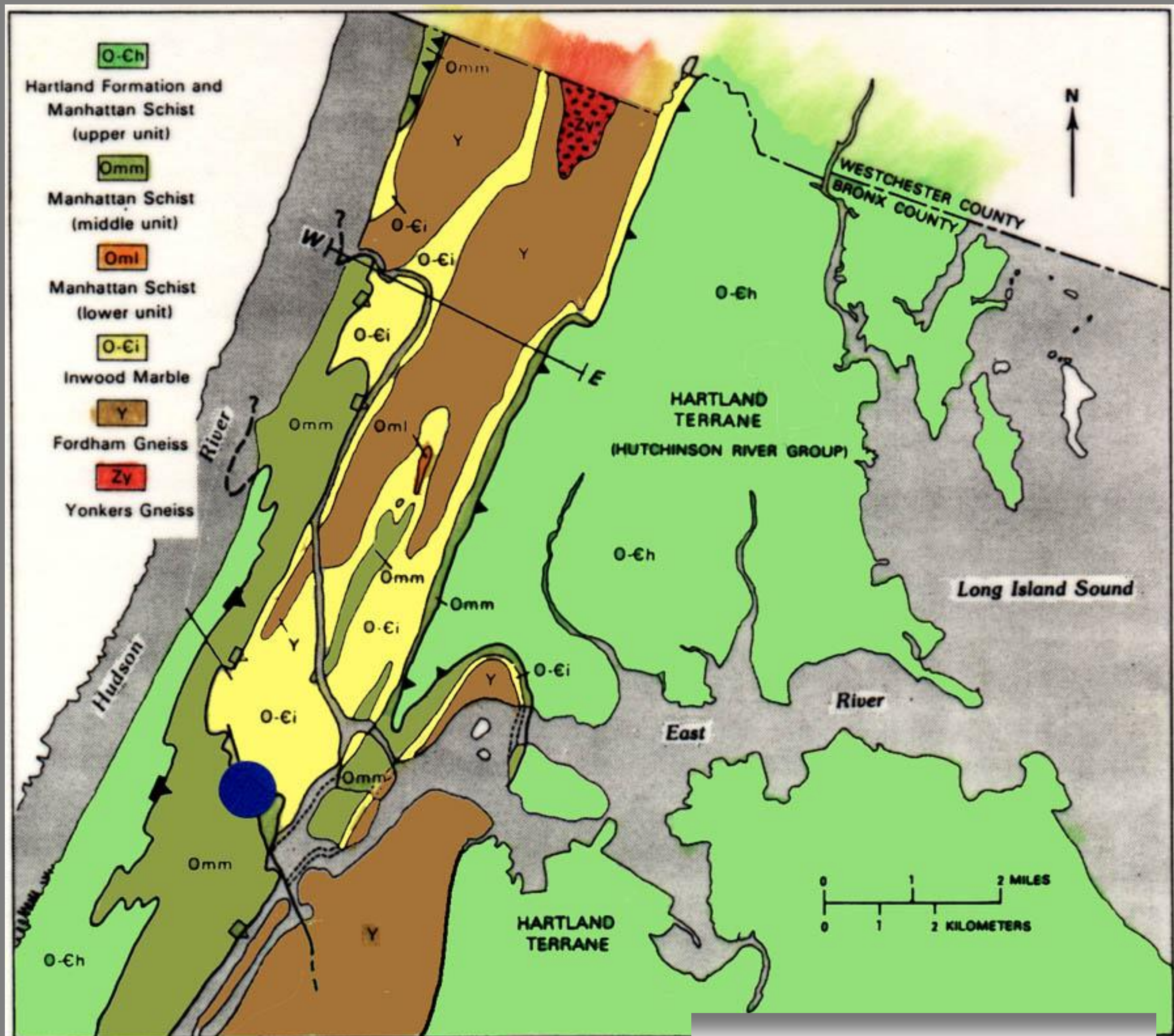


125th Street "Manhattanville" Fault, Amsterdam Avenue

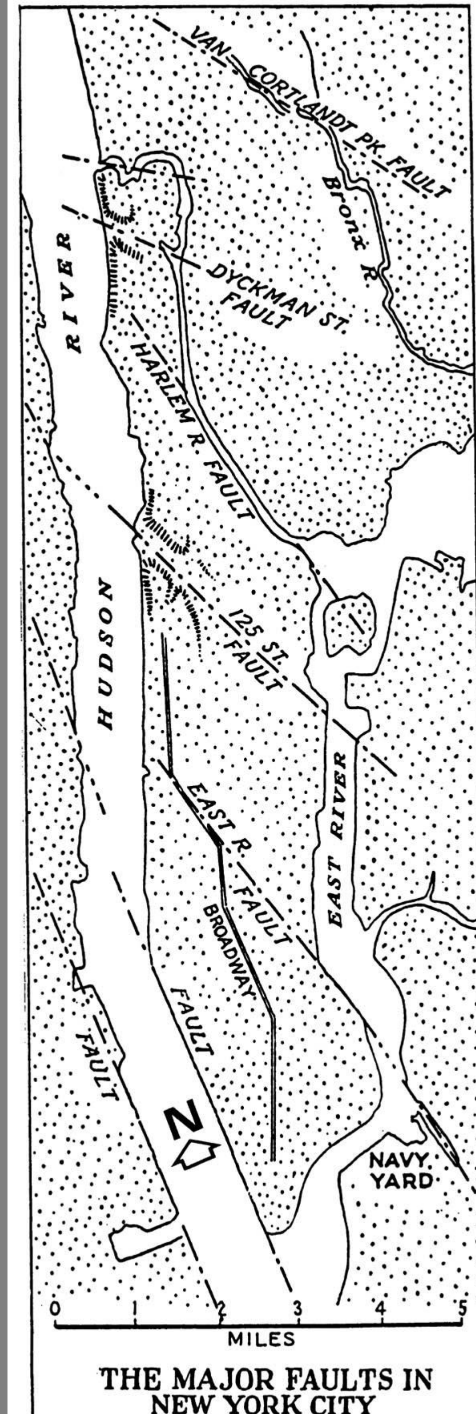
125th Street Fault

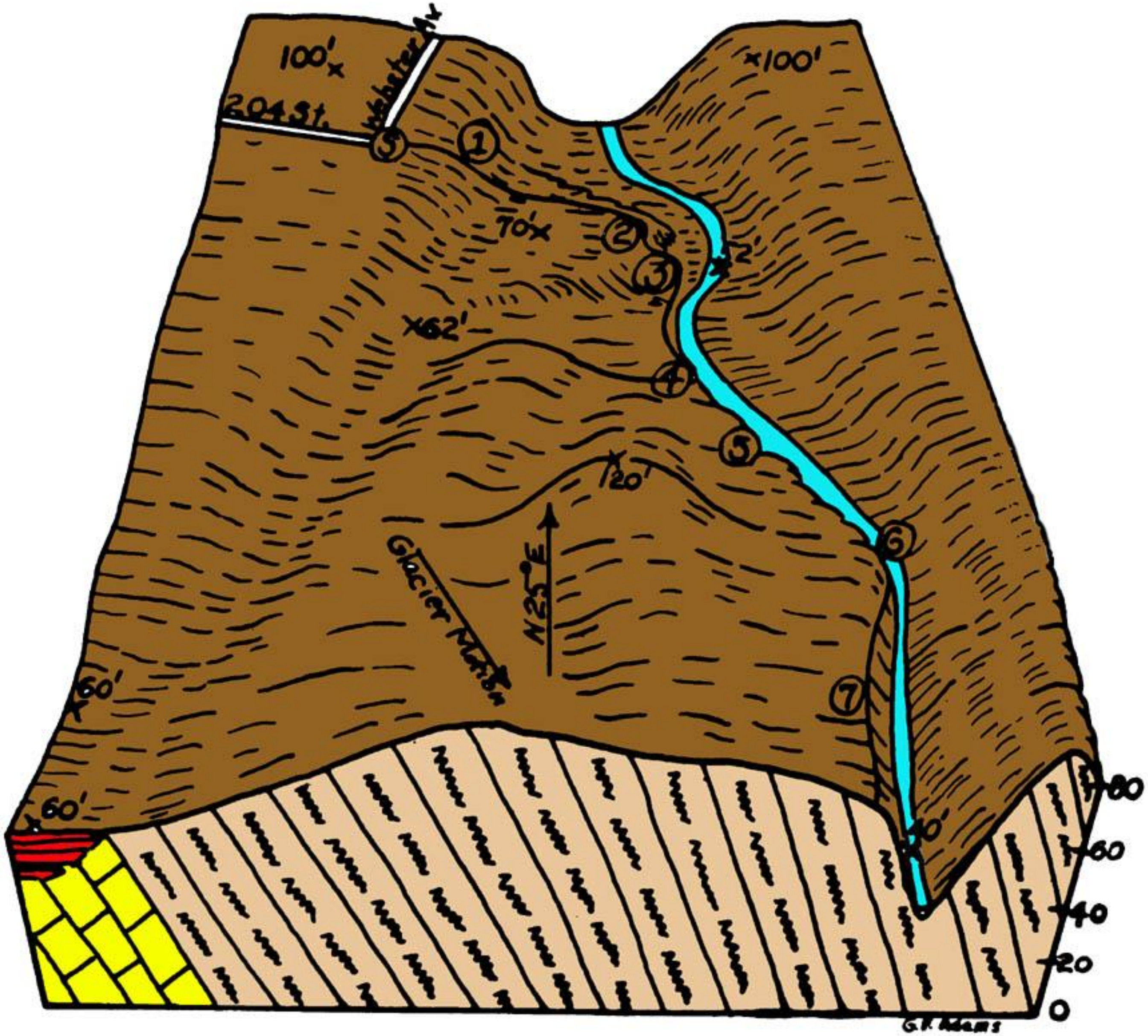
Examined on 30 May and 02 July 1985
150 m wide zone of highly fractured rock
2-3 m wide zones of fault breccia
Large blocks show right-lateral rotation in crown
NW strike and steep SW dip
Steep SE-plunging slickensides overprinted by subhorizontal slicks
Thus, reverse oblique slip offset is indicated

NW-Trending "Manhattanville" Faults



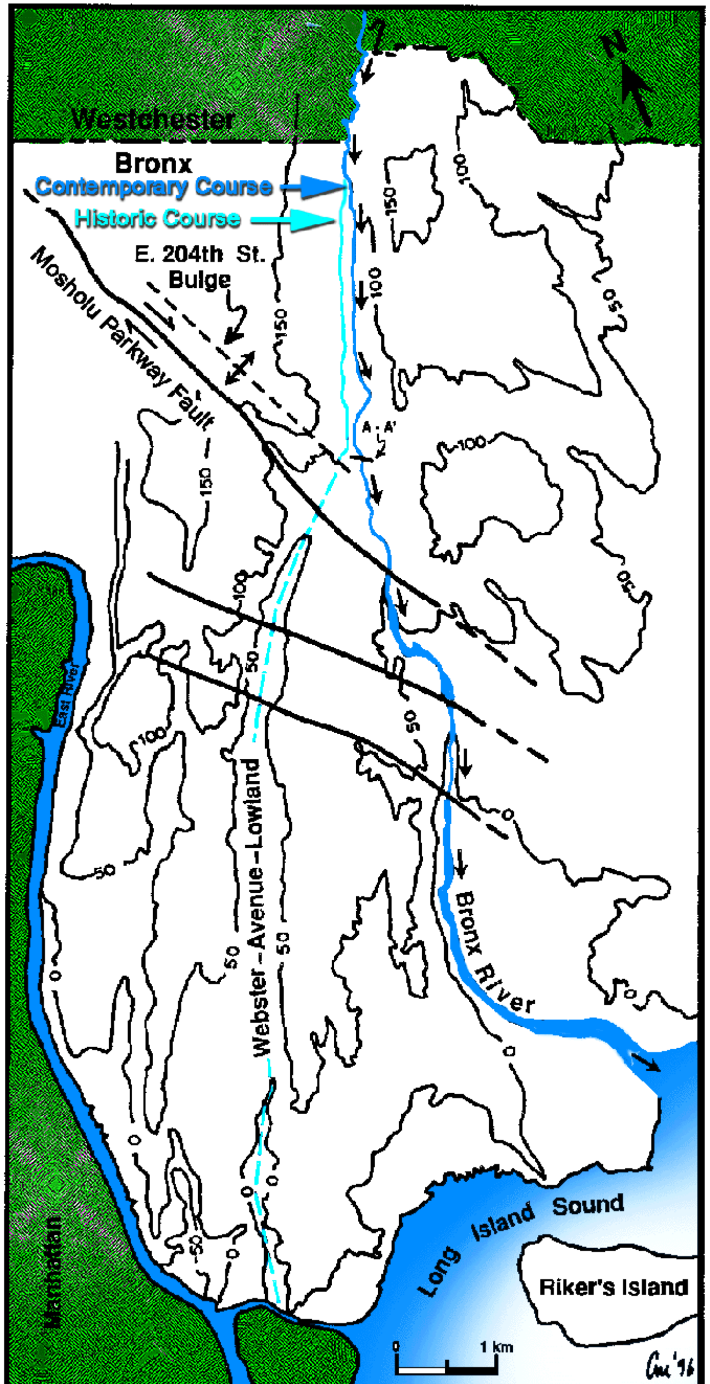
Merguerian, 2002





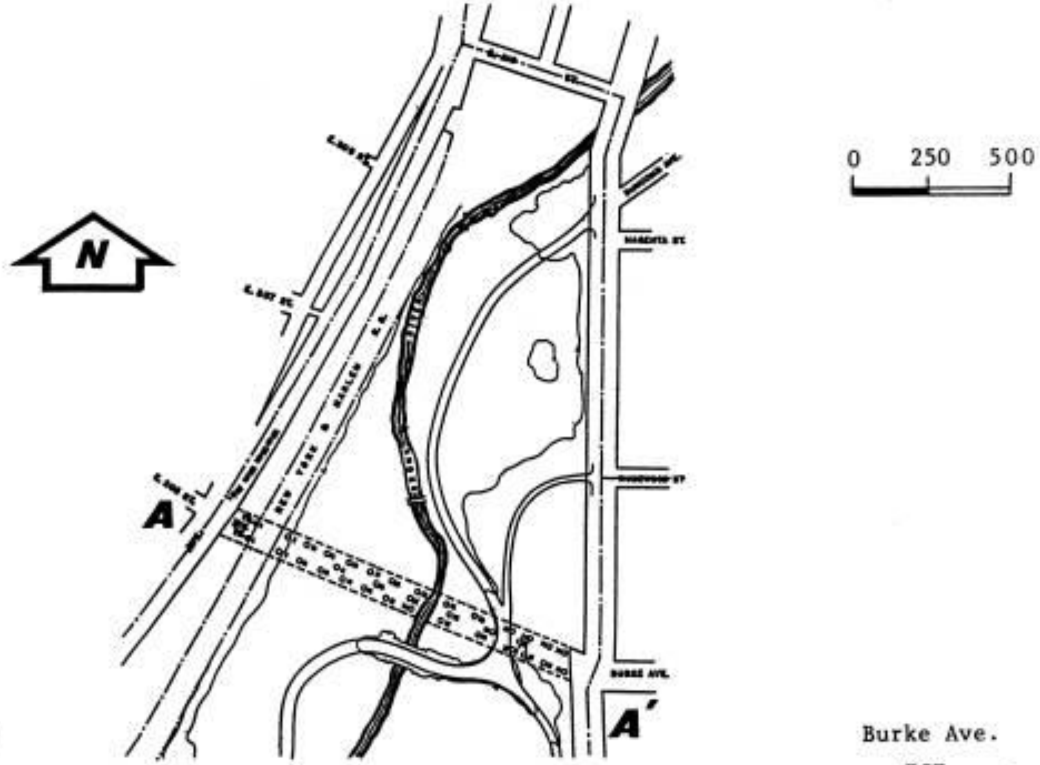
BRONX BOTANICAL GARDENS

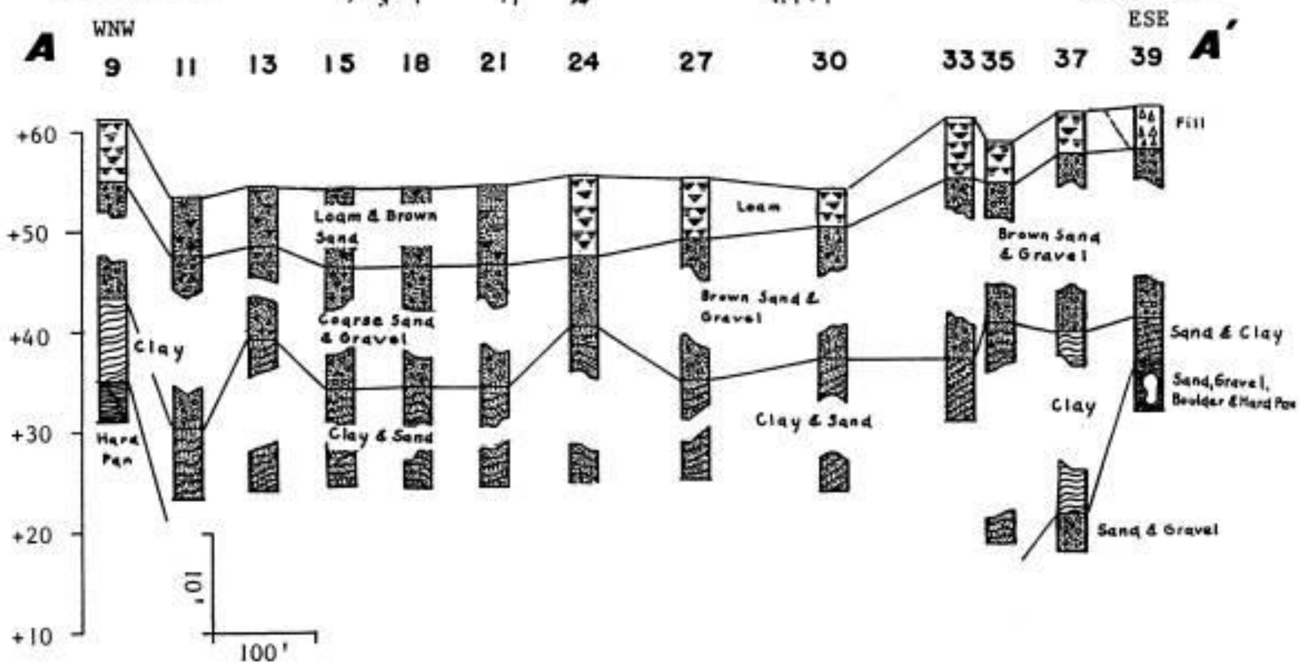
V-Shaped Bronx River Valley at Snuff Mill, NY Botanical Gardens

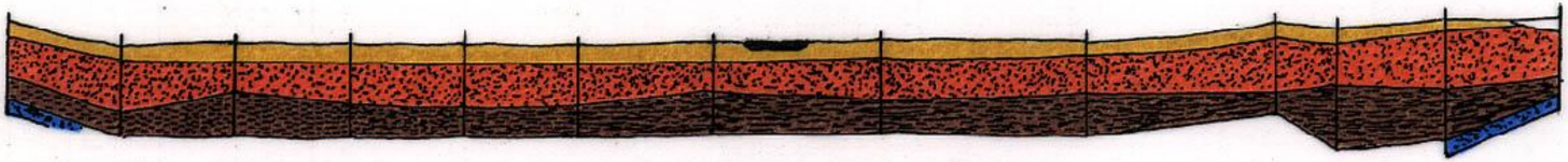


Westchester
Bronx
Contemporary Course
Historic Course
E. 204th St. Bulge
Mosholu Parkway Fault
A - A'
East River
Webster - Avenue - Lowland
Bronx River
Long Island Sound
Riker's Island
Manhattan
N
0
1 km
150
100
50
0

Mosholu Fault, Bronx, NY

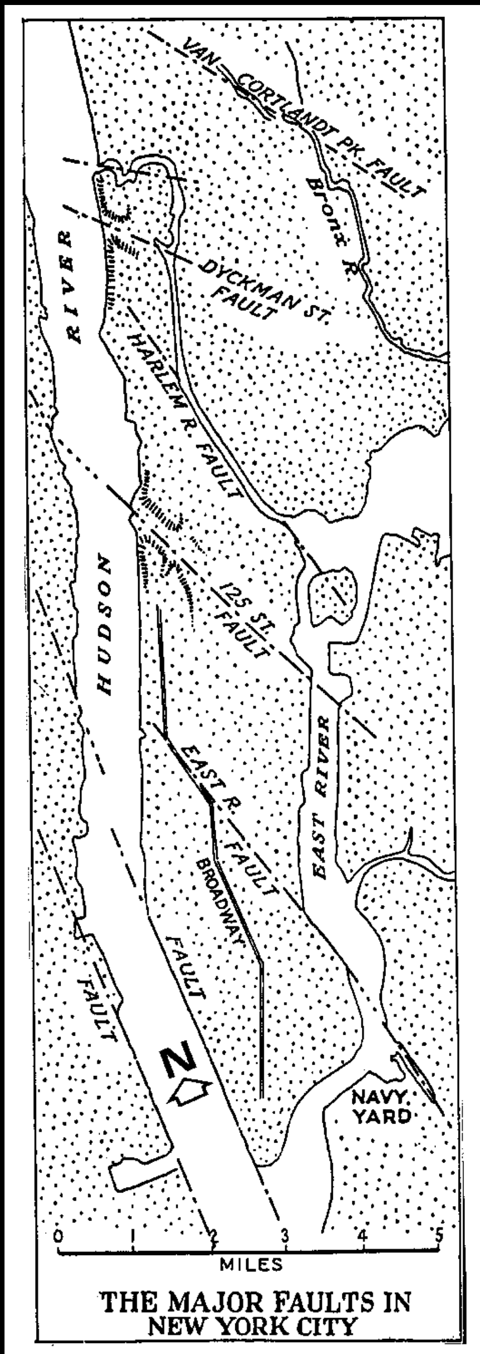

N
0 250 500'
A
A'

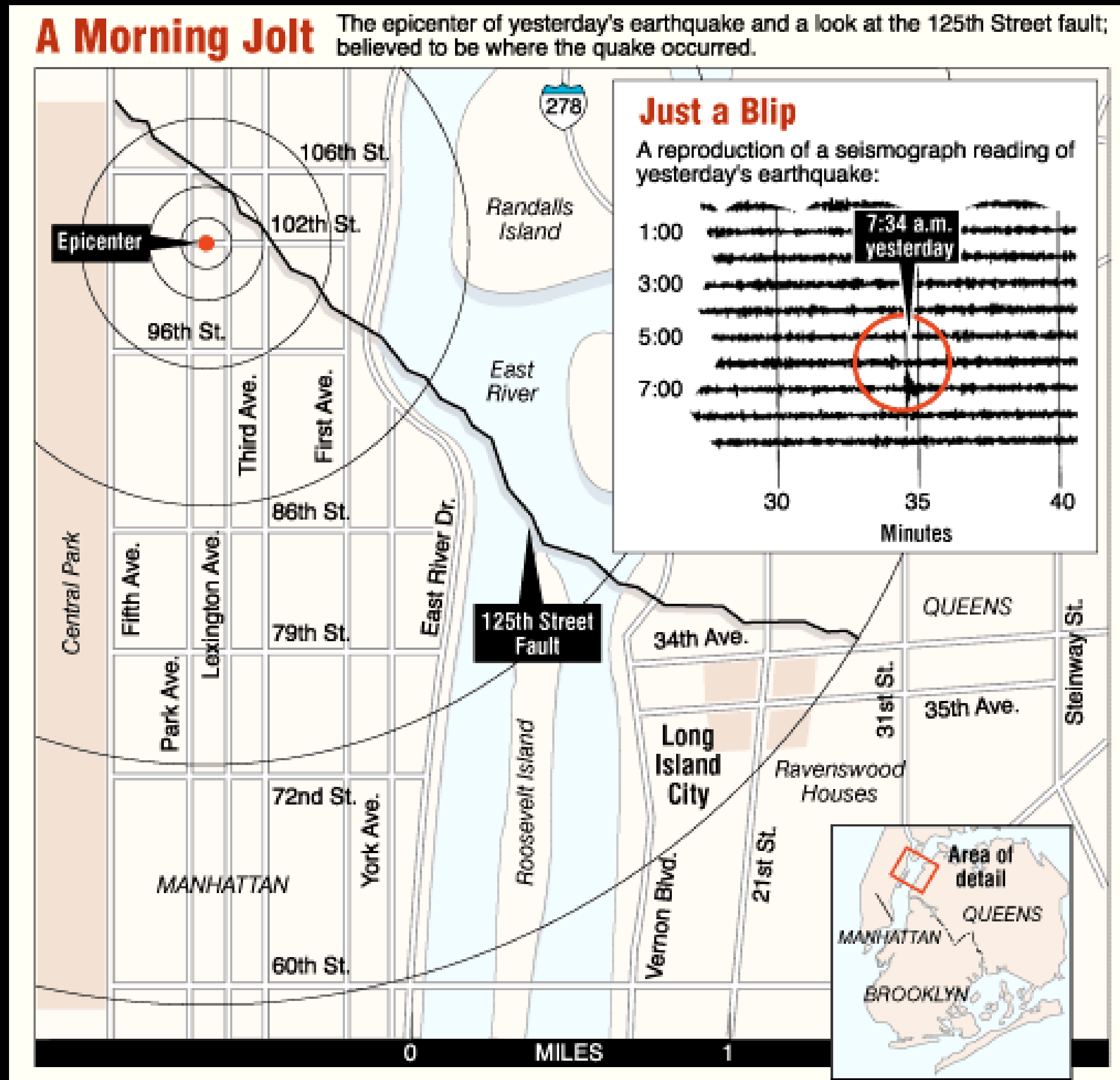

E. 205th St.
Burke Ave.
WNW
ESE
A
A'
9 11 13 15 18 21 24 27 30 33 35 37 39
+60
+50
+40
+30
+20
+10
Fill
Loam & Brown Sand
Loam
Brown Sand & Gravel
Brown Sand & Gravel
Coarse Sand & Gravel
Clay
Clay & Sand
Clay & Sand
Sand & Clay
Sand, Gravel, Boulder & Hard Pan
Clay
Hard Pan
Sand & Gravel
10'
100'



N66W Right Lateral S/S Fault, So. Twin Is., NY

17 January 2001, M = 2.4





A New York City Earthquake
Can it Happen Here? YES

1737

1884

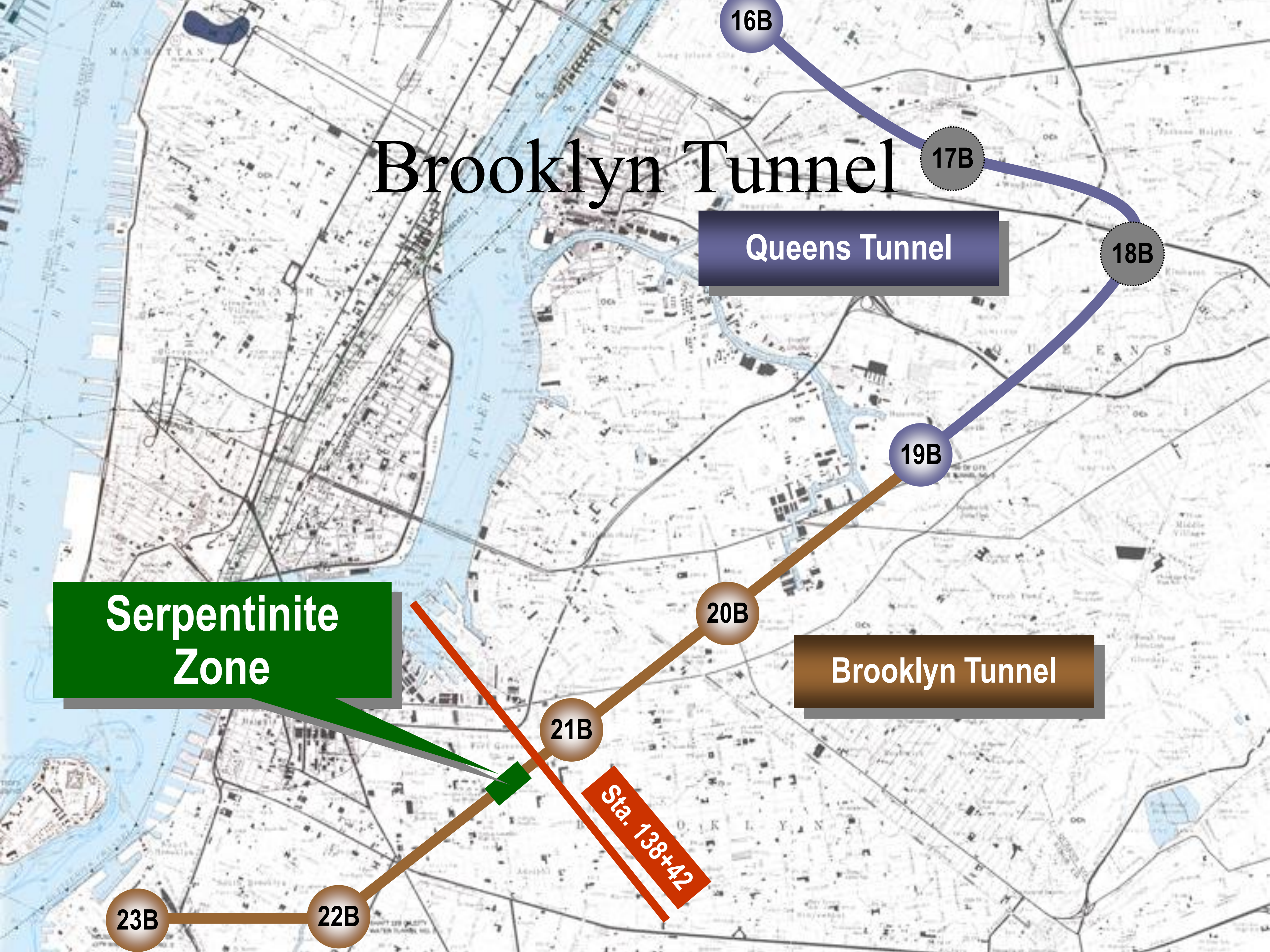
20??

How Well Will NYC Withstand A Moderate Earthquake?

How is NYC Built?

Extra Slides

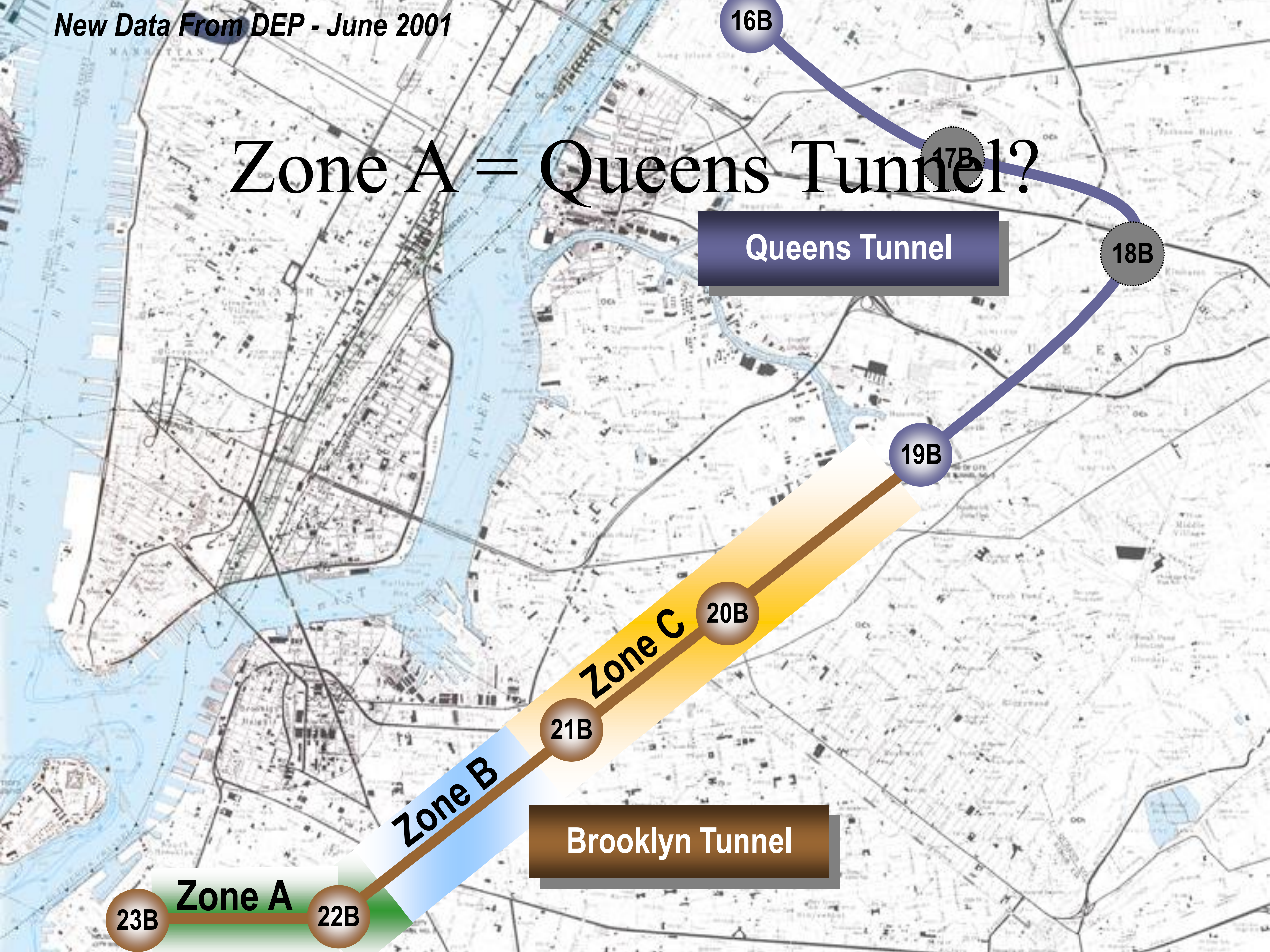
Brooklyn Tunnel




Major Serpentinite Zone
Brooklyn Tunnel – Sta. 128+30

New Data From DEP - June 2001

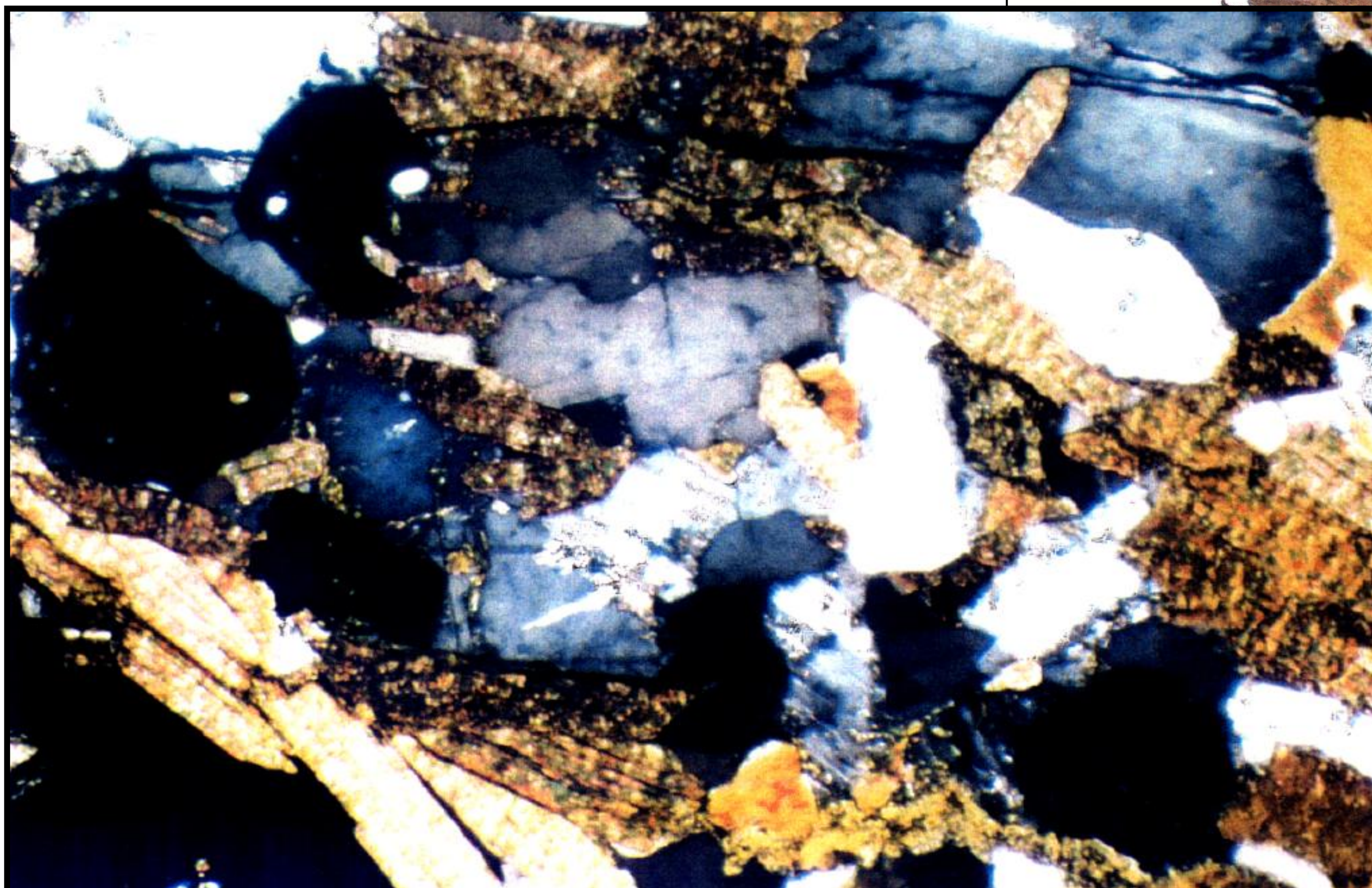
Zone A = Queens Tunnel?

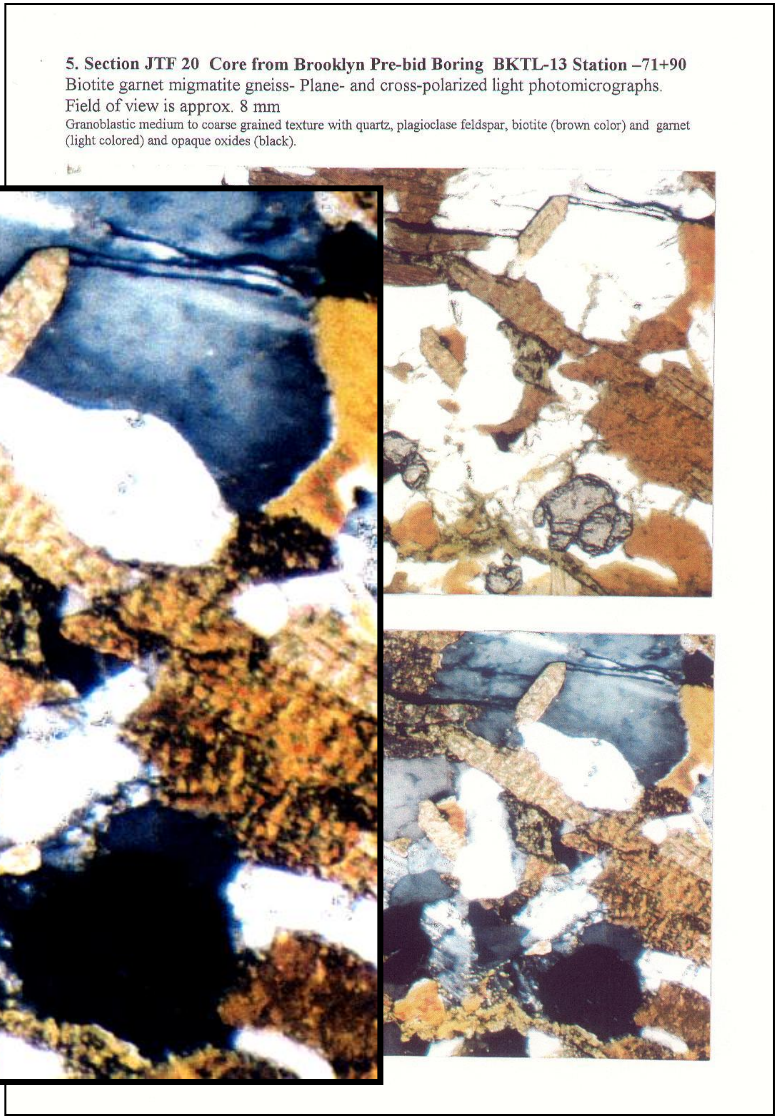


New Data From Brooklyn Tunnel

- DEP Petrographic Analysis

Biotite Foliation (Zone A)





5. Section JTF 20 Core from Brooklyn Pre-bid Boring BKTL-13 Station –71+90
Biotite garnet migmatite gneiss- Plane- and cross-polarized light photomicrographs.
Field of view is approx. 8 mm
Granoblastic medium to coarse grained texture with quartz, plagioclase feldspar, biotite (brown color) and garnet (light colored) and opaque oxides (black).

Source: DEP Response, App. 11, Rpt. 2

New Data From Brooklyn Tun

- **DEP modal analysis proves grea foliation in Zone A**

Table: 2 Modes Volume % of rocks from Brooklyn Tunnel

JTF TS=Jenny Thin section;PTS*=Jenny Polished thin section; [ ] = No TS

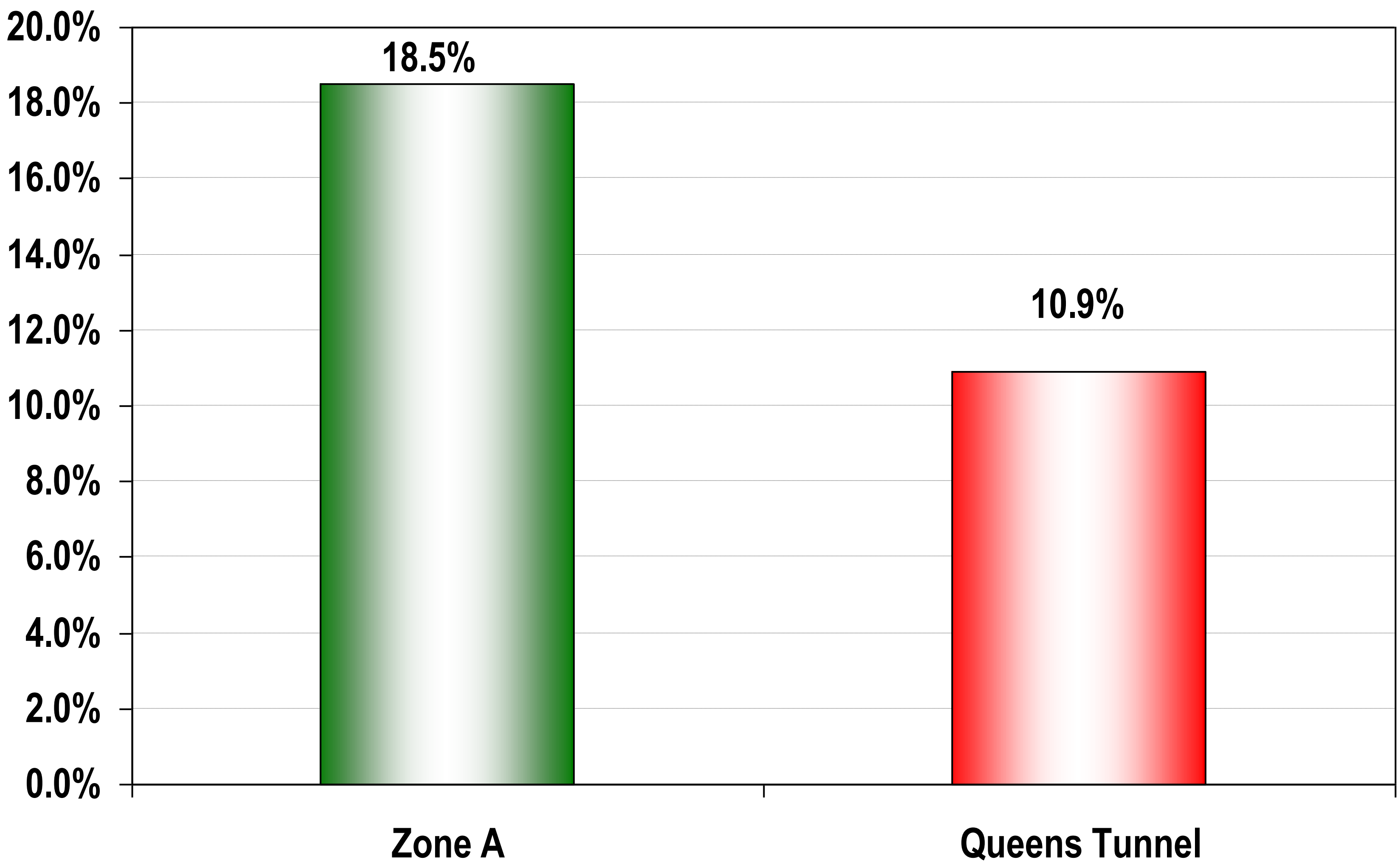
Shaft Borehole	Sample #	JTF TS/PTS*	Rock Name	Quartz	K-feldspar	Plag	Garnet	Biotite	Hb+ Relict Pyx	Epi	Sphene	Apatite	Opaque	Others
23B Shaft		No slide												
BTL-14 BH	BTL-14 R 39	JTF-22	Gt Bt Migmatite	24.0	36.5	21.5	2.0	10.0		0.		0.5	2.0	0.5
BTL 14 BH	BTL 14 R-42	[JTF-6]	Gt Bt Migmatite											
BTL-1 BH	BTL-1d R-47	JTF-7	Gt Bt Hb Migmatite	30.0	51.0	15.0	1.0	3.0						
BTL-1 BH	BTL-1g R-47	JTF-8*	Granophyric Migmatite	30.0	9.0	30.0	7.0	15.0			1.0			Sillimanite
BTL-2 BH	BTL-2 R-49	JTF-4	Gt Bt Migmatite	14.0	3.0	38.0	8.0	26.0	2.0		Tr		9.0	
22B Shaft	22B-A R-44	JTF-5*	Hornblendite					18.0	68.0	8.		1.0	3.0	
22B Shaft	22B-A R-49	JTF-20	Gt Bt Migmatite	16.0	2.0	28.0	7.0	34.0	3.0	3.	1.0		6.0	
BTL-13 BH	BTL-13 R-44	JTF-9	Hb Gt Migmatite	23.0		41.0	3.5	2.3	8.0	0.		0.5	0.5	
BTL-3 BH	BTL-3 R-52	JTF-19	Bt Migmatite	25.0	33.0	18.0	1.0							
BTL-12 BH	BTL-12 R-45	JTF-10	Gt Bt Migmatite	24.0		20.0	7.5	18.0	14.0			0.5	7.0	
BTL-4C BH	BTL-4 R-57	[JTF-23]	Gt Bt Hb Migmatite	25.0		36.0	4.0	14.0	12.0	2.	4.0		2.0	1.0
K-52 BH	K-52 R-21	JTF-24	Gt Bt Migmatite	23.0	14.0	46.0		15.0				1.0	1.0	
K-51 BH	K51 R-28	JTF-3	Gt Hb Migmatite	14.0		23.0	9.0	20.0	10.0				2.0	Tr
21B Shaft	21B-E R-53	JTF-18*	Gt Hb Bt Migmatite	32.5	1.5	47.0	1.5	4.5	7.5	1			4.0	Tr
BTL-11	BTL-11 R-48	JTF-12*	Gt Amphibolite	10 ?		20.0	12.0		42.0			<1	5.5	Tr
BTL-6	BTL-6A R-44	[JTF-11]	Gt Hb Migmatite	18.0		37.0	4.0	4.0	32.0	2			2.0	Tr
BTL-6	BTL-6A R-55	JTF-15	Gt Amphibolite	11.0		29.0	3.5	3.0	45.0	3			5.5	Tr
BTL-9	BTL-9 R-47	JTF-16	Gt Hb Migmatite	38.0		45.0	3.0	6.0		2		<1		<1
BTL-9	BTL-9R-59	JTF-2*	Gt Hbt Migmatite											
20B Shaft	20B R-29	JTF-25	Gt Bt Migmatite	15.0		33.0			48.0				4.0	
20B Shaft	20B R 525	JTF-17*	Gt amphibolite	5.0	2.0	22.0	8.0	5.0	48.0	11			7.0	Tr
BTL-10	BTL-10 R-46	JTF-13	Bt Gt Migmatite	32.0	2.0	36.0	7.0	14.0		T		1.0	8.0	
BTL-7	BTL-7 R-44	JTF-14	Migmatite	25.0	34.0	24.0	2.0	5.5		2	Tr	<1	7.0	Tr
BTL-8	BTL-8 R-47	JTF-21	Gt Bt Migmatite	14.0	4.0	45.0	7.0	25.0	1.0	1	Tr		3.0	Tr
BTL-8	BTL-8 R-48	JTF-1	Gt Migmatite	38.0	4.0	35.0		7.5	8.0	2		0.5	8.5	Tr
BTL-19B	BTL-19B R-57													

Biotite
10.0
3.0
15.0
26.0
18.0
34.0
2.3
18.0
14.0
15.0
20.0
4.5
4.0
3.0
6.0
5.0
14.0
5.5
25.0
7.5

Source: DEP 2001 Response, App. 11, Rpt. 2

New Data From DEP - June 2001

Biotite Content



Foliation Index

$$\text{Foliation Index} = \frac{\%\ \text{biotite}}{\%\ \text{hornblende} + \%\ \text{pyroxene}}$$

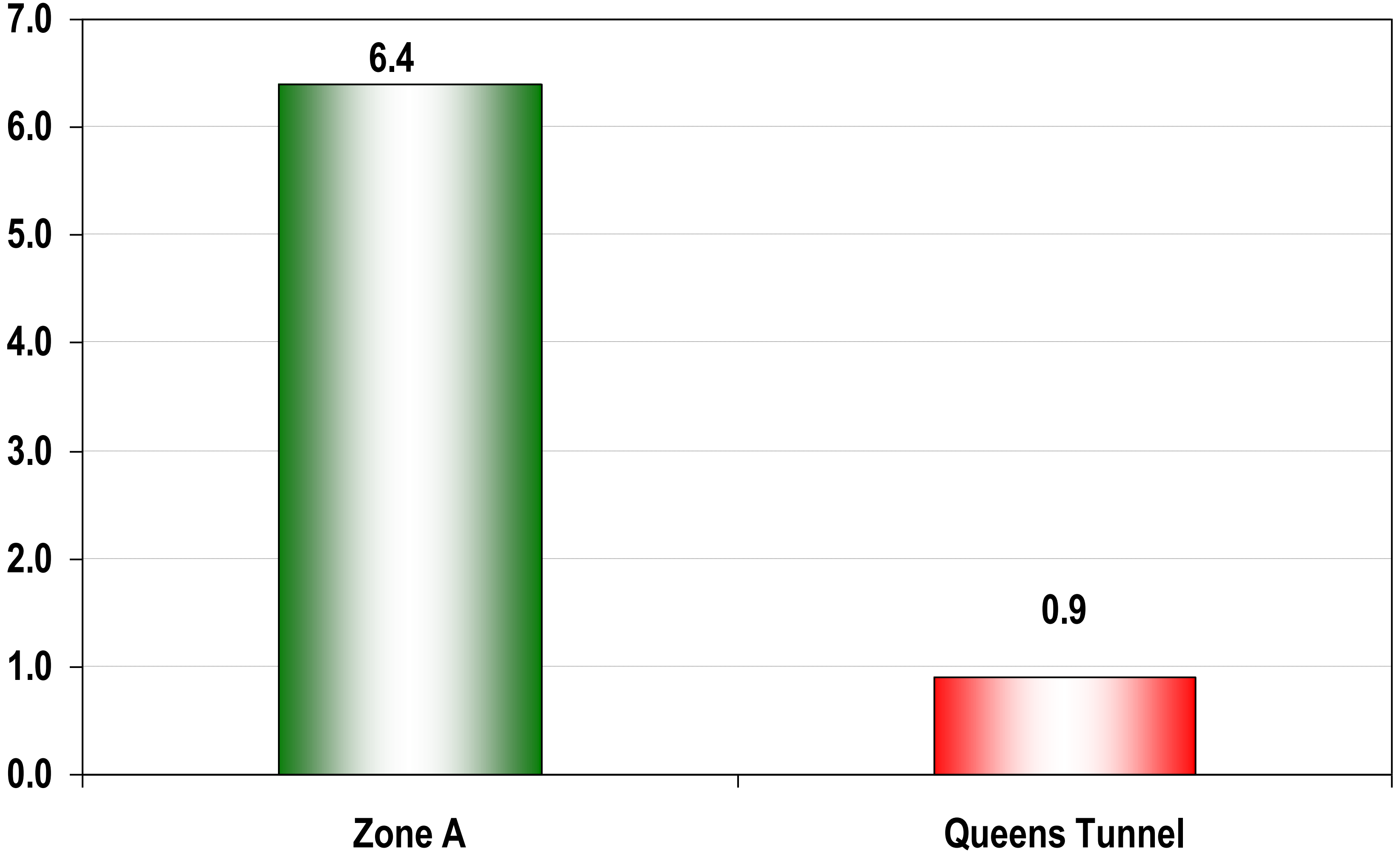
– Indicates relative degree of regeneration of weak mica during retrograde metamorphism

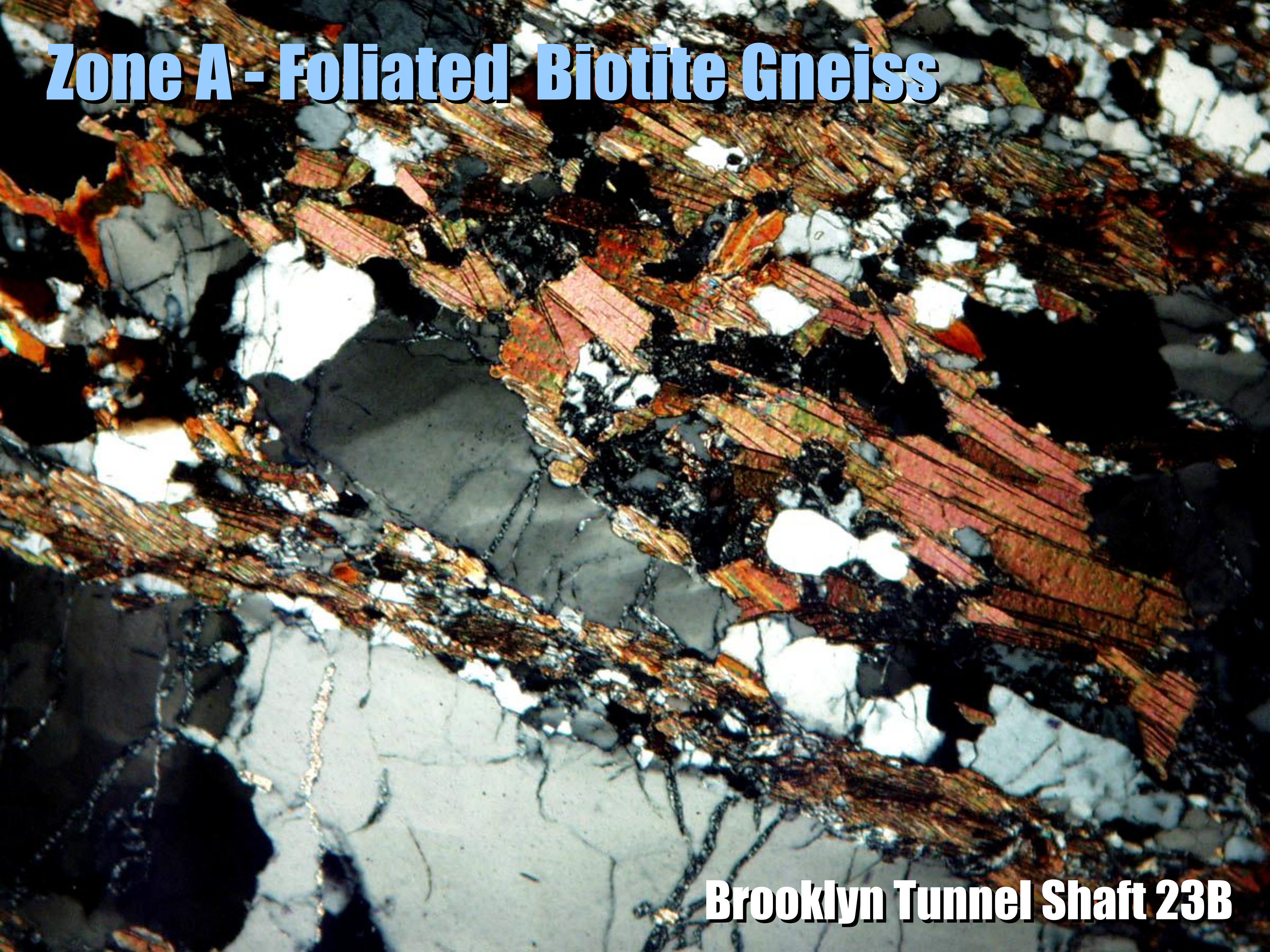
– Foliated rocks fail more readily because of the continuous nature of the mica crystals, a soft mineral with perfect basal cleavage

– Aligned biotite produces a penetrative metamorphic foliation in Zone A of the Brooklyn Tunnel, not found in the Queens Tunnel

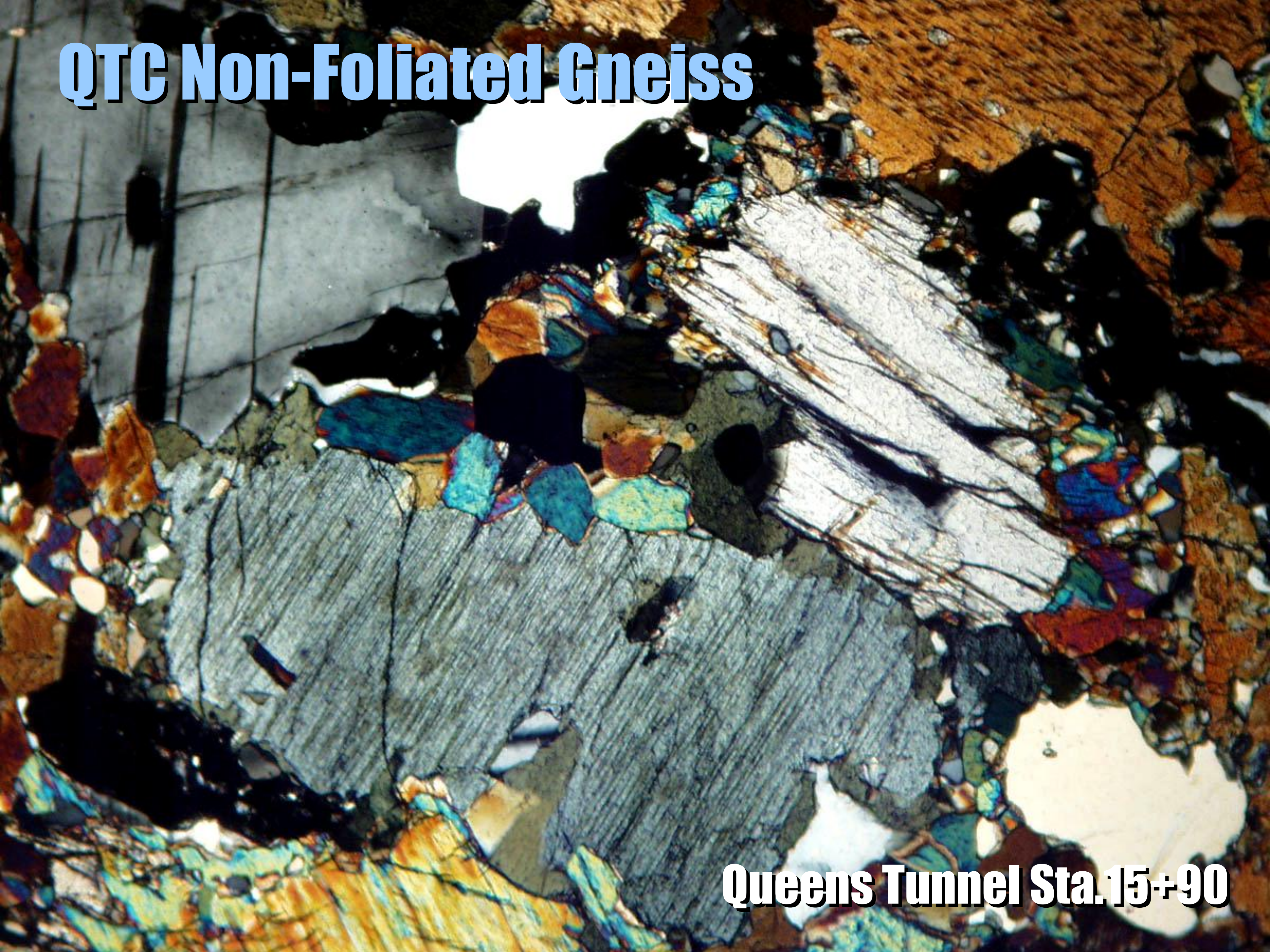
Foliation Index

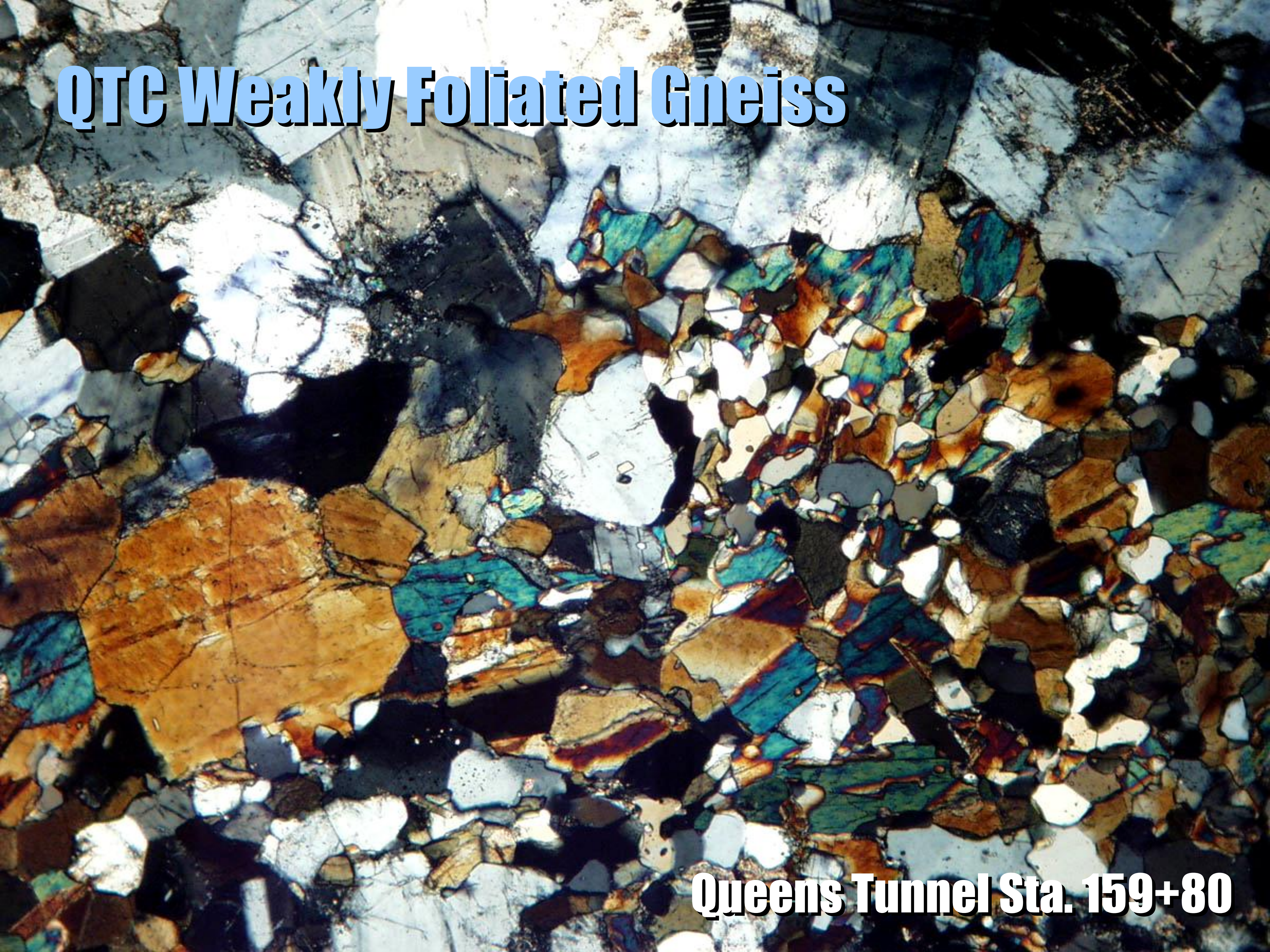
- Ratio of % biotite to % [hornblende + pyroxene]



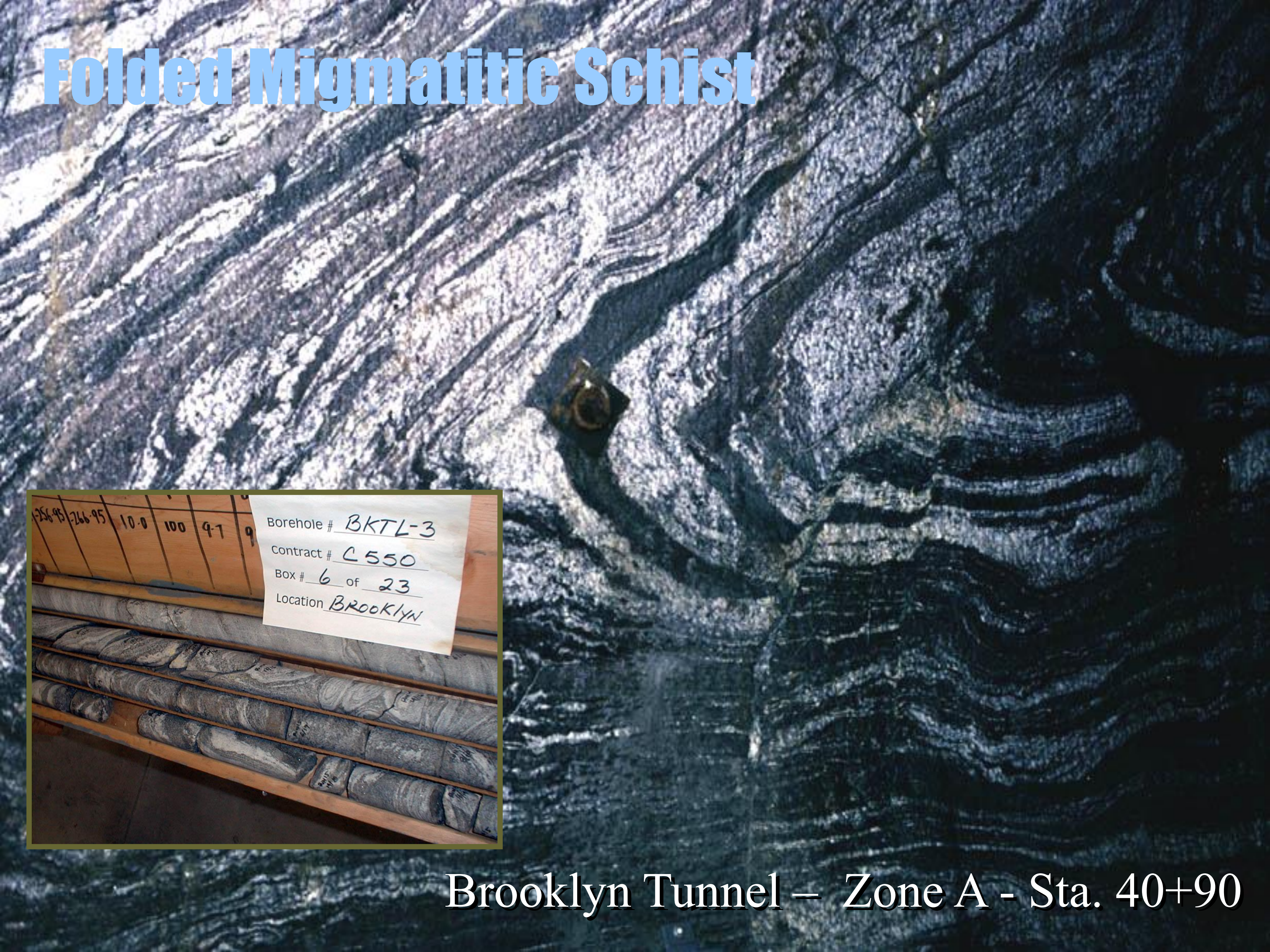

Zone A - Foliated Biotite Gneiss
Brooklyn Tunnel Shaft 23B


Zone A - Foliated Biotite Gneiss
Brooklyn Tunnel Shaft 22B


QTC Non-Foliated Gneiss
Queens Tunnel Sta.15+90


QTC Weakly Foliated Gneiss
Queens Tunnel Sta. 159+80

Folded Migmatitic Schist



Brooklyn Tunnel – Zone A - Sta. 40+90

Brooklyn Tunnel - Zone A ≠ Queens Tunnel

	Zone A	Zone C/Queens
Texture	Highly foliated	Weakly foliated
Mineralogy Biotite	18.5% Biotite	8.3%/10.9%
Foliation Index	6.4	0.5/0.9

The Queens Tunnel Complex

Grenvillian Granulite Minerals and Fabrics

Oldest fabrics are medium- to coarse grained with interlocking plagioclase and pyroxene

Early, coarse-grained garnet coexists with clinopyroxene (cpx) in several rocks and coexists with orthopyroxene (opx) with or without additional cpx in others

Orthopyroxene is a diagnostic indicator of granulite facies metamorphism

The Queens Tunnel Complex

The garnet-clinopyroxene-orthopyroxene-plagioclase assemblages indicate that M_1 metamorphism occurred in the high-pressure granulite facies

Queens Tunnel gneisses exhibit some light- and dark mineral layering but sparse foliation

The interlocking granoblastic texture, lack of a penetrative foliation, mafic mineral content and resulting high density produced a homogenous, weakly foliated, "tough" rock mass

The Queens Tunnel Complex

Fordham Lithologies

1.0 Ga mesocratic, leucocratic, and mafic gneiss
Primary granulite-facies texture and mineralogy
Granulite "green" coloration

Non-Fordham Lithologies

<465 Ma granite and pegmatite
biotite+garnet rich metasedimentary rock (Walloomsac Formation)
Metamorphosed mafic dikes
Unmetamorphosed rhyodacite dikes

The Queens Tunnel Complex

I. Garnet-Clinopyroxene-Plagioclase Rocks +/- Hornblende, Quartz, K-feldspar

Probable Fordham Calc-silicate rocks
Fordham Metaigneous Rocks

II. Leuco- to Mesocratic Gneiss

Fordham "granulite" mineralogy and -texture

The Queens Tunnel Complex

III. Mafic to Mesocratic Rocks

Contain Hornblende, Orthopyroxene, Clinopyroxene, Garnet, Biotite, and Cummingtonite all with Plagioclase, +/- Quartz, +/- K-feldspar

Leucocratic (0%-35% mafic mineral content), Mesocratic (35%-65% mafic mineral content), and Melanocratic (65%-90% mafic mineral content) gneiss form the bulk of the Queens Tunnel Complex

The Queens Tunnel Complex

Coarse granoblastic granulite facies gneiss
Orthopyroxene + clinopyroxene ± garnet with plagioclase
Primary garnet form during initial M_1 metamorphism

M_2 recrystallization of hornblende, biotite, and secondary garnet overprints primary plagioclase and pyroxene(s)

Porphyroblastic garnet indicates a later (younger) stage of metamorphism (M_2)

Symplectic rims (M_2) "garnet necklace" around mafic minerals

Later Stage (M2) Metamorphism

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

Sample Reactions

opx + cpx + plag = hbl + garnet

opx + quartz = cummingtonite

garnet + opx + plag = hbl + quartz

K-spar + opx = biotite + quartz

The Queens Tunnel Complex

Secondary (M_2) Metamorphism

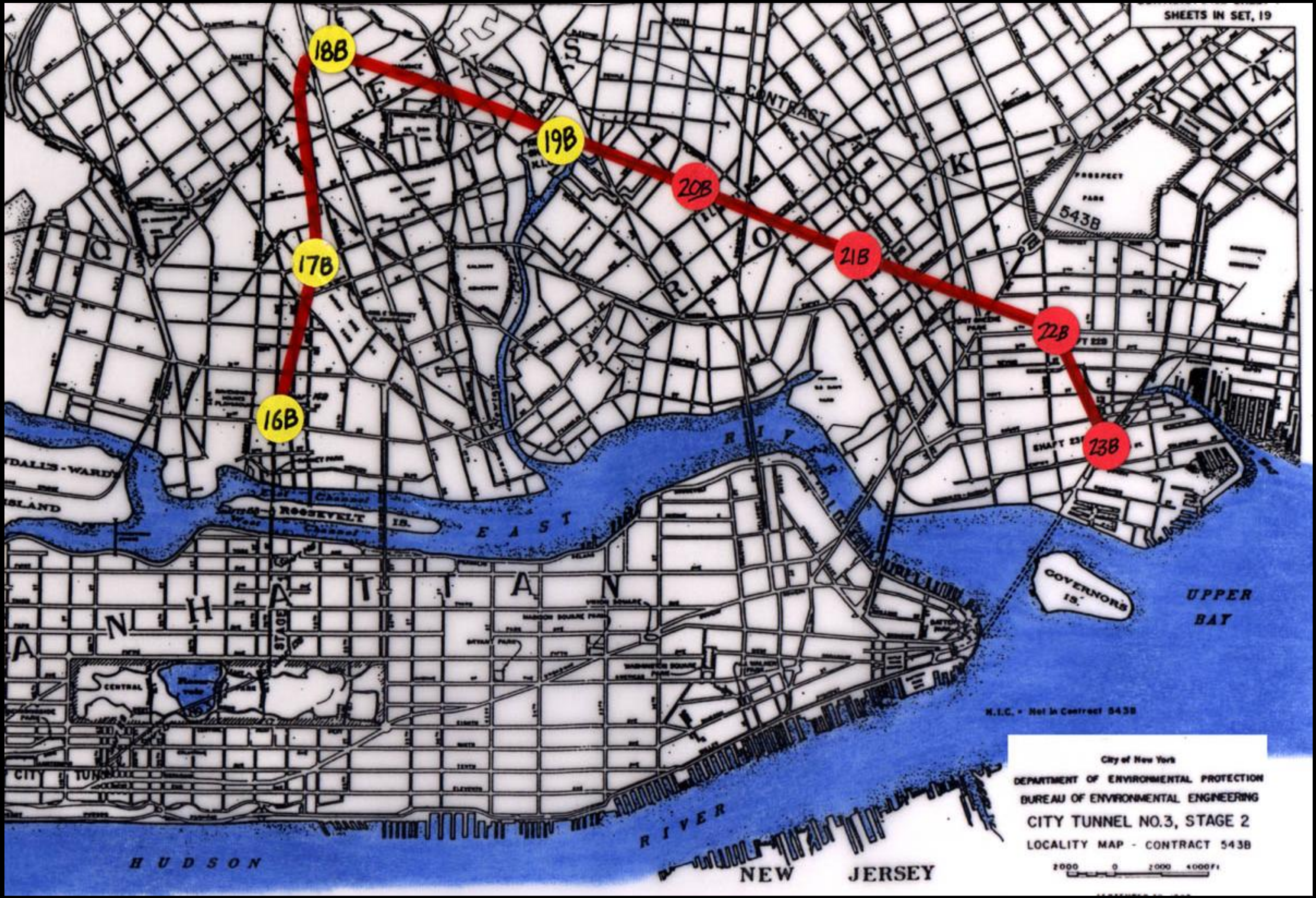
Coronas of hydrated minerals such as amphibole and biotite envelope relict pyroxene crystals

Garnet "necklace" textures +/- hornblende once contained pyroxene(s)

Late-stage garnet and amphibole are breakdown products of opx

The retrogression involved introduction of hydrous minerals into the gneisses, and almost certainly took place at higher H_2O activity than did the original granulite metamorphism

Stage 2, City Tunnel 3



HERRENKNECHT TBM ADVERTISEMENT

Rock Does Not Equal Rock

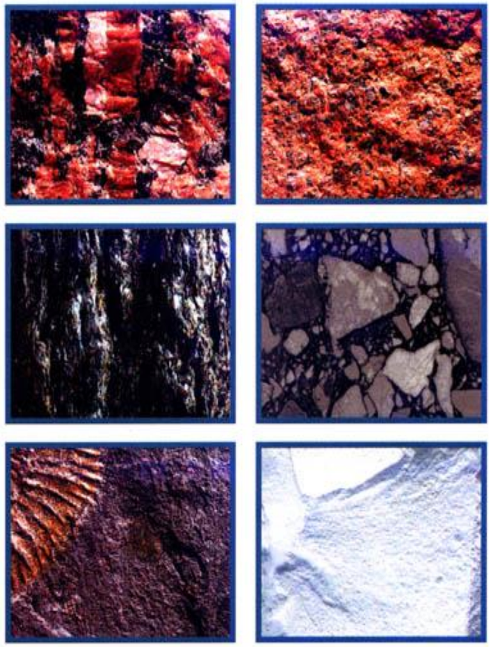
At Herrenknecht, maximum tunnelling performance and the greatest possible safety are the ultimate goals for the development of tunnelling machines. Expert analysis of the geological conditions result in a "tailored hard rock machine".

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.