Hudson-Mohawk Professional Geologists Association

Geological Controls on Megaconstruction Tunneling Projects, NYC

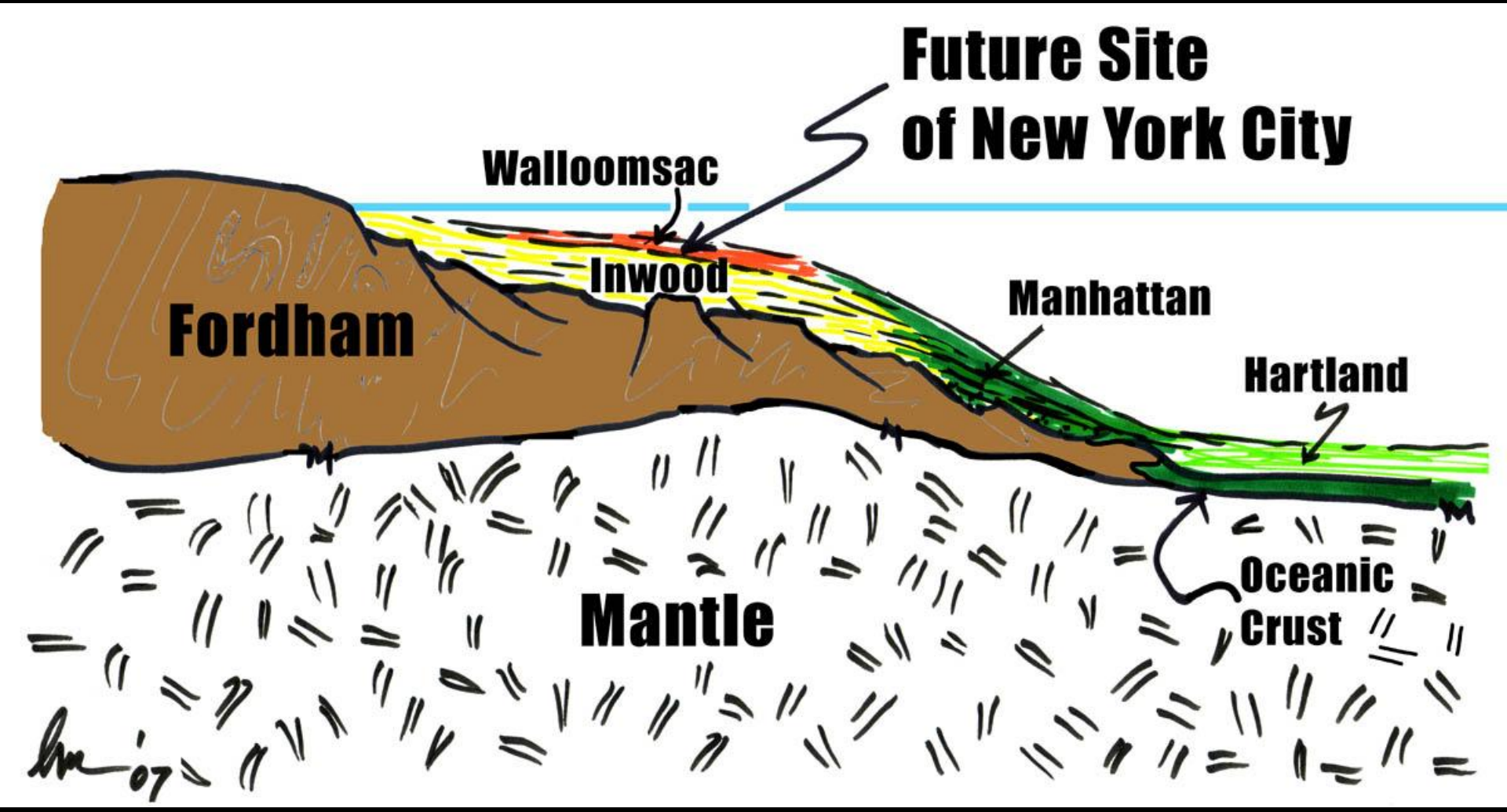
Charles Merguerian

Principal – Duke Geological Lab

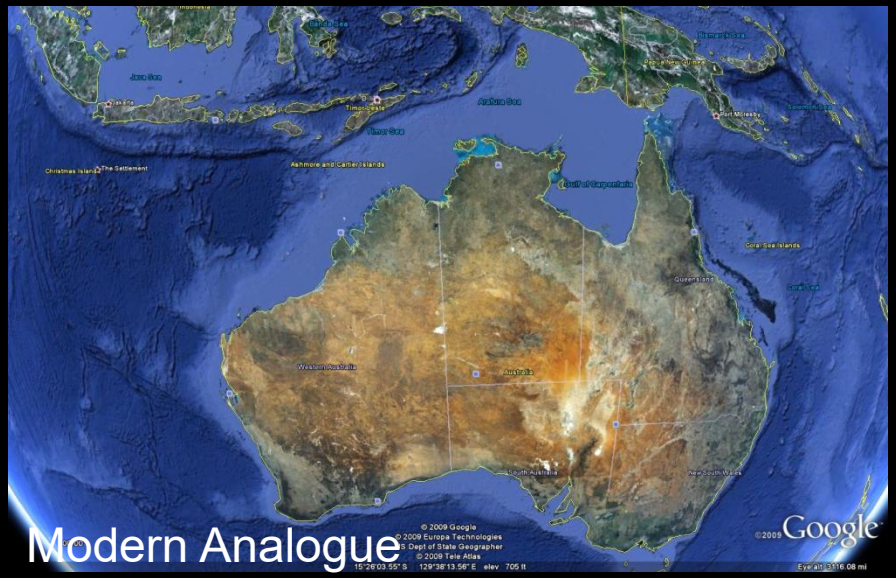
Professor Emeritus – Hofstra University

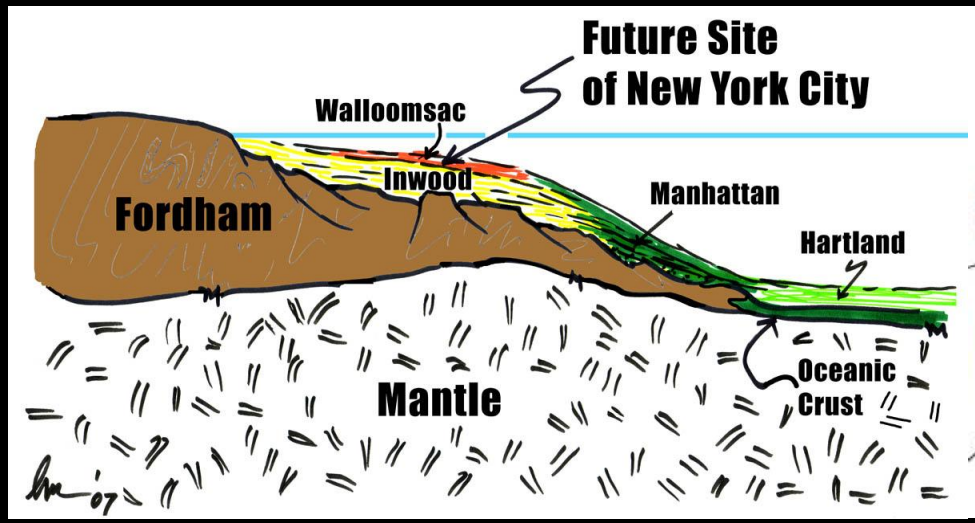
Research Fellow – Yale University

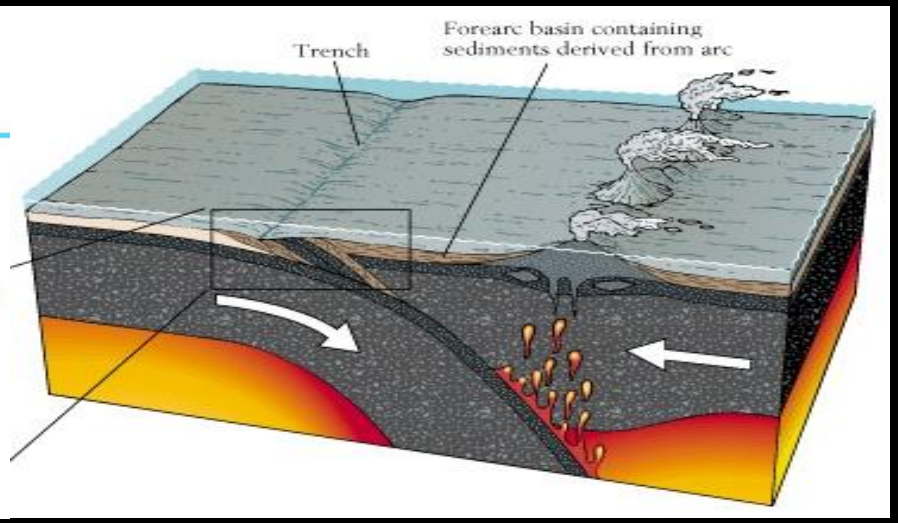
18 March 2015

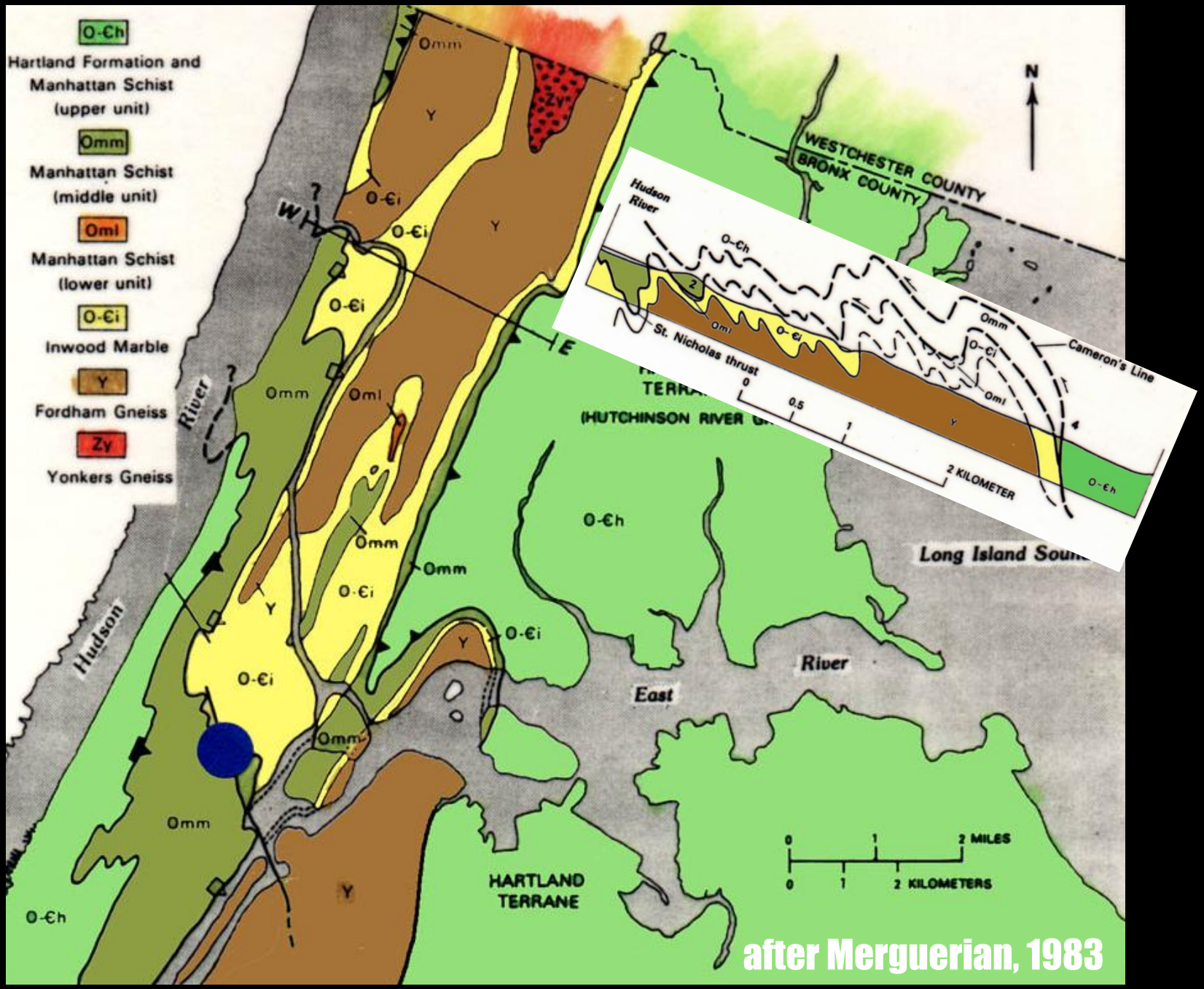

Future Site
of New York City
Walloomsac
Inwood
Fordham
Manhattan
Hartland
Oceanic
Crust
Mantle

~ 450 Ma Taconian Arc – Passive Margin Collision

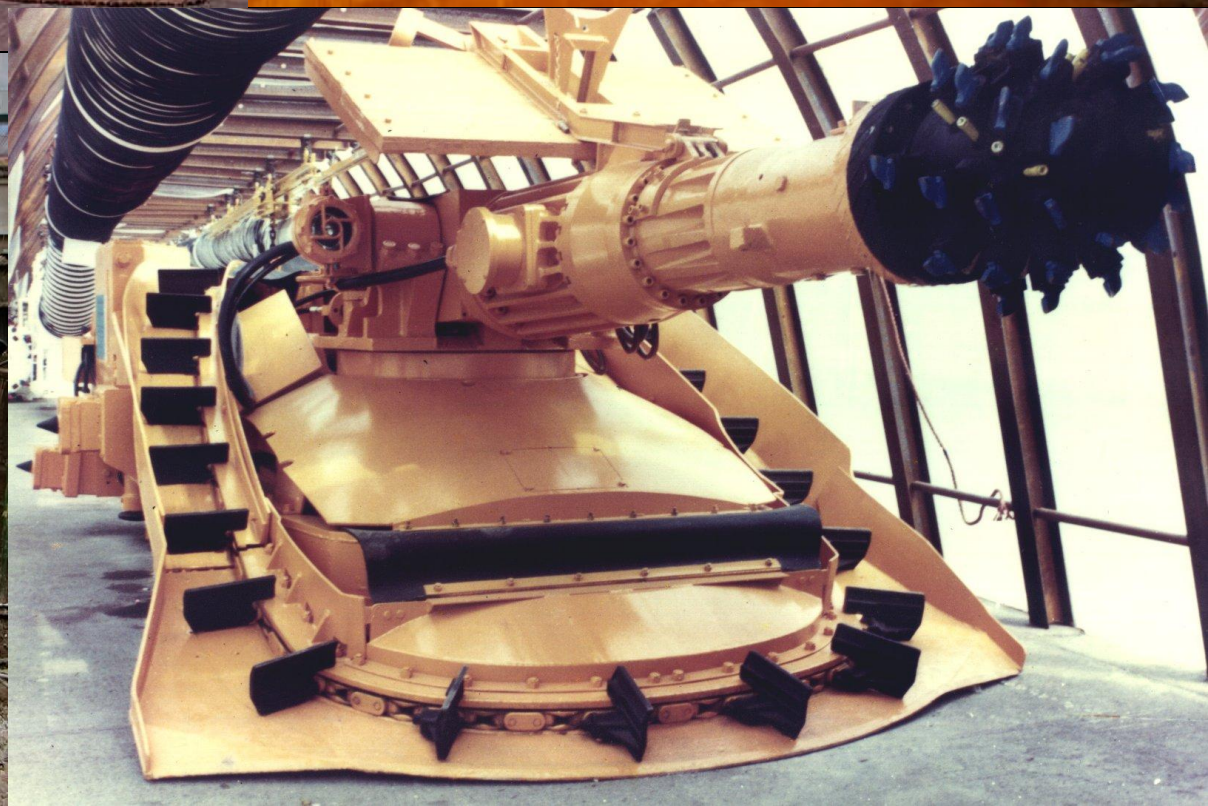







O-Ch
Hartland Formation and Manhattan Schist (upper unit)
Omm
Manhattan Schist (middle unit)
Oml
Manhattan Schist (lower unit)
O-Ci
Inwood Marble
Y
Fordham Gneiss
Zy
Yonkers Gneiss
N
WESTCHESTER COUNTY
BRONX COUNTY
Hudson River
O-Ch
Oml
O-Ci
Omm
Cameron's Line
St. Nicholas thrust
0
0.5
1
2 KILOMETER
O-Ch
Long Island Sound
Hudson
River
East
River
HARTLAND TERRANE
(HUTCHINSON RIVER
0
1
2 MILES
0
1
2 KILOMETERS
after Merguerian, 1983

What Are the Geological Controls on Effective Hard Rock Removal in Crystalline Terrains?



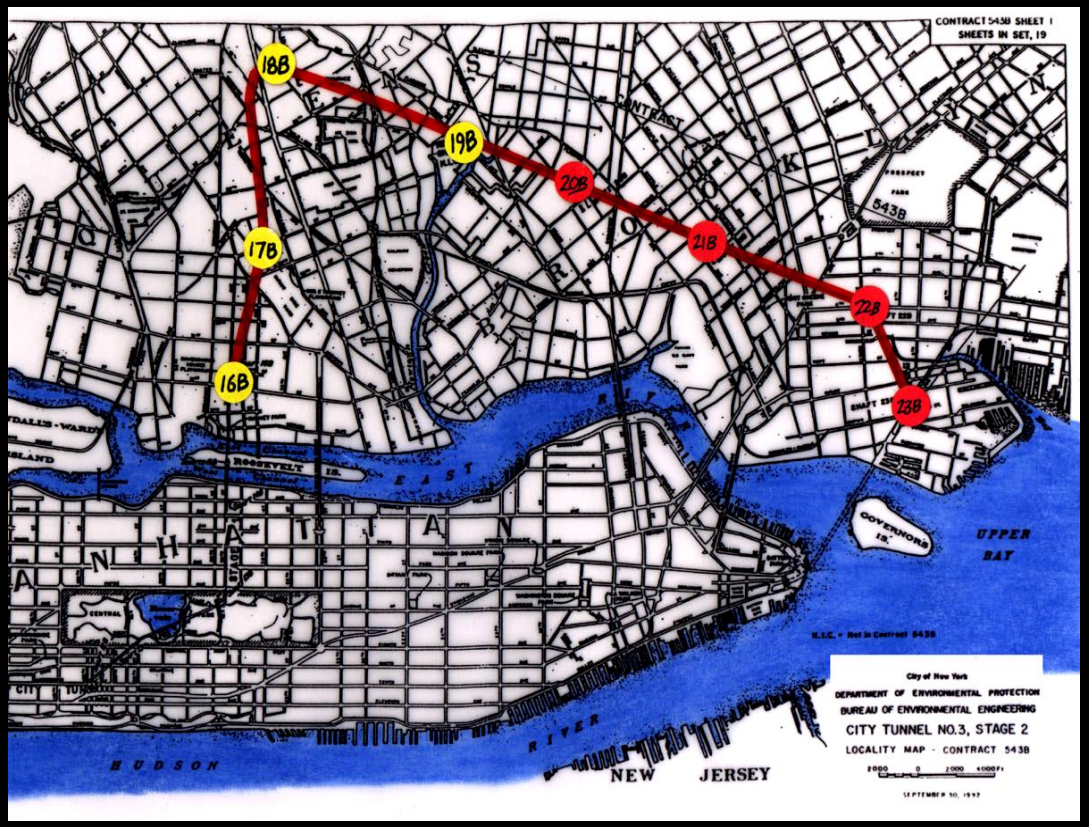
NYC Megaconstruction Projects (1971-2015)

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 Extension
Con Edison Utility Tunnel (D&B)
Second Avenue Subway (D&B/Mech)
Brooklyn Siphon Tunnel

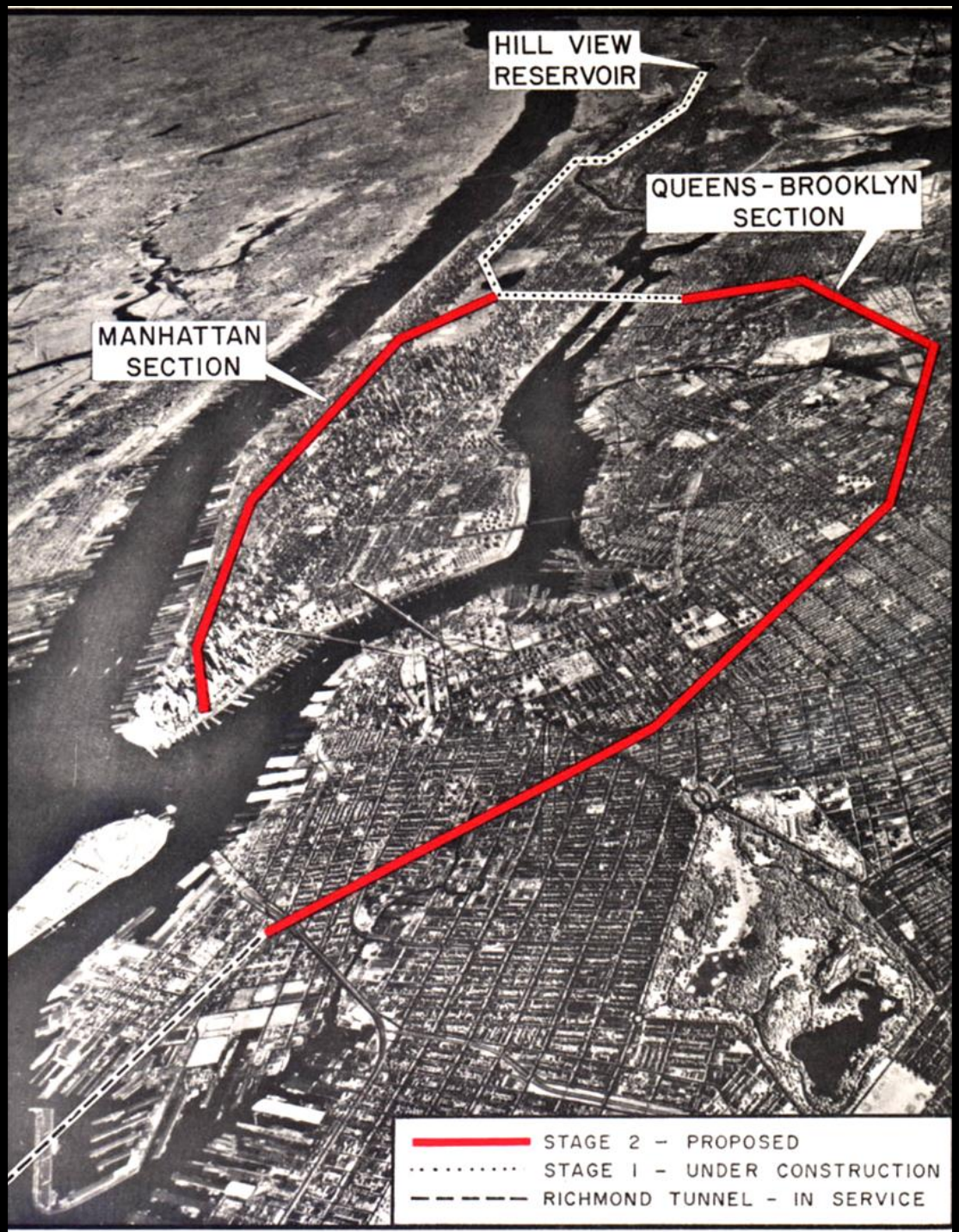
Excavation Methods

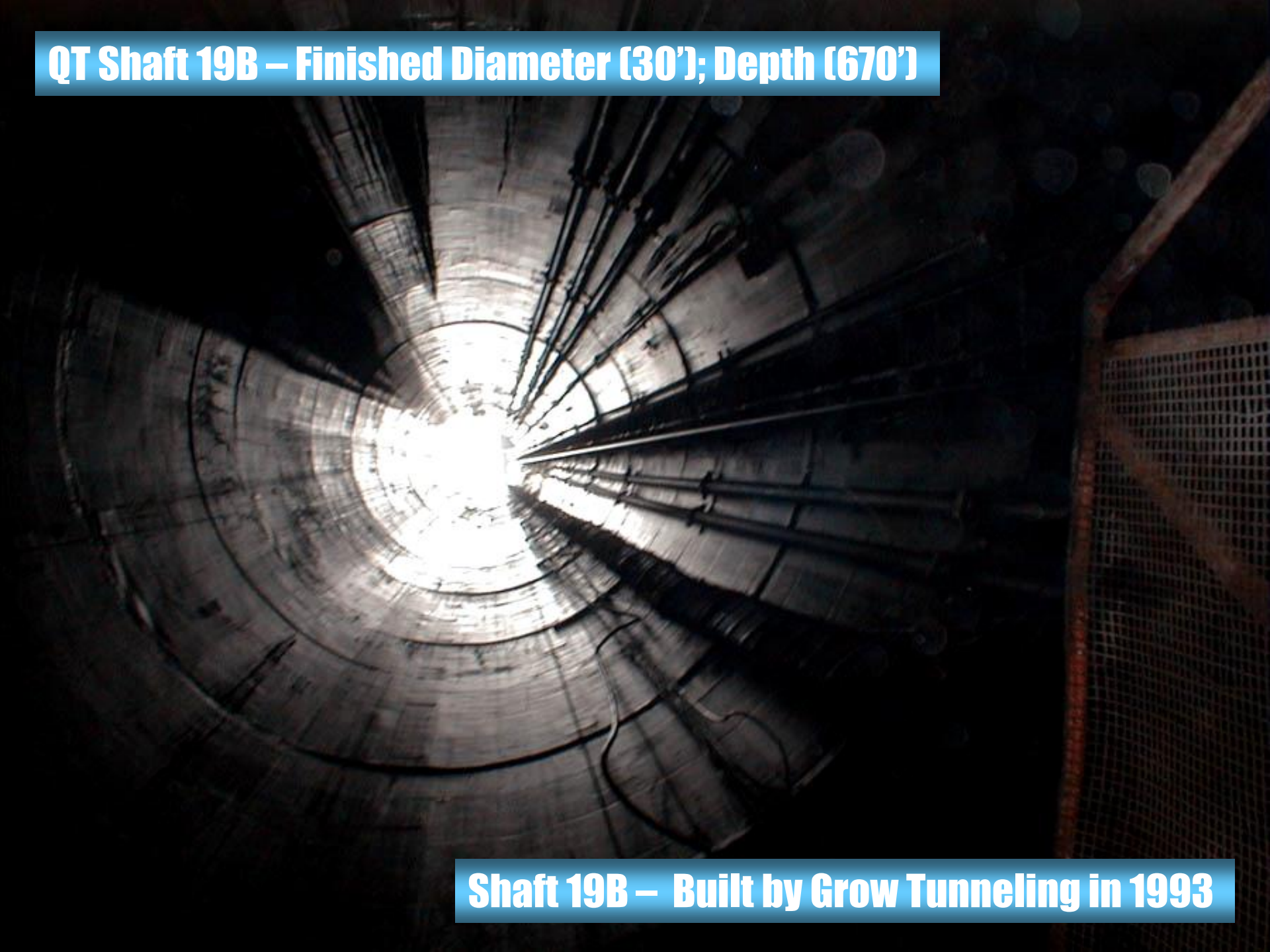
Queens Water Tunnel

- 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

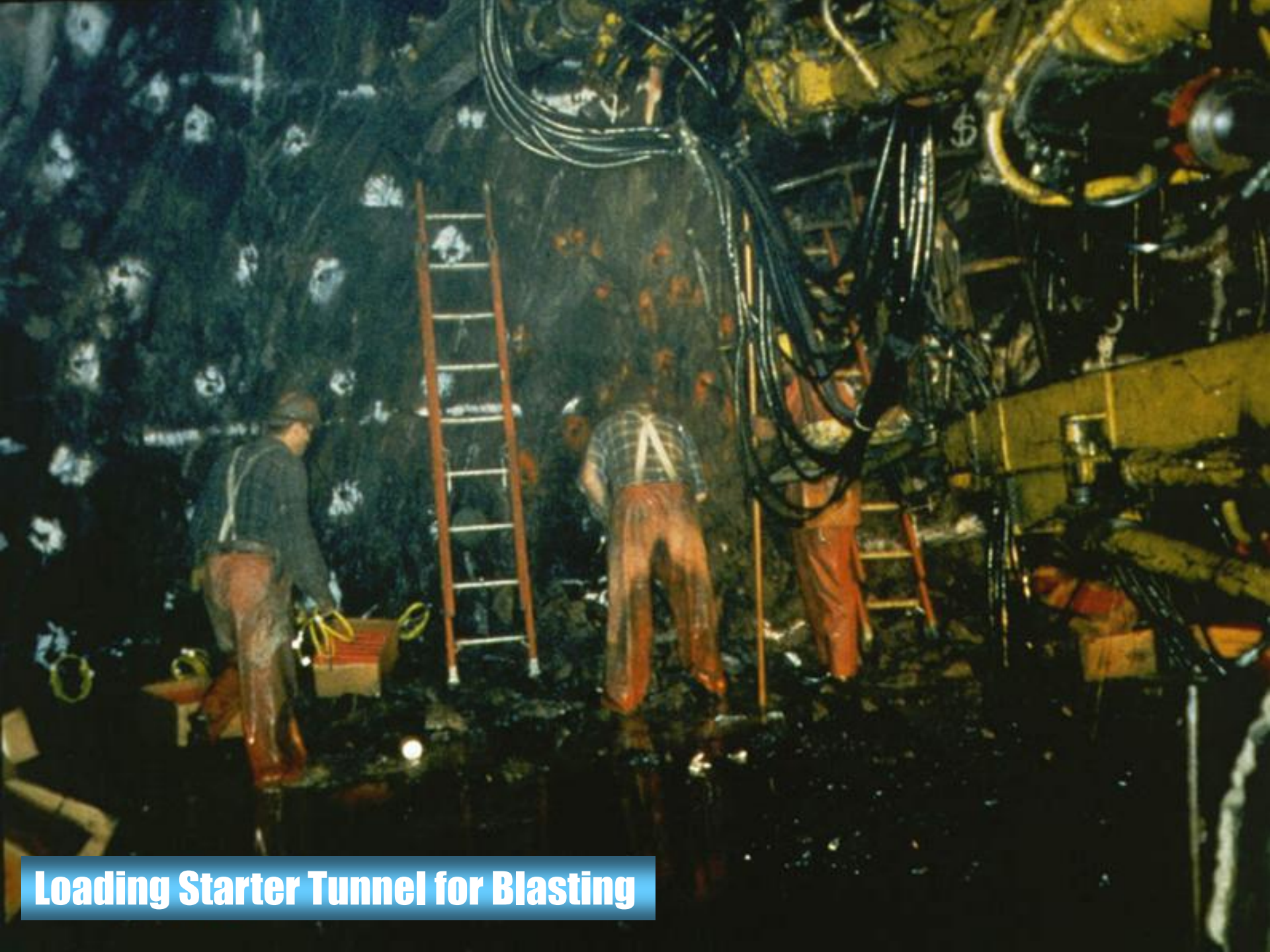


CT3, Stages 1 and 2




QT Shaft 19B – Finished Diameter (30'); Depth (670')
Shaft 19B – Built by Grow Tunneling in 1993

Bottom of the Shaft



Loading Starter Tunnel for Blasting

Poured Starter Tunnel

Robbins 235-282 HP Hard Rock Main Beam TBM

Chesterfield, England - 1996

Flipping TBM Cutterhead

Lowering TBM Cutterhead

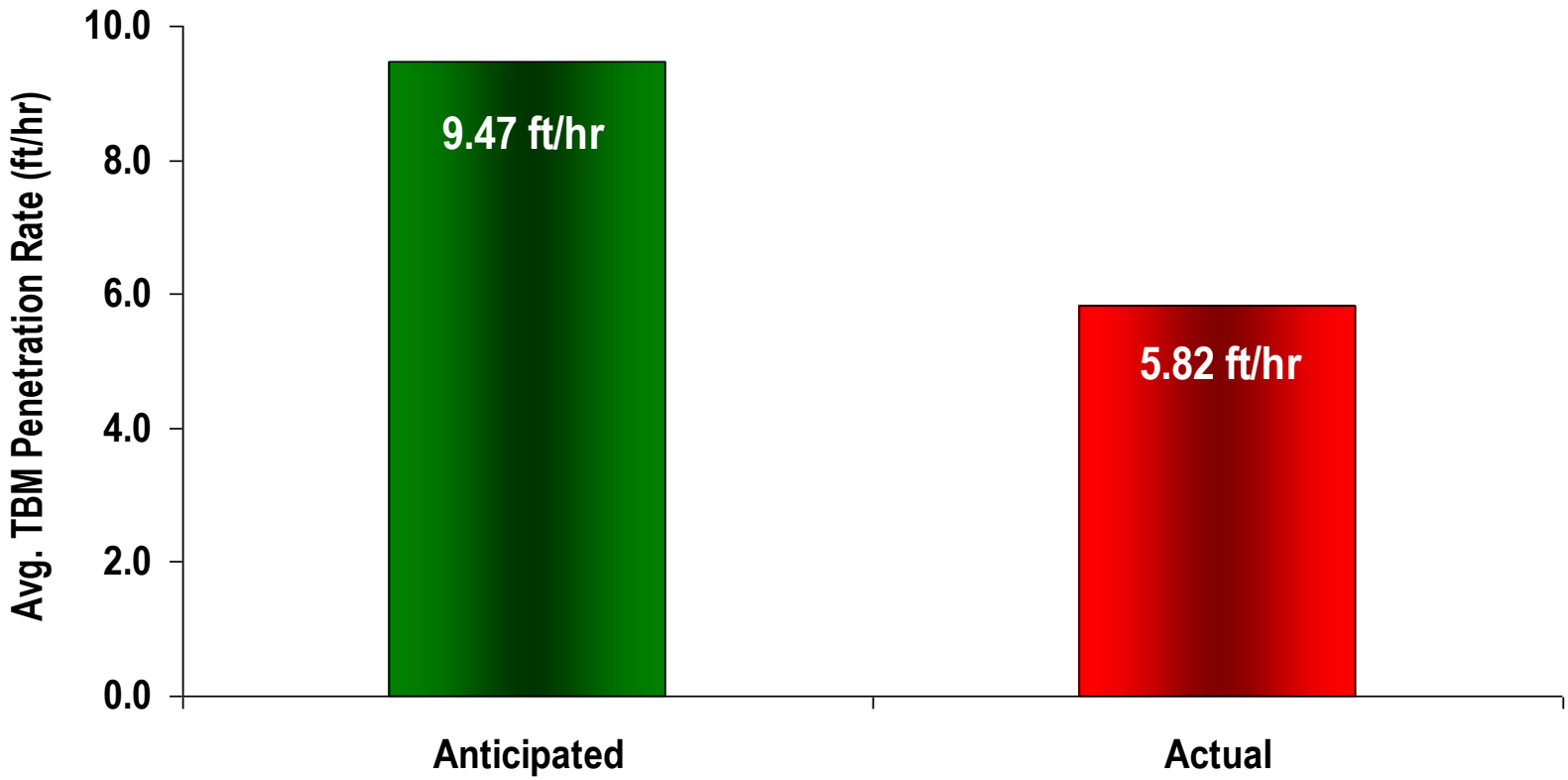
Lowering TBM Mainbeam

Shaft 19B Headframe and Alimak

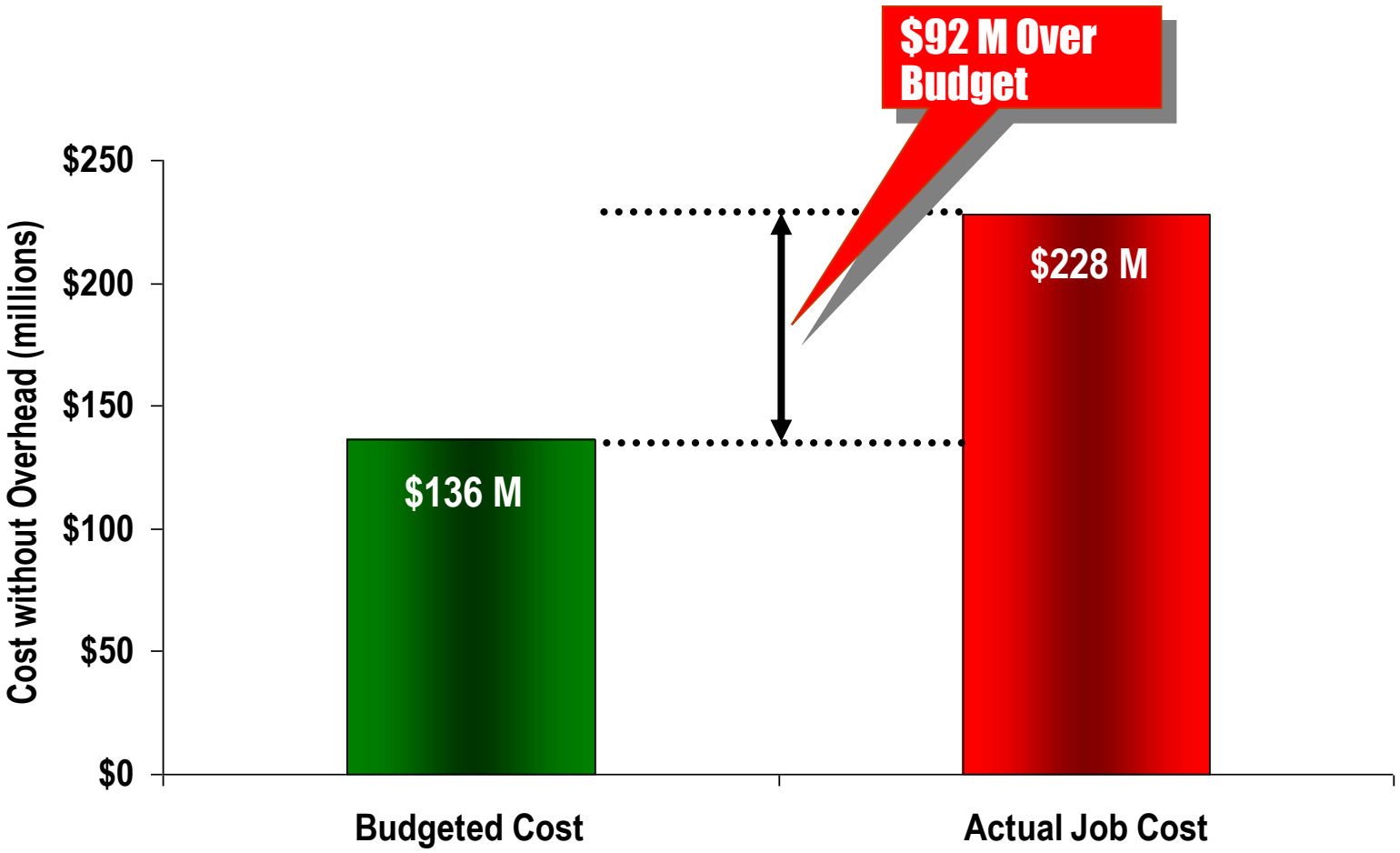
Walking TBM Mainbeam

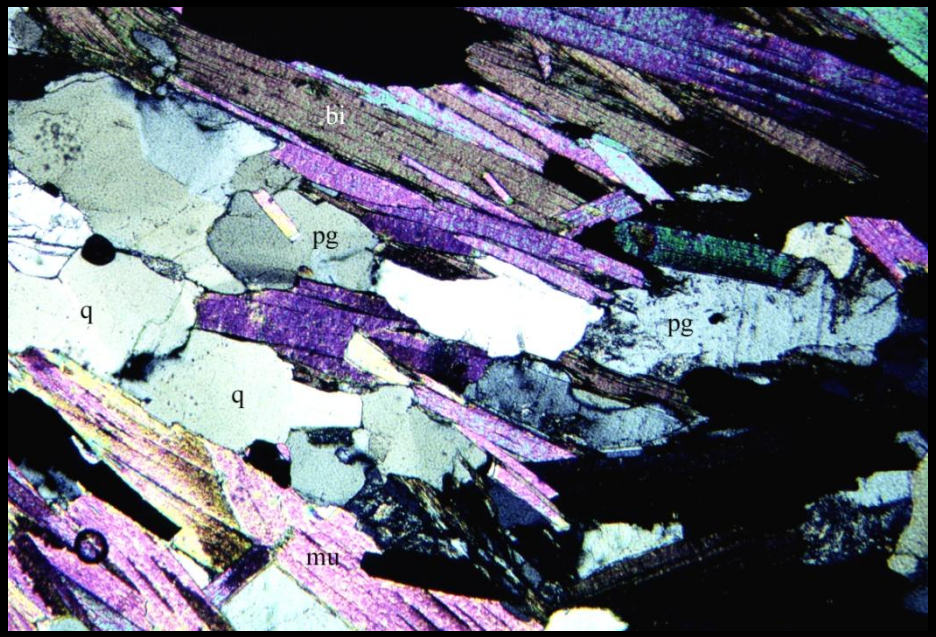
Offloading Vent Pipe

Anticipated vs. Actual Penetration Rate

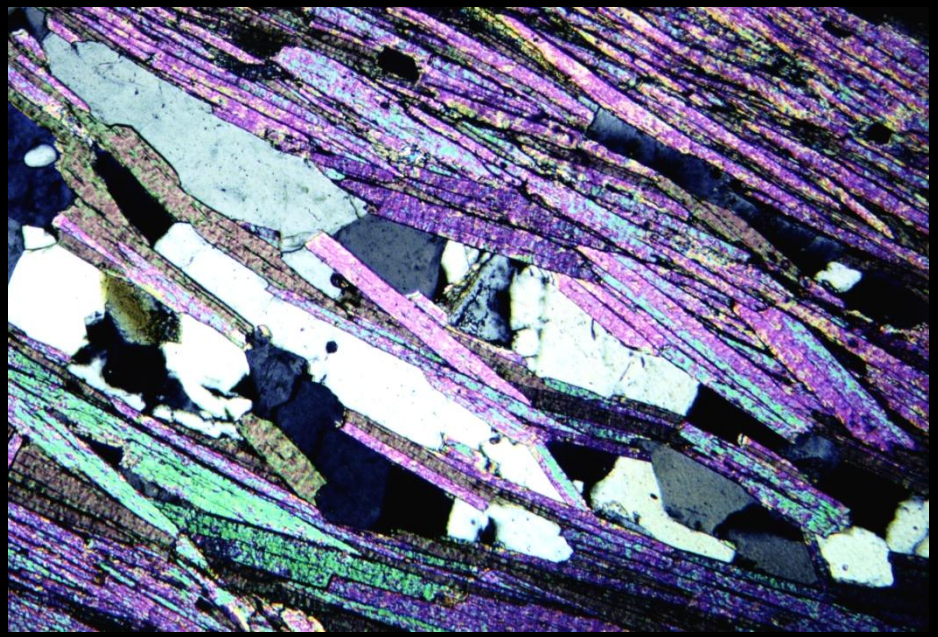


Anticipated vs. Actual Cost

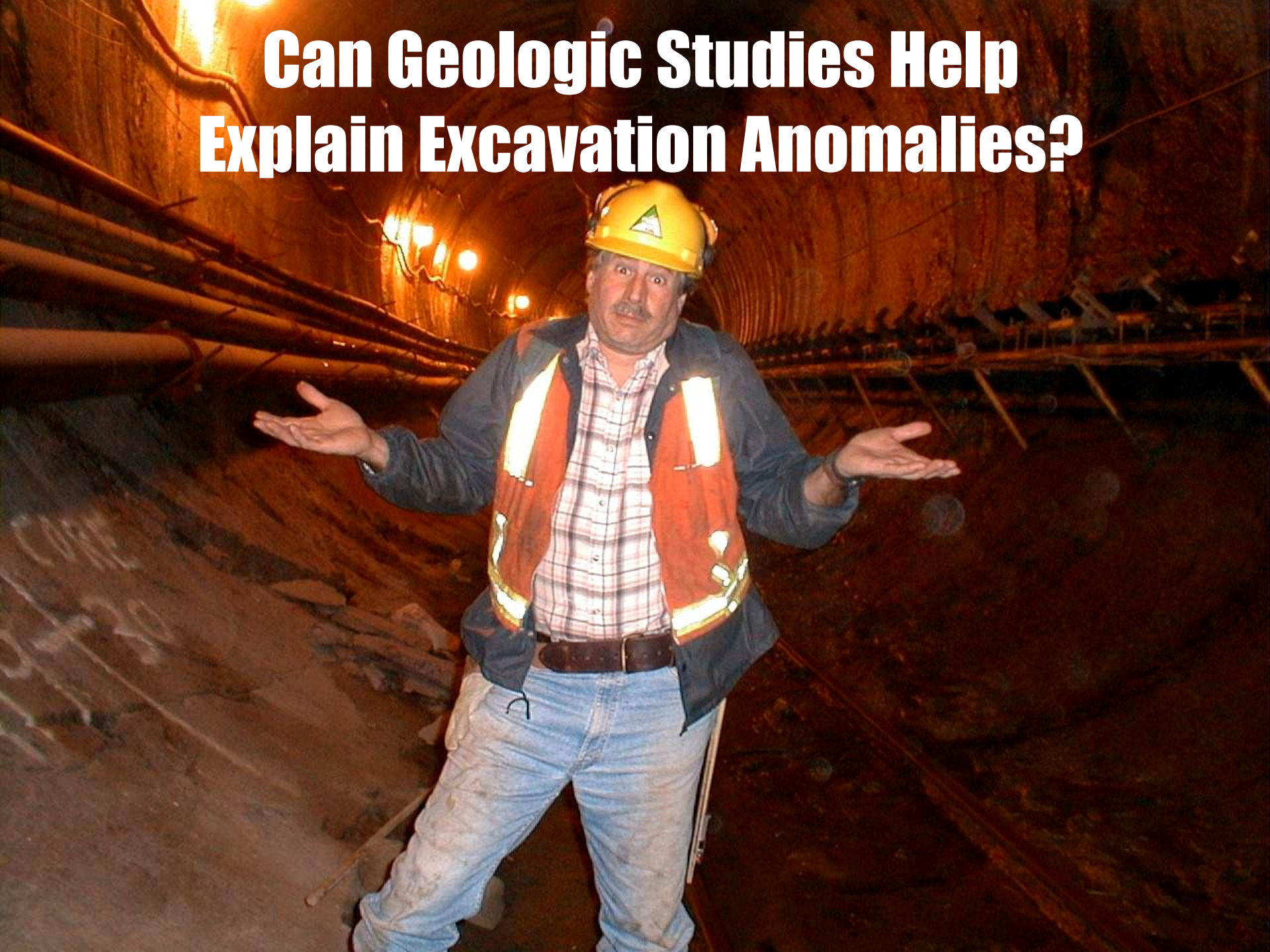




In Western and Central Manhattan:
Amphibolite Facies Schists
Well-layered Hartland Fm.
Penetrative Foliated Textures
Great Rocks for Tunneling and Excavation!

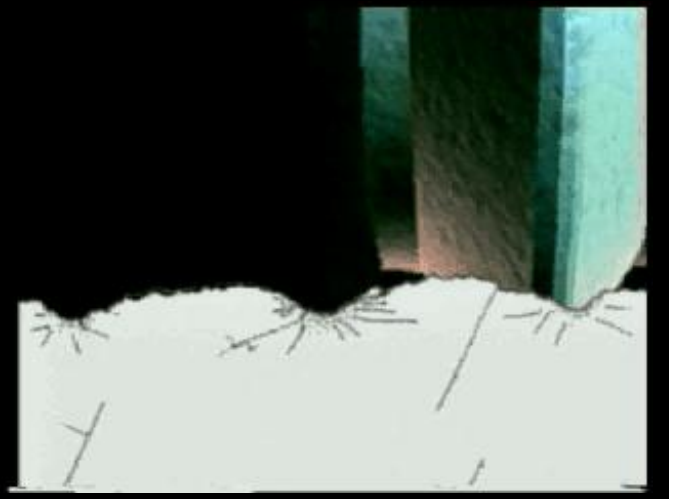


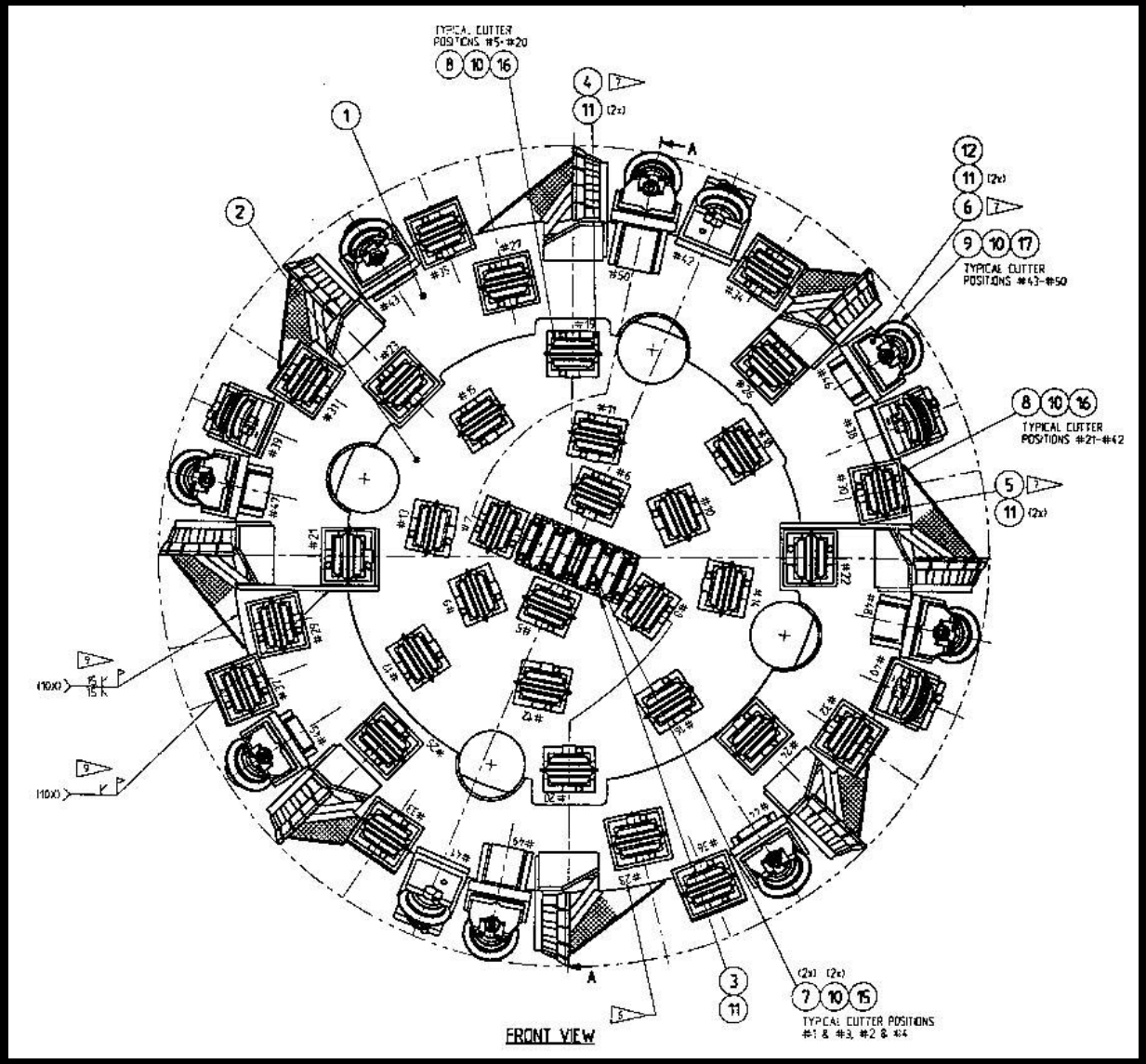
Can Geologic Studies Help Explain Excavation Anomalies?

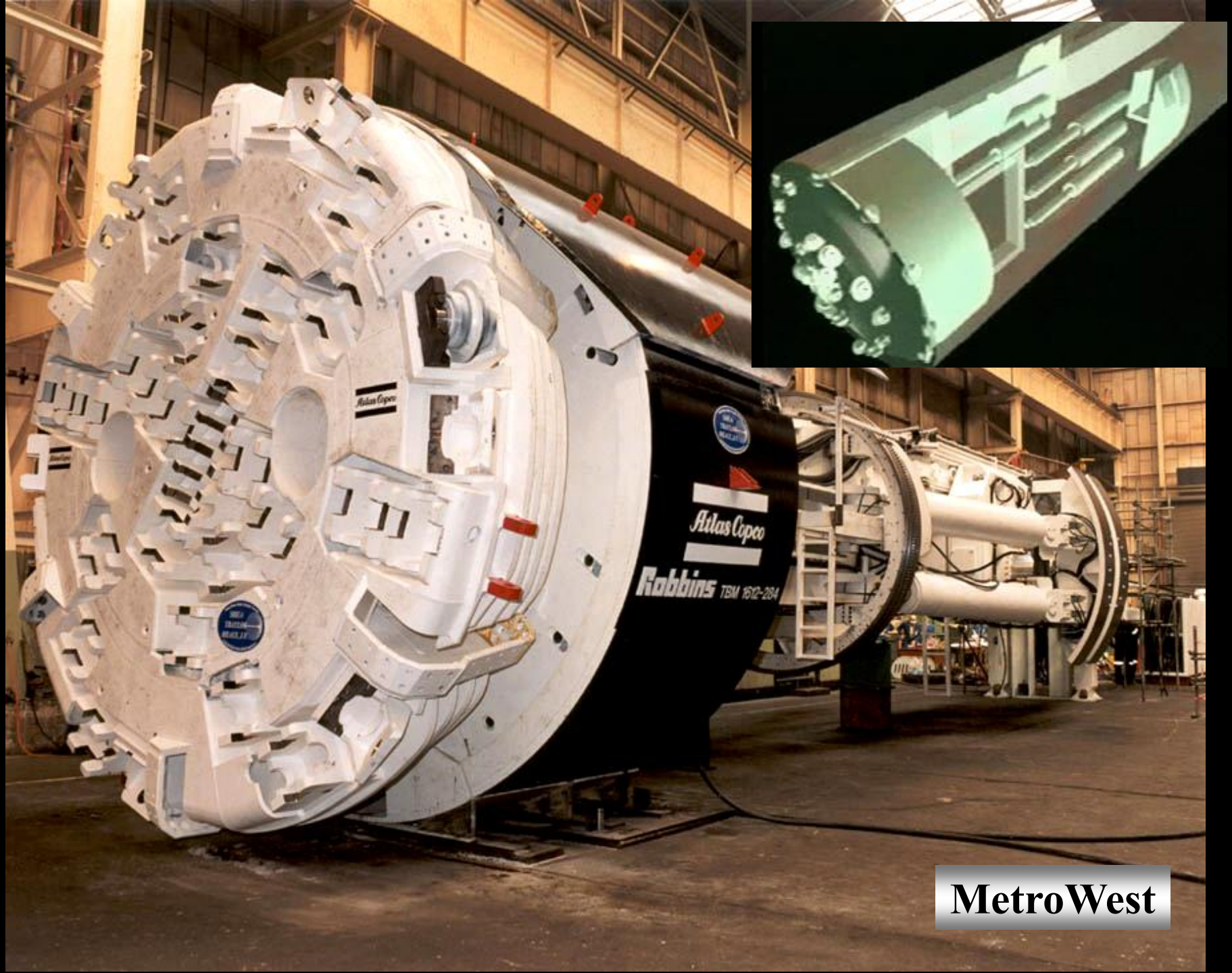


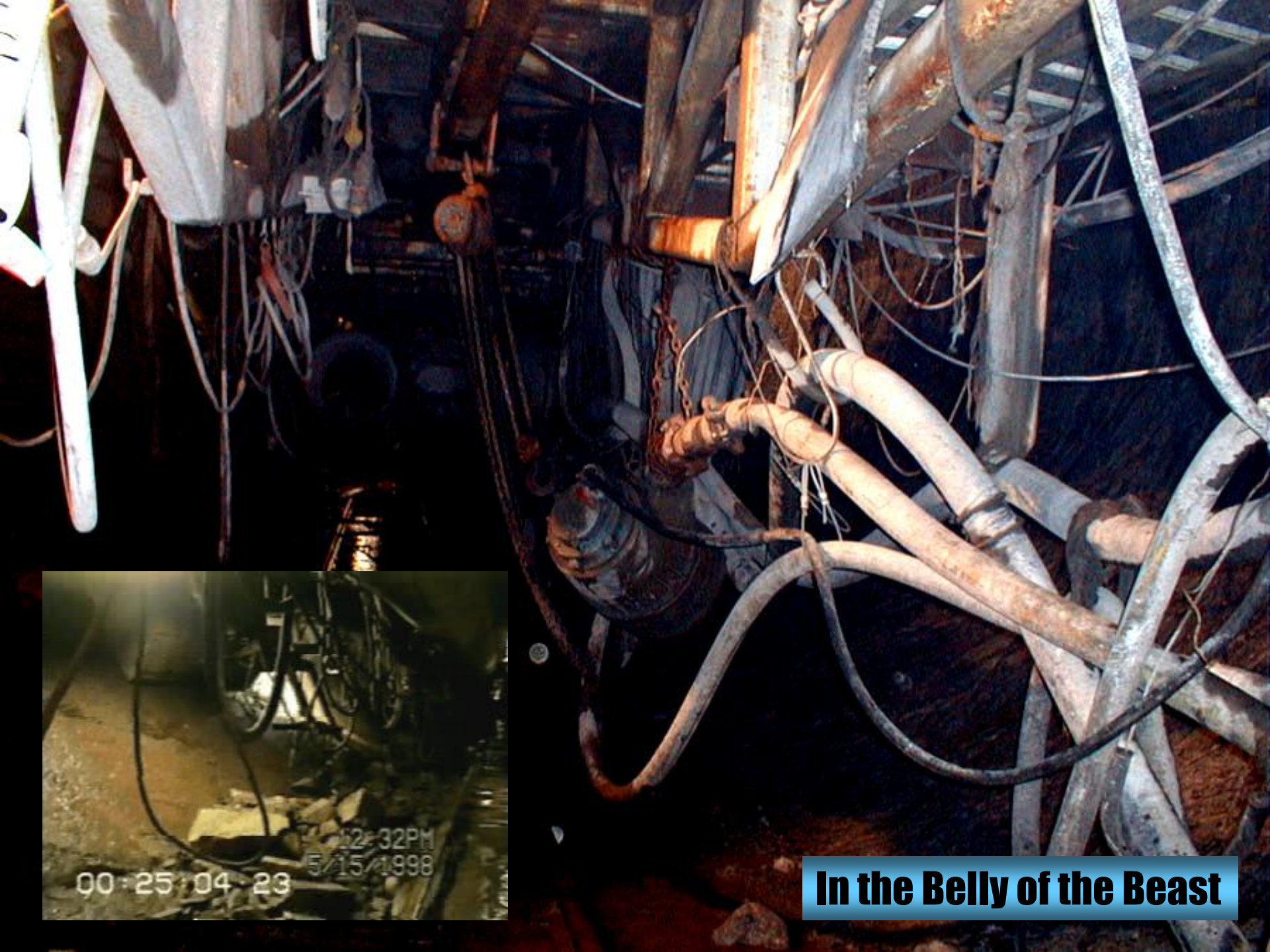
Dukelabs Queens Tunnel Field Office No Windows!

TBM Chip Production



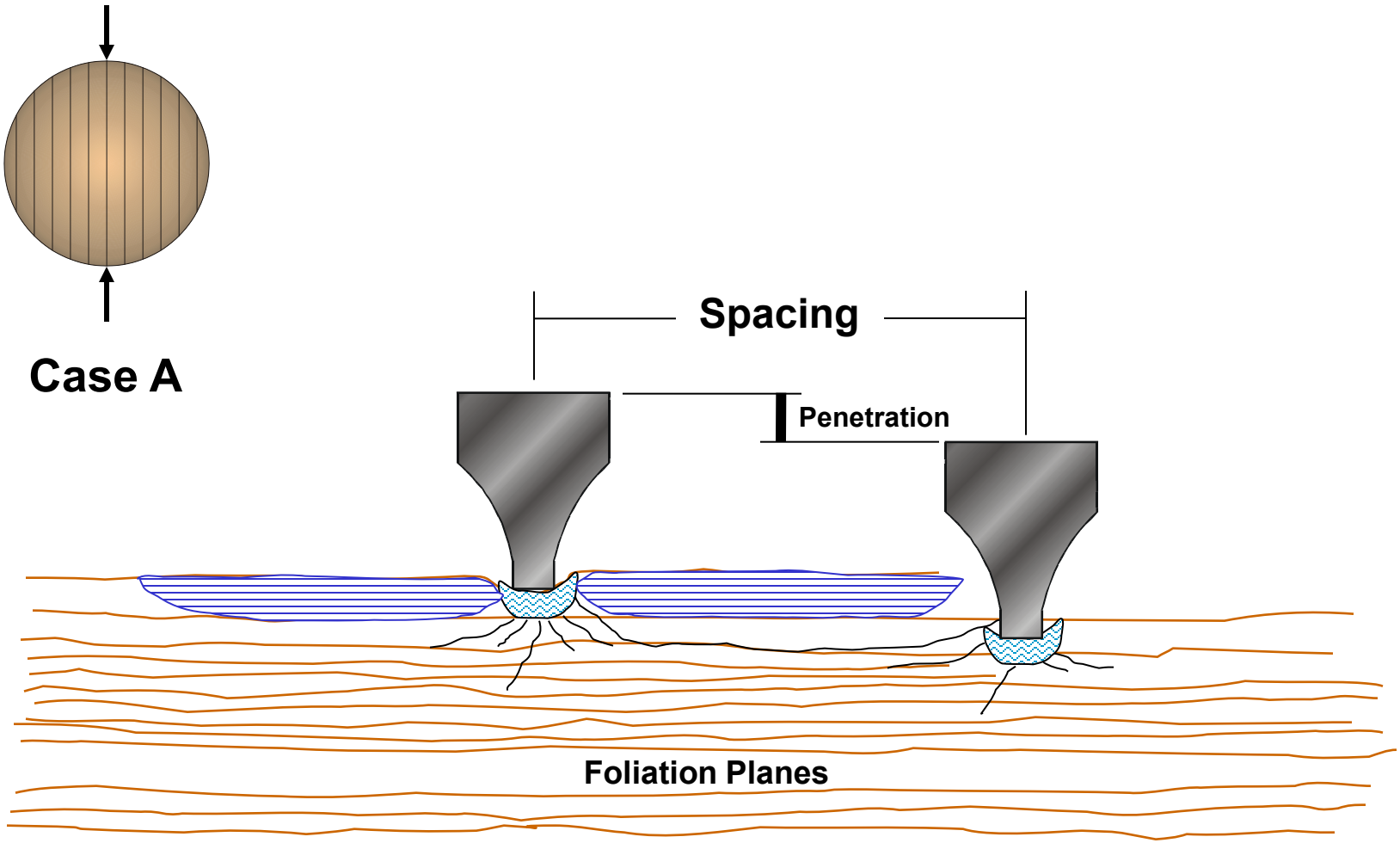



Atlas Copco
Robbins TBM 160-284
MetroWest



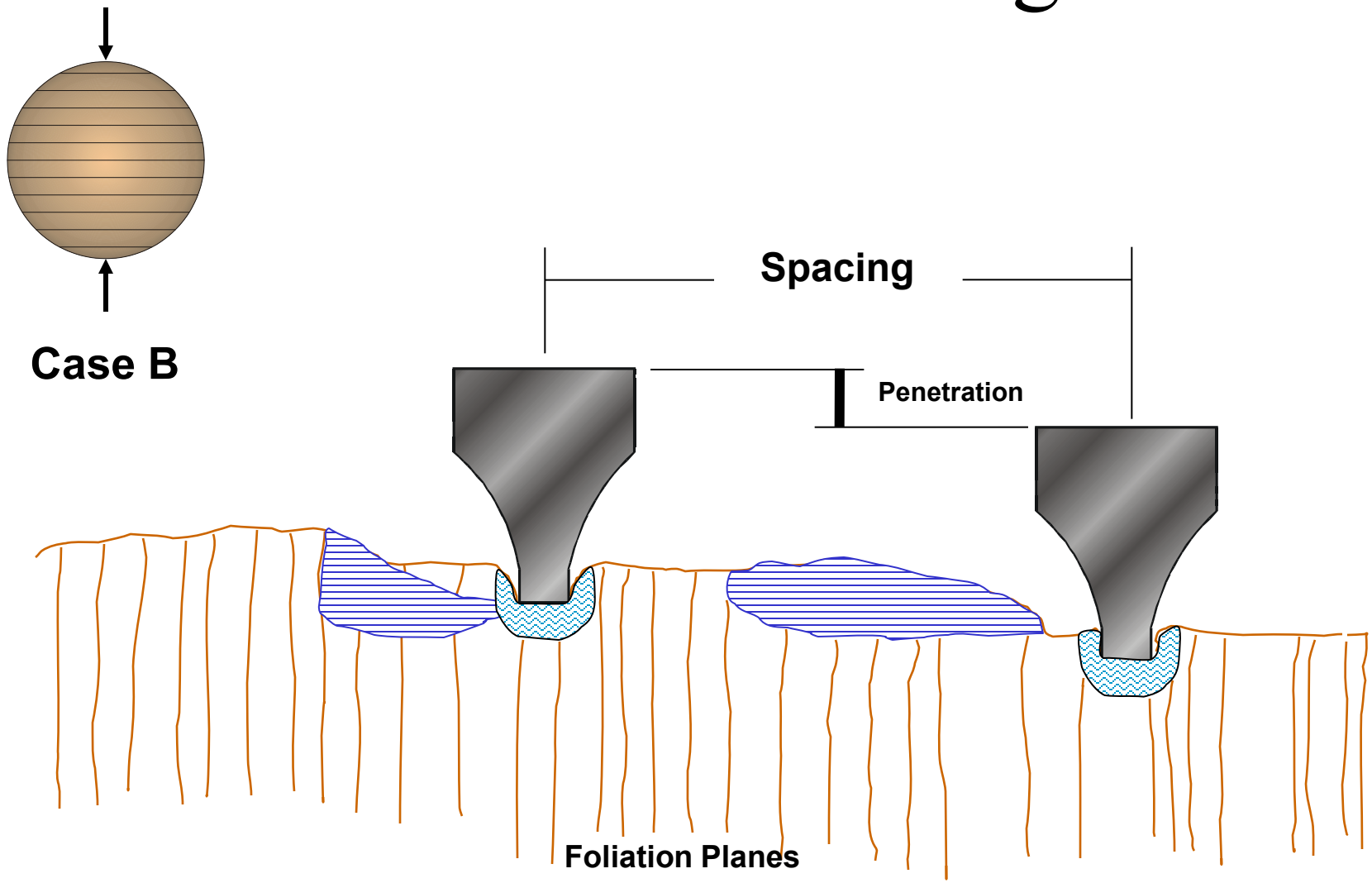
In the Belly of the Beast

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)

Normal TBM Chips

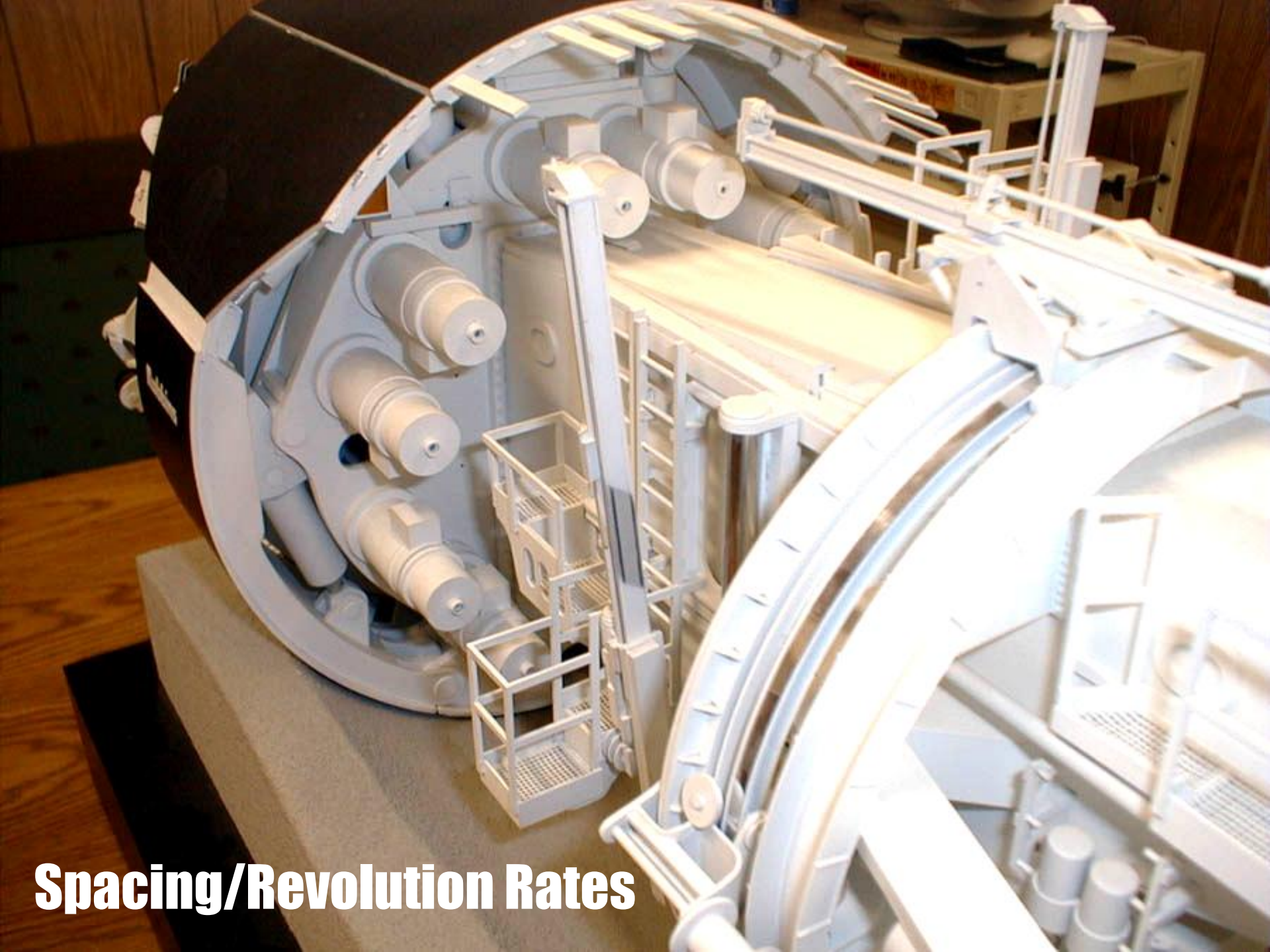
Excessive Fines

Desirable Kerf Pattern in Hard Rocks

Before

After

TBM-Bored Tunnel



Spacing/Revolution Rates

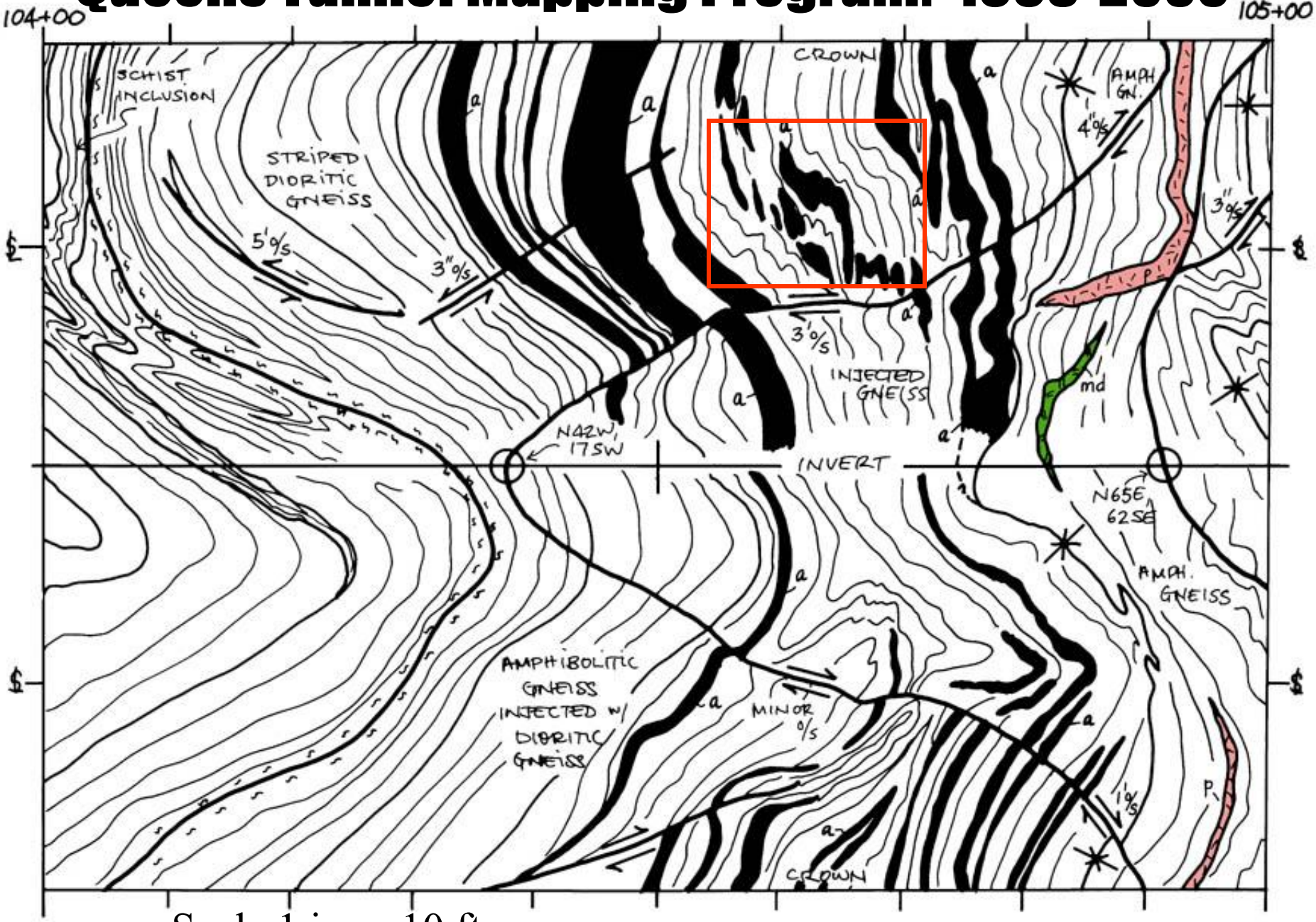
Queens Tunnel TBM
422 HP Electric
Water Cooled,
Three Phase Motors

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

New Research on TBM Cutter Head Torque Dynamics

Six-Month Training Period Beset by Aimless, Lackluster Performance

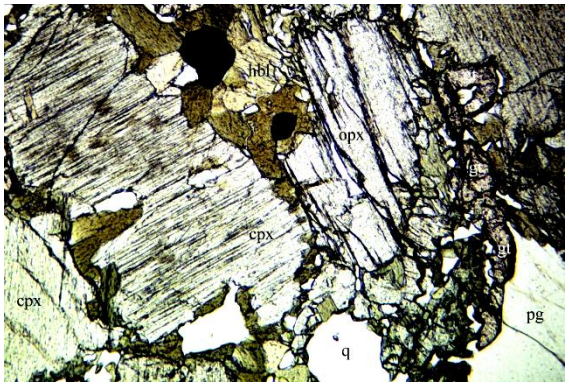
Queens Tunnel Mapping Program: 1998-2000



- Scale 1 in. = 10 ft

330
315
104+00
104+65

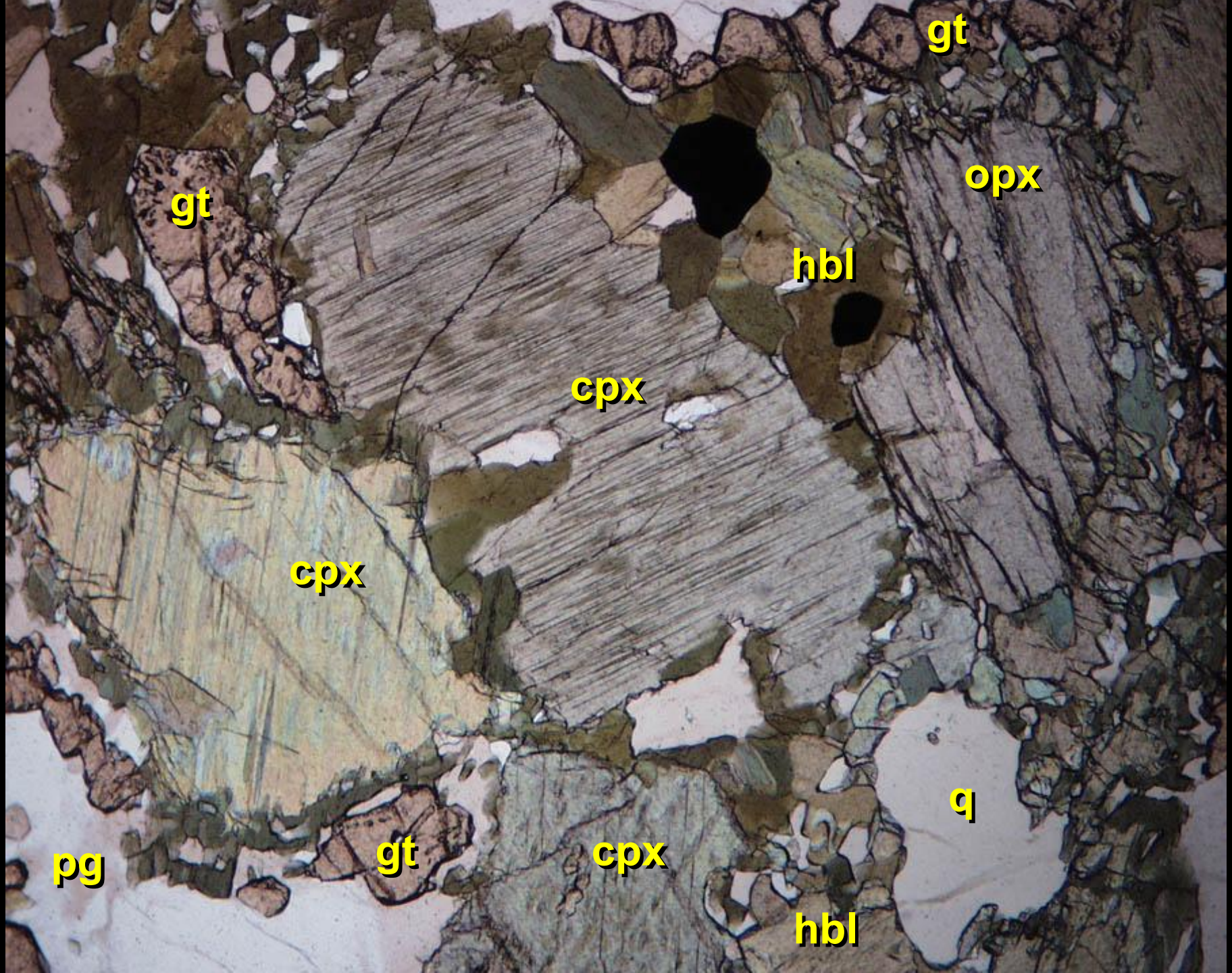
- **Petrographic Analysis (92 Samples)**
  - **Texture**
  - **Mineralogy**
  - **Internal Structure**
  - **Metamorphism**



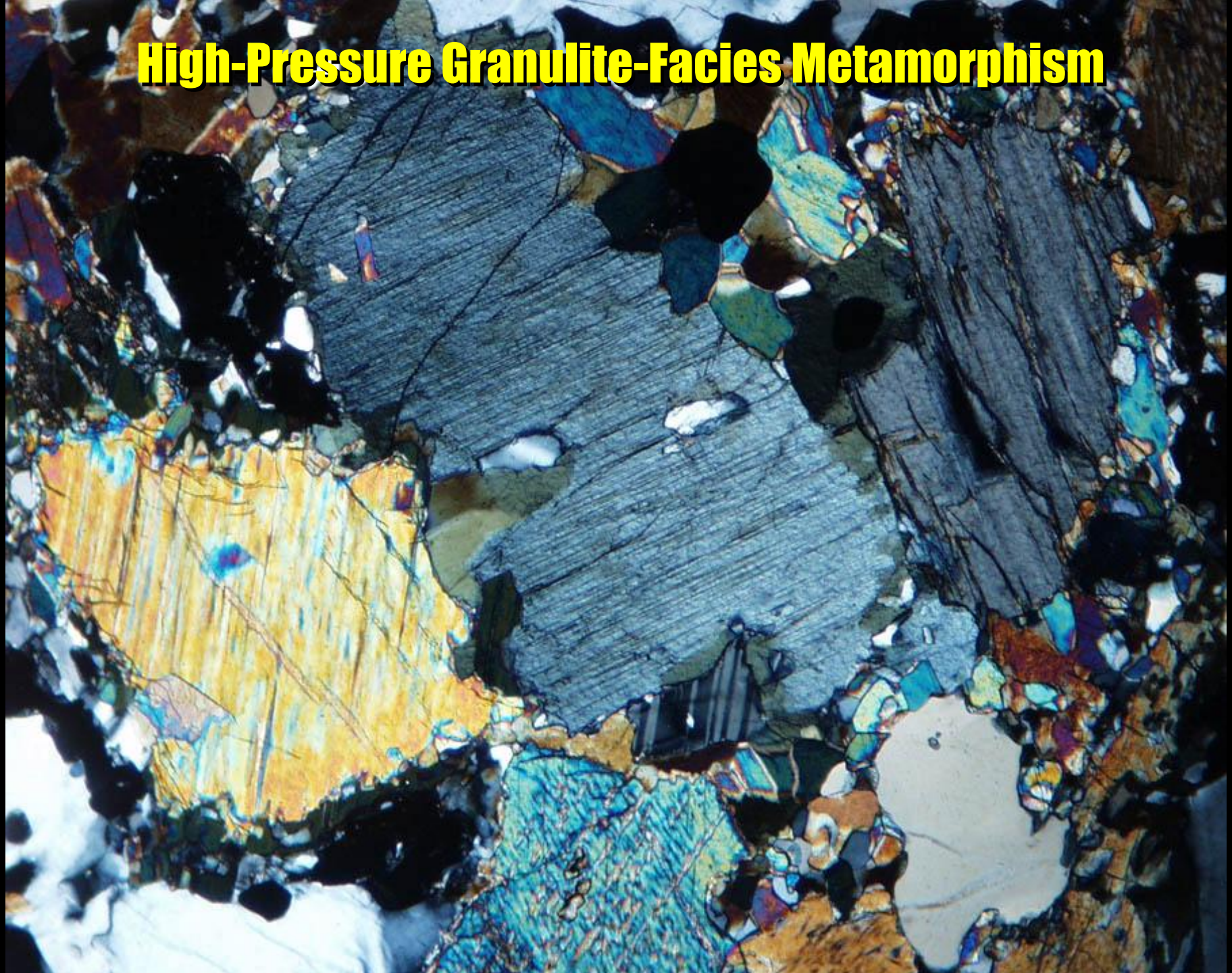
Thin section photomicrograph

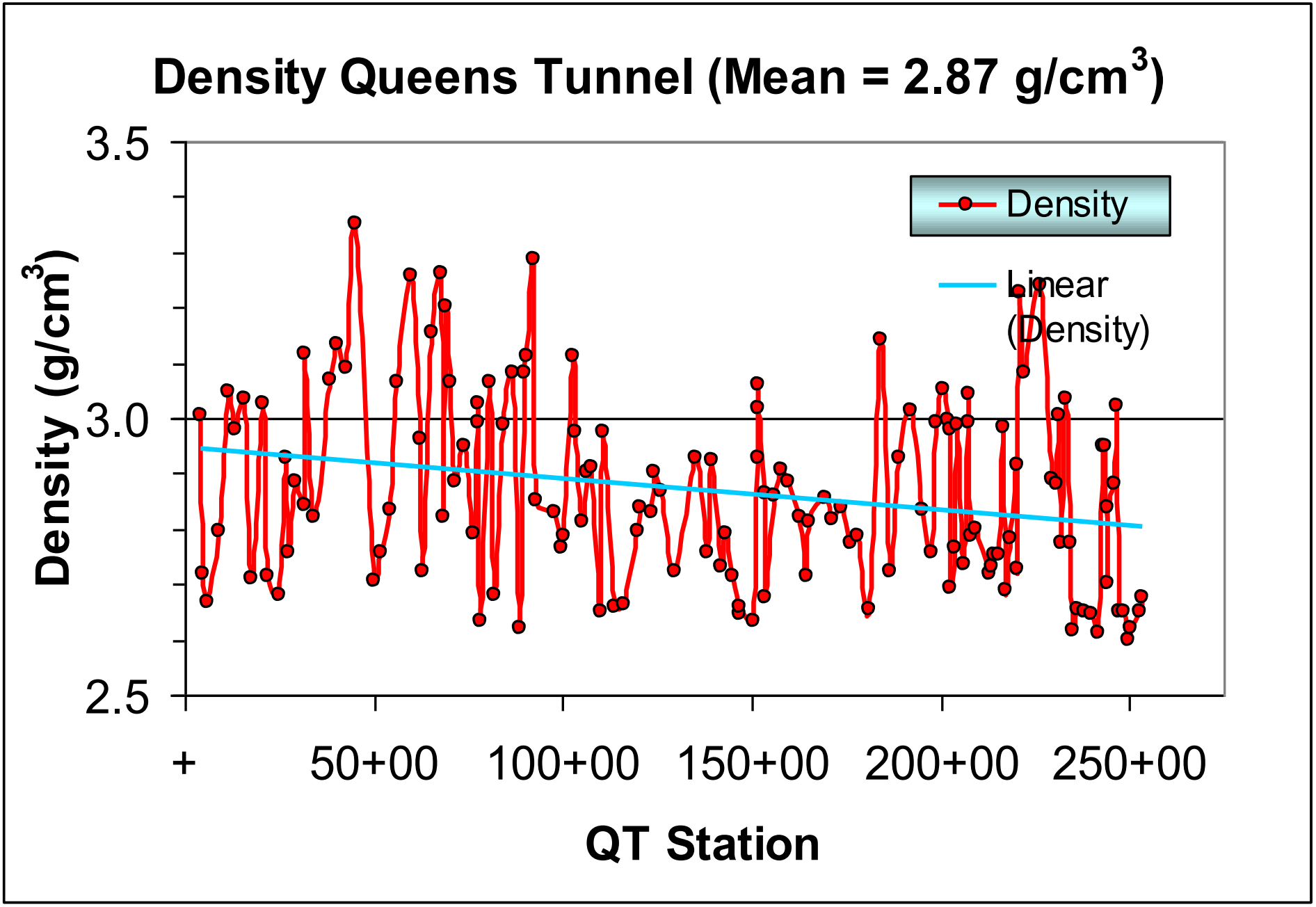
Number	Location	Color	Density	Qtz	Kspar	Plagio/	**An**	Opx	Cpx	Hbld	Bio	Garnet	Opaque
Q109	004+80					M	35	M		M			
Q109	004+80	25	2.72	M		M	35			m	m	m	
Q110	006+42	10	2.66	M	tr+AP	M					m gnbk	tr	tr
Q111	009+25	25	2.79	M		M		m		tr	m	M py encl Q	tr
Q112	011+60	35	3.05	m		M	51		M exsol	m gnkh		M py	
Q114	015+90	45	3.03	m		M	53-39	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	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	trms
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*	
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

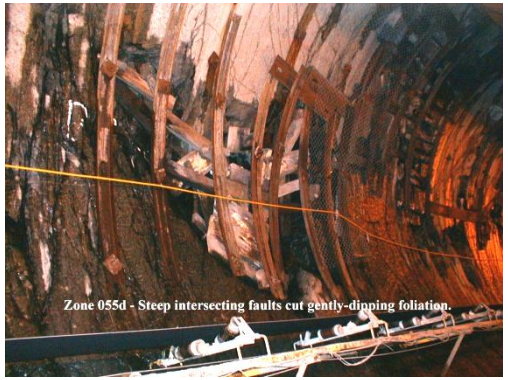

gt
opx
gt
hbl
cpx
cpx
q
pg
gt
cpx
hbl

High-Pressure Granulite-Facies Metamorphism




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

Orientation of Rock Layering



NE strike and moderate 57° dip anticipated

- **[Based on borings, Chesman, Tarkoy]**

Highly variable trends found

- **Extended reaches of tunnel exhibited gentle dips**

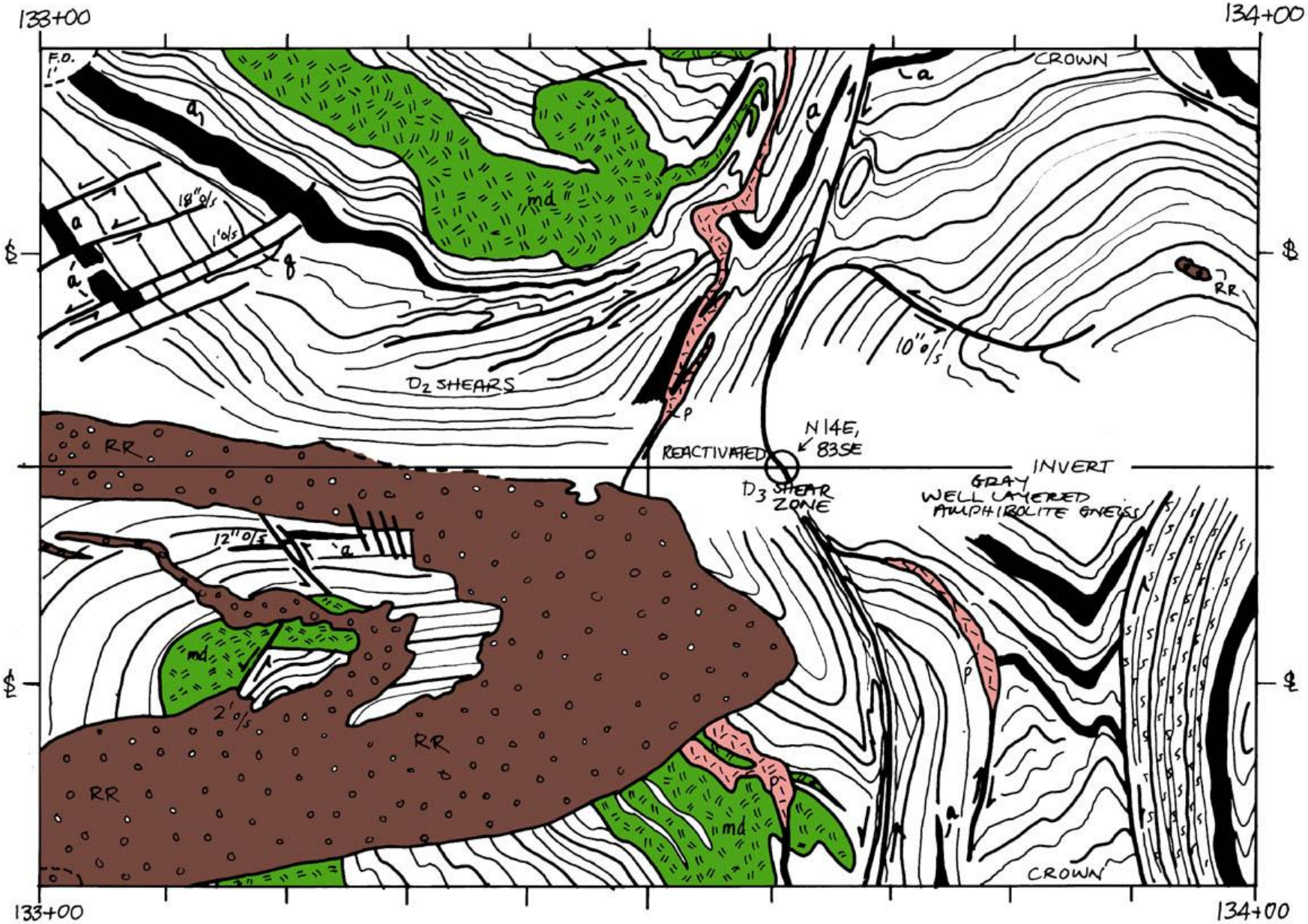
Only one boring (QTL-12) exhibited gentle dips at tunnel horizon

		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%

High Garnet Content

Increased Density and Abrasivity of Rock Mass

Rhyodacite Dike Swarm

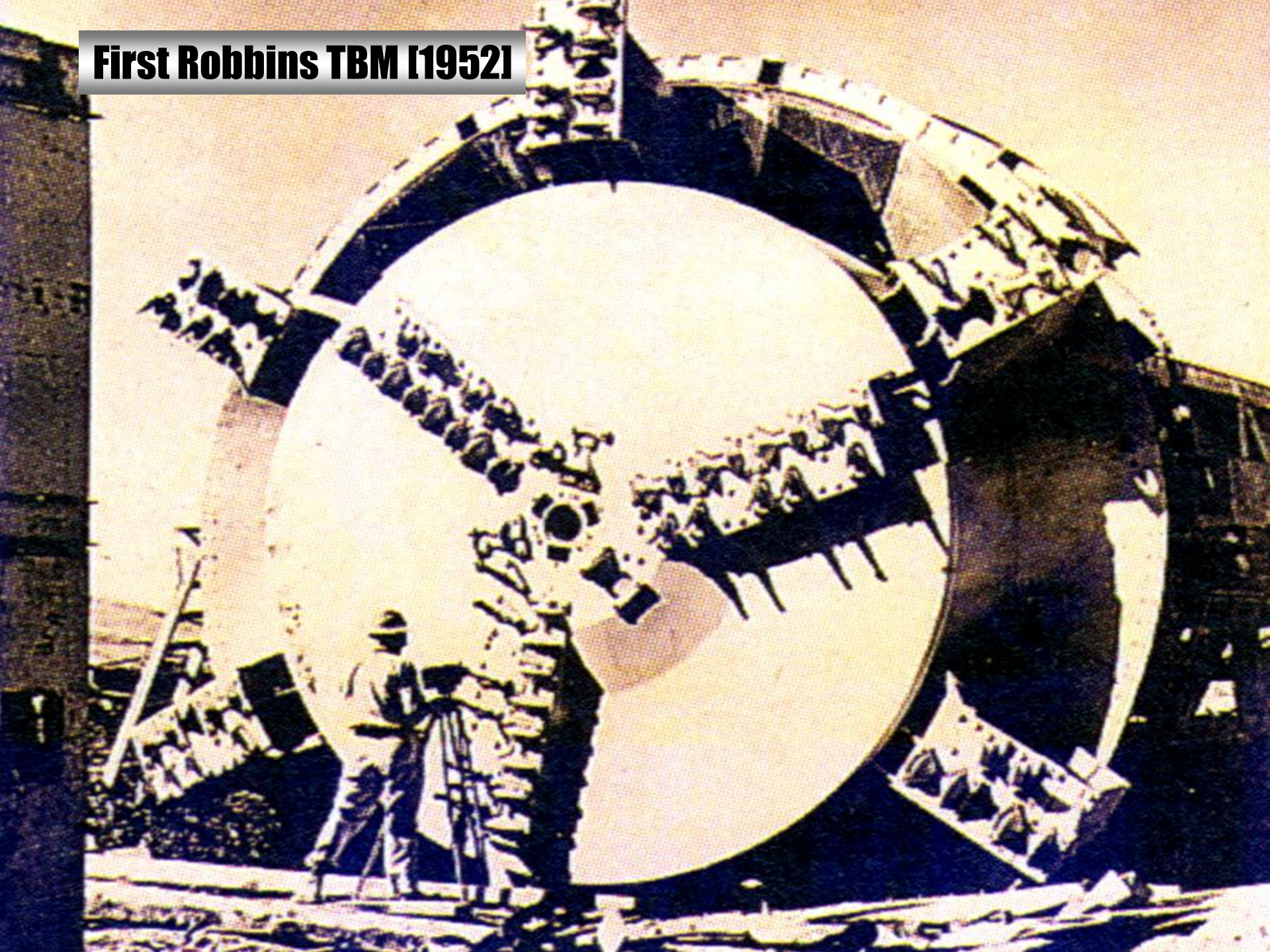


Major Lithologic Contrast
No Counterpart in NYC!

12:05PM
5/15/1998
00:15

Short Stand-up Times

First Robbins TBM [1952]



Factors: TBM Penetration Destiny

Intrinsic Factors (Controlling Penetration Rate)

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

Episodic Factors (Controlling Utilization)

- Convergent Fault Zones
- Unusual (Unanticipated) Rock Types/Structures
- Stress Popping/Heave
- Excessive Water Inflows

Unforseen Tunneling Problems

NYC TBM Projects

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

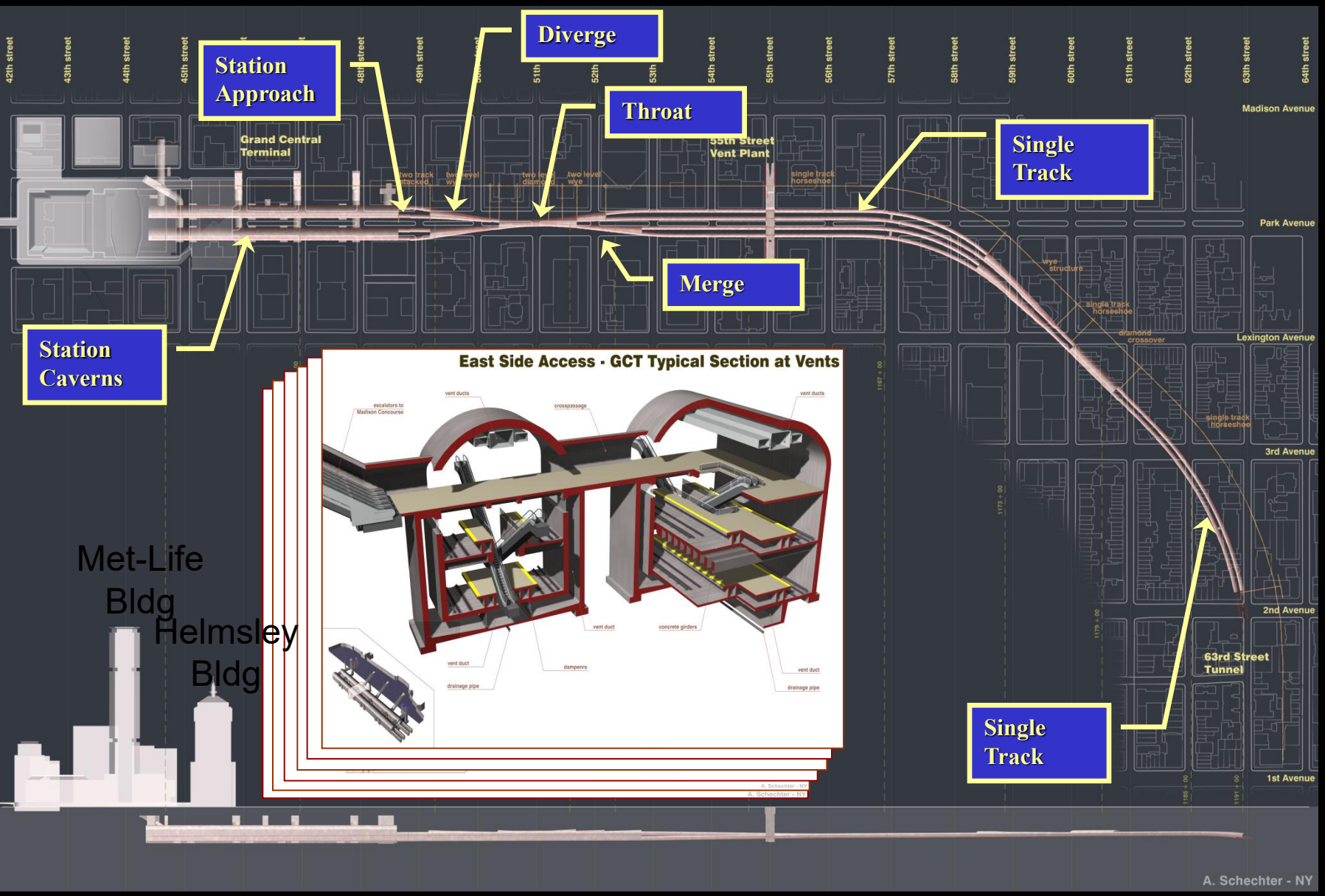
NYC TBM Projects

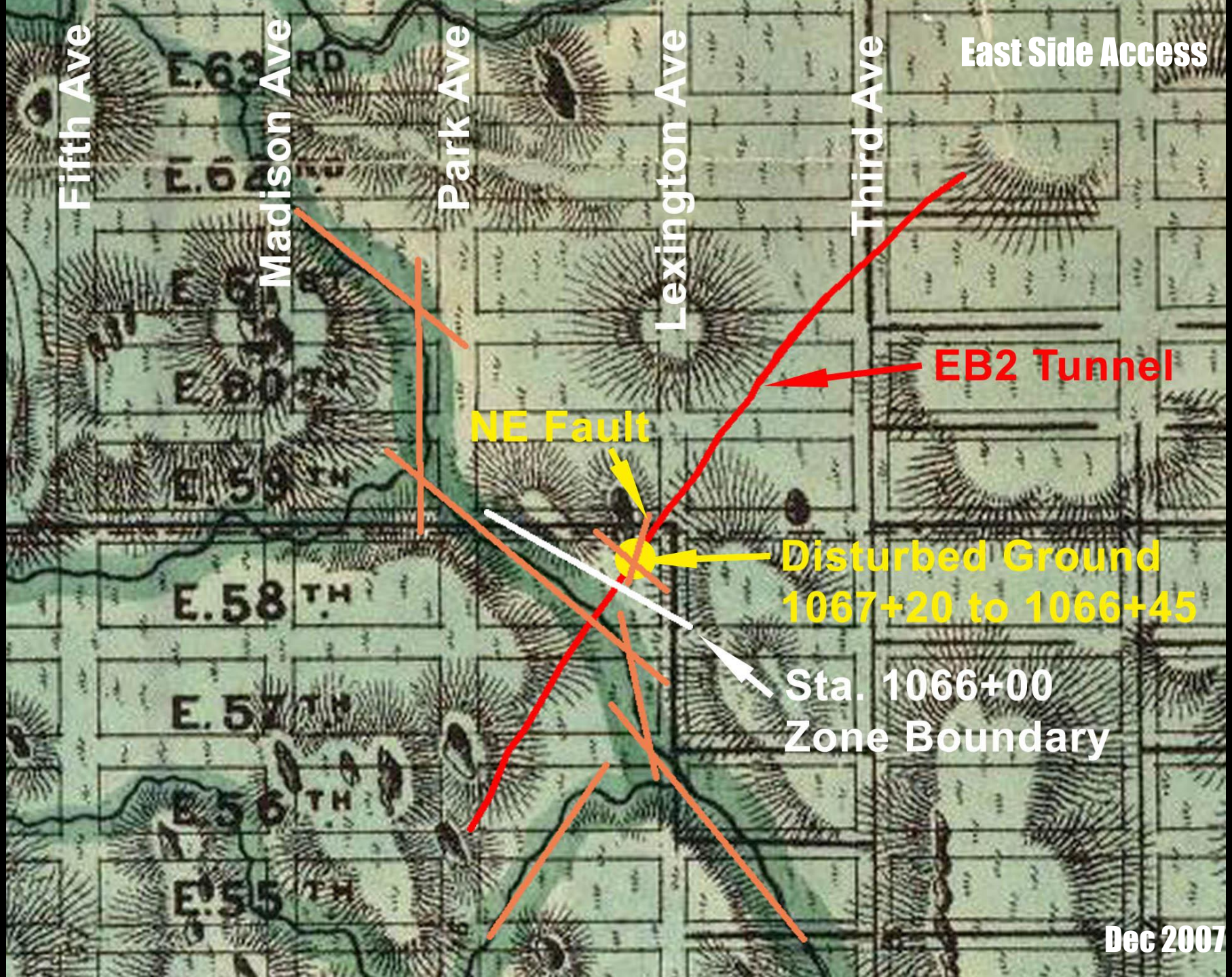
63rd Street Tunnels

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

East Side Access
13 Aug 2007

East Side Access Project Plans

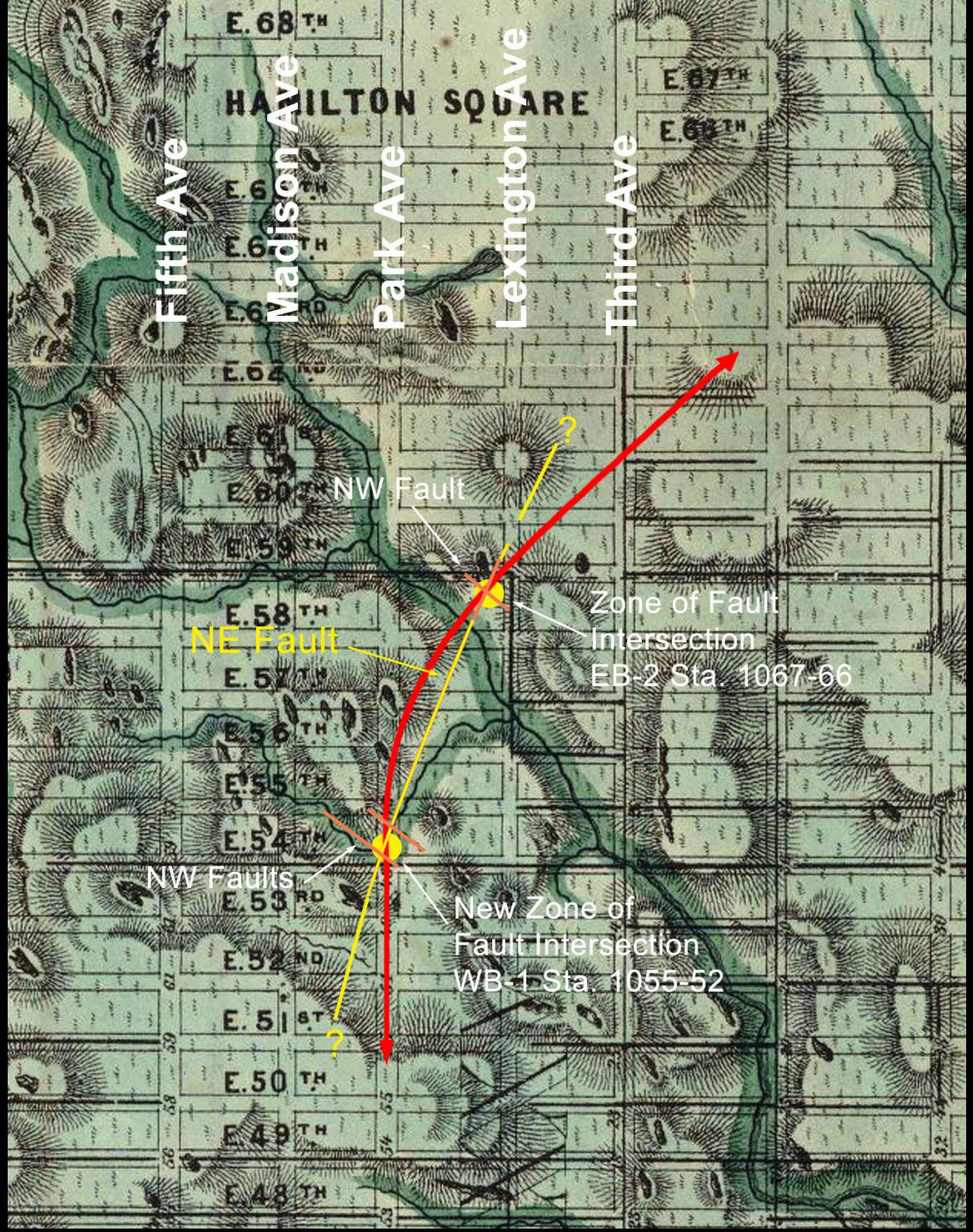



East Side Access
Fifth Ave
Madison Ave
Park Ave
Lexington Ave
Third Ave
E.63RD
E.62ND
E.61ST
E.60TH
E.59TH
E.58TH
E.57TH
E.56TH
E.55TH
EB2 Tunnel
NE Fault
Disturbed Ground
1067+20 to 1066+45
Sta. 1066+00
Zone Boundary
Dec 2007

East Side Access
Dec 2007

East Side Access
Dec 2007

East Side Access



Nov 2009

East Side Access

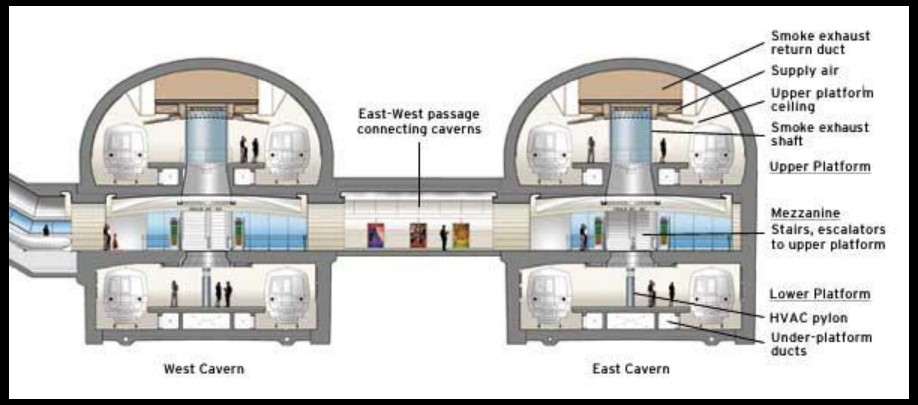
Nov 2009

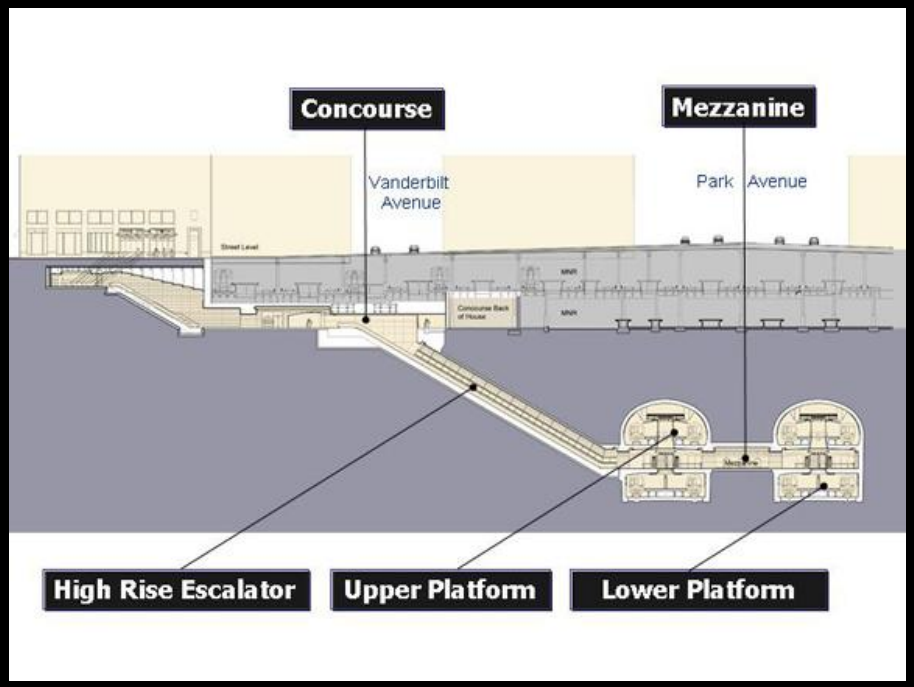
East Side Access
ZONE 2
ZONE 1
Nov 2009

East Side Access

Nov 2009

Construction Took Place Under Existing GCT





East Side Access
GCT
Jan 2010

East Side Access
GCT
Jan 2010

East Side Access
GCT
Jan 2010

East Side Access
304
CUT 10'
GCT
Jan 2010

East Side Access
AH
30+05
GCT
Jan 2010

NYC TBM Projects

Second Avenue Subway

1929 – NYC BOT Proposes Second Avenue Subway

1931 – Plans Postponed for Depression Era

$86M → $249M → $500M

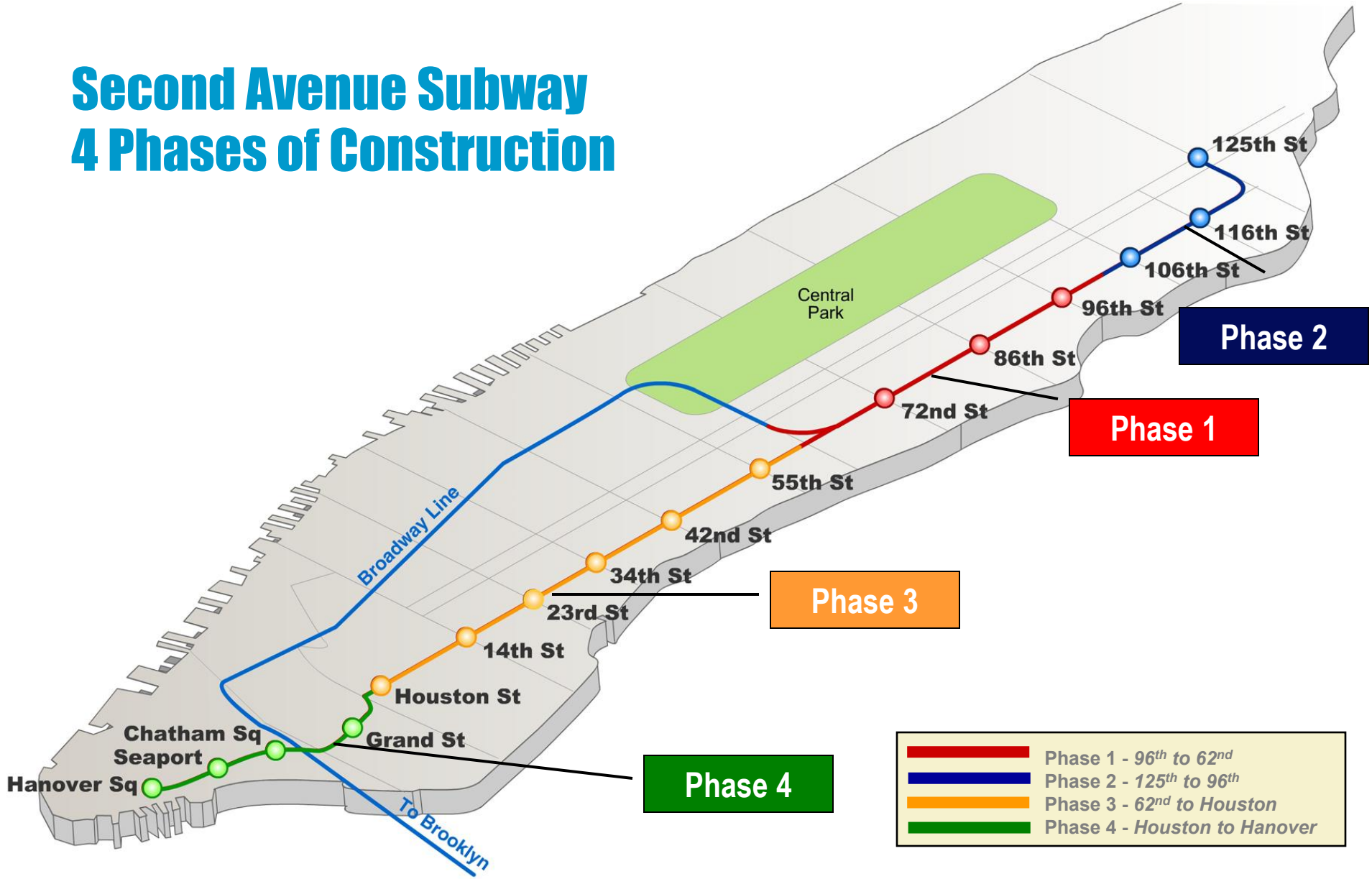
By 1948 – Abandonment

June 2010 – TBM Starts S Tube

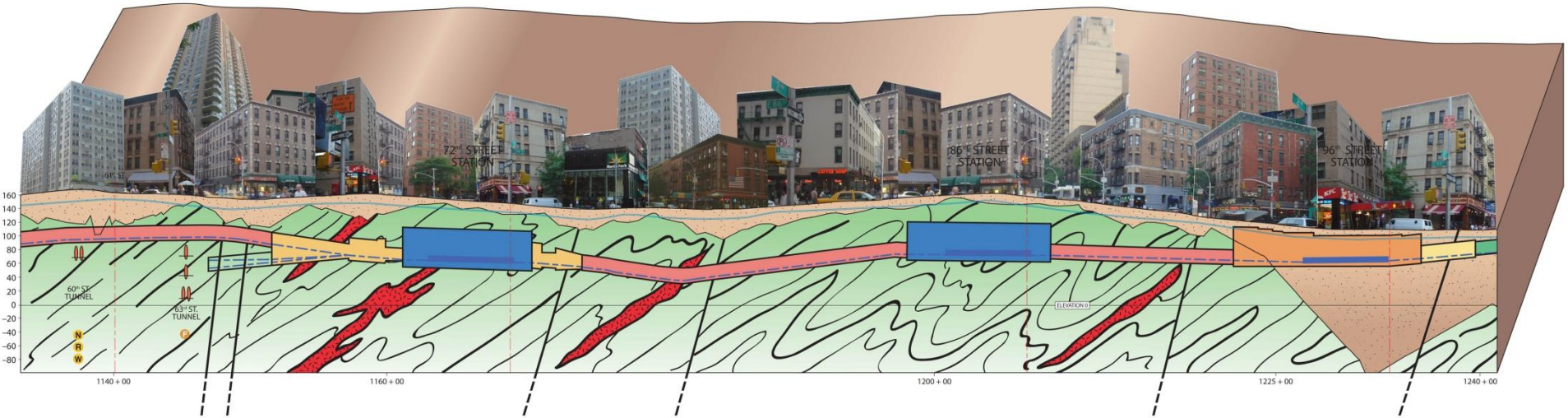
2013 – Station Complexes

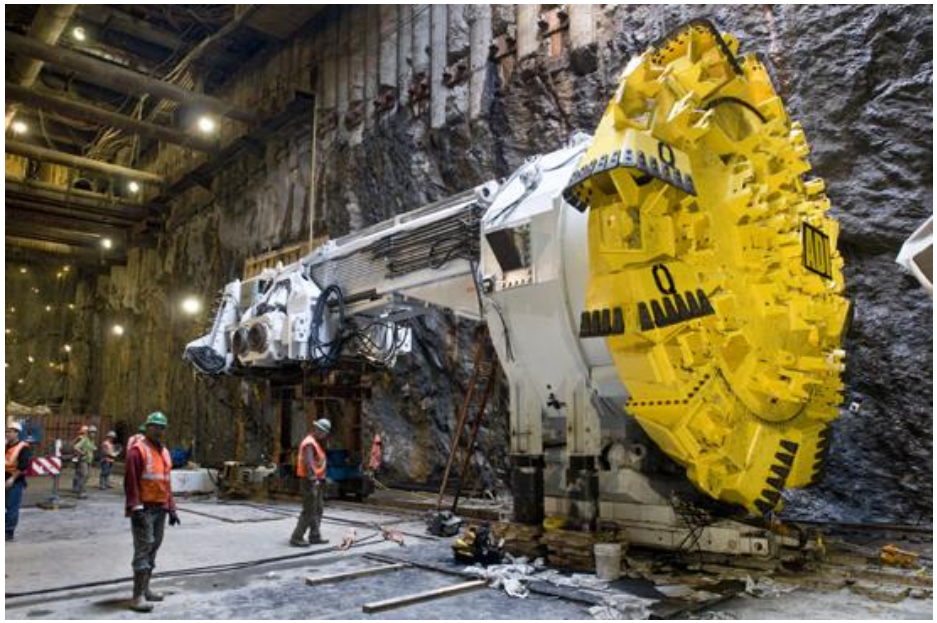
ROUTE 72A SECTION 13
2ND AVENUE SUBWAY - CONTRACT 0-2091-4
EAST 110TH ST. TO EAST 120TH ST., MAN.
CAYUGA-CRIMMINS
VIEW 2nd AVE @ 115th ST. X-ing

Second Avenue Subway
4 Phases of Construction



Threading The Needle





Second Avenue Subway
96th Street Station Complex
27 Mar 2011

Second Avenue Subway
96th Street Station Complex
27 Mar 2011

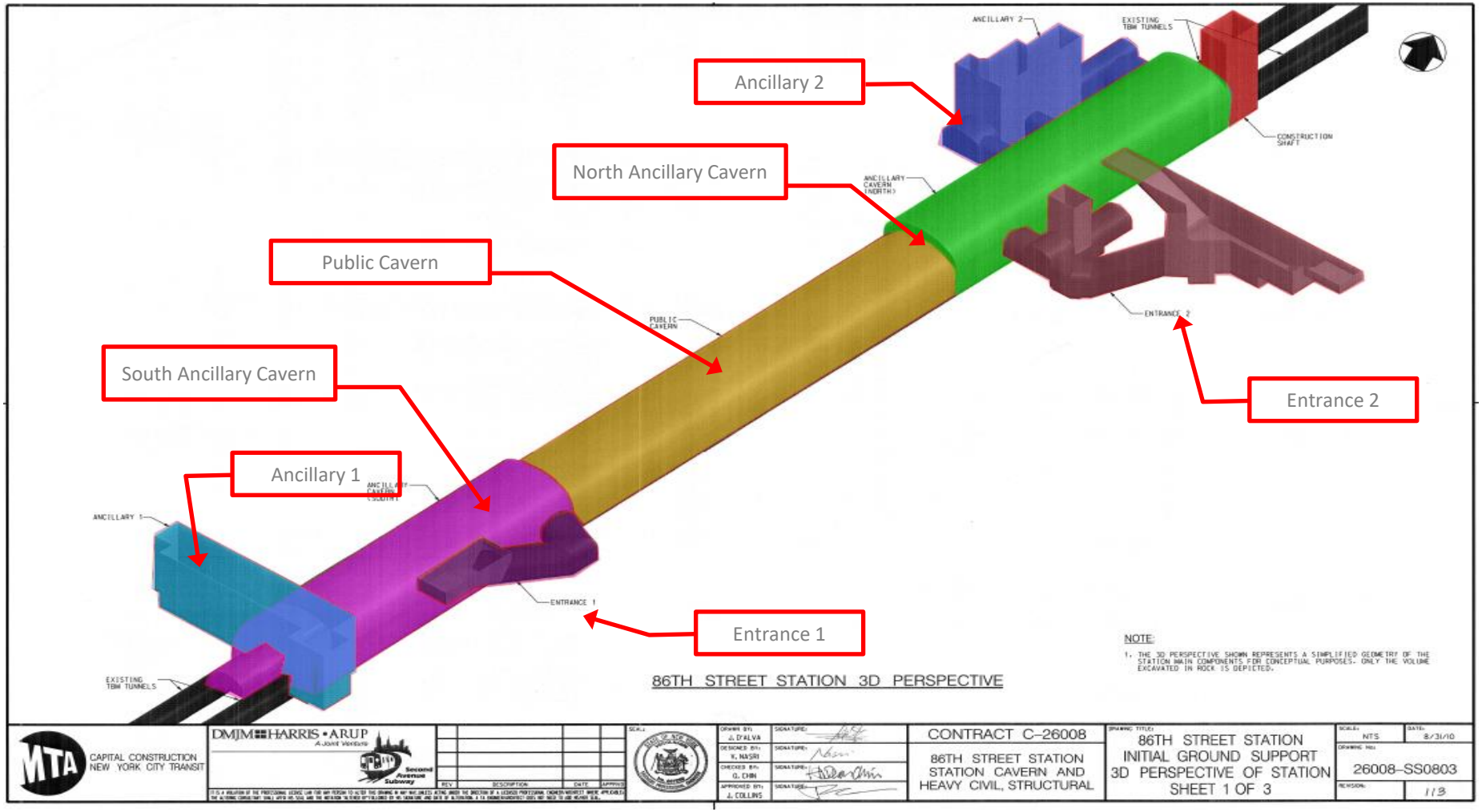
Second Avenue Subway
96th Street Station Complex
27 Mar 2011

Second Avenue Subway
27 Mar 2011

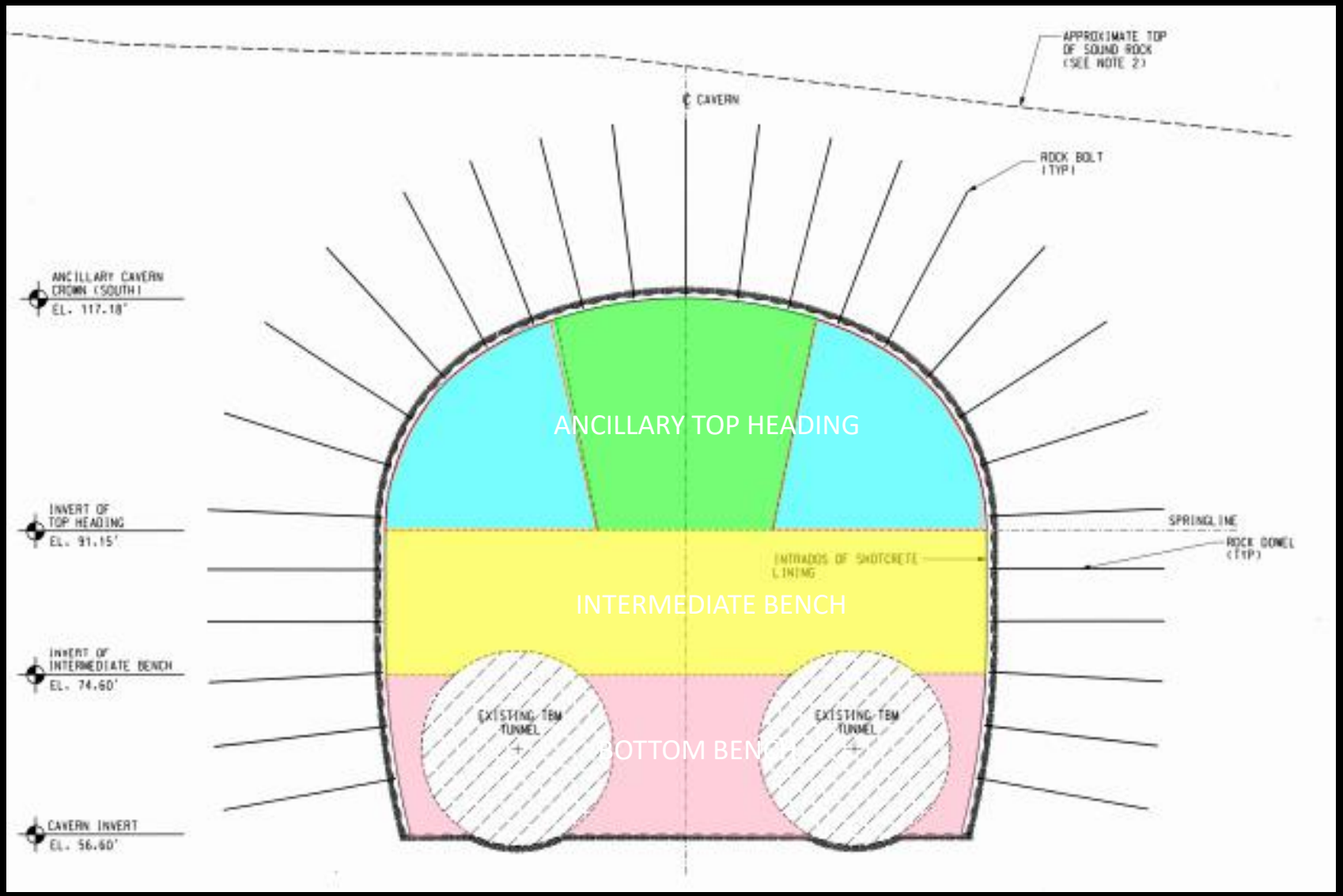
Second Avenue Subway
S Tube – Sta. 1172+80 LW F2 COh
27 Mar 2011

Second Avenue Subway
South Tube – Sta. 1188+30 LW Gentle Foln
27 Mar 2011

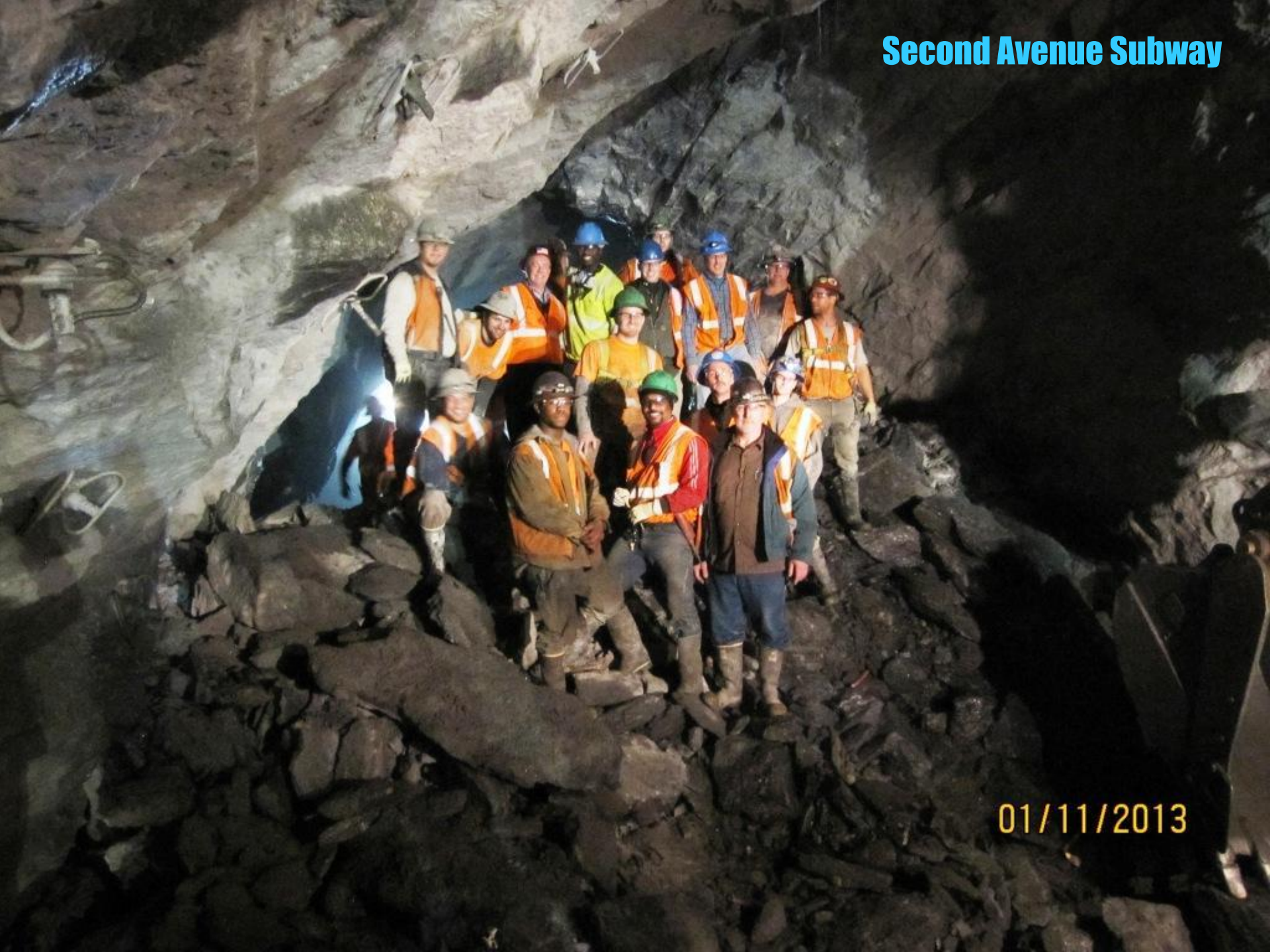
86th Street Station - Cavern Excavation



86th Street Station – Main Cavern Excavation



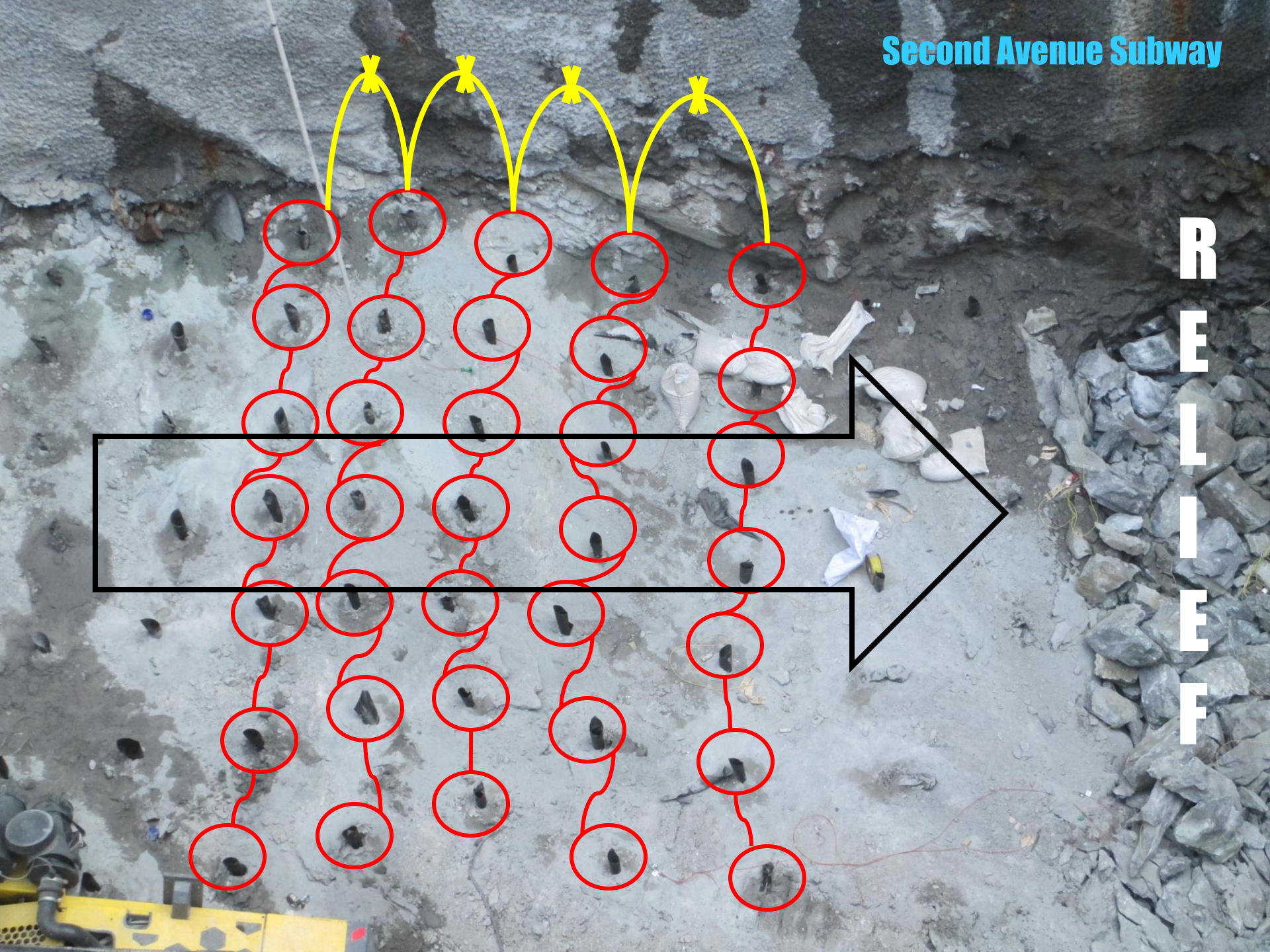
Second Avenue Subway


Second Avenue Subway
01/11/2013

Second Avenue Subway
01/23/2013

Second Avenue Subway
Second Avenue Subway
86th Street Station Complex
Ancillary #2
25 Sept 2012

Second Avenue Subway
SKANSKA
Second Avenue Subway
86th Street Station Complex
Ancillary #2
06 Nov 2012


Second Avenue Subway
RELIEF

Second Avenue Subway
86th Street Station Complex
Ancillary #2

19 Dec 2012

Second Avenue Subway
86th Street Ancillary #2
Southward View of South Wall
Elevation +155' to +133'

Plate 1

0 5 10 Feet

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Second Avenue Subway
86th Street Ancillary #2
Southward View of South Wall
Elevation +155' to +133'

Plate 2

0 5 10 Feet

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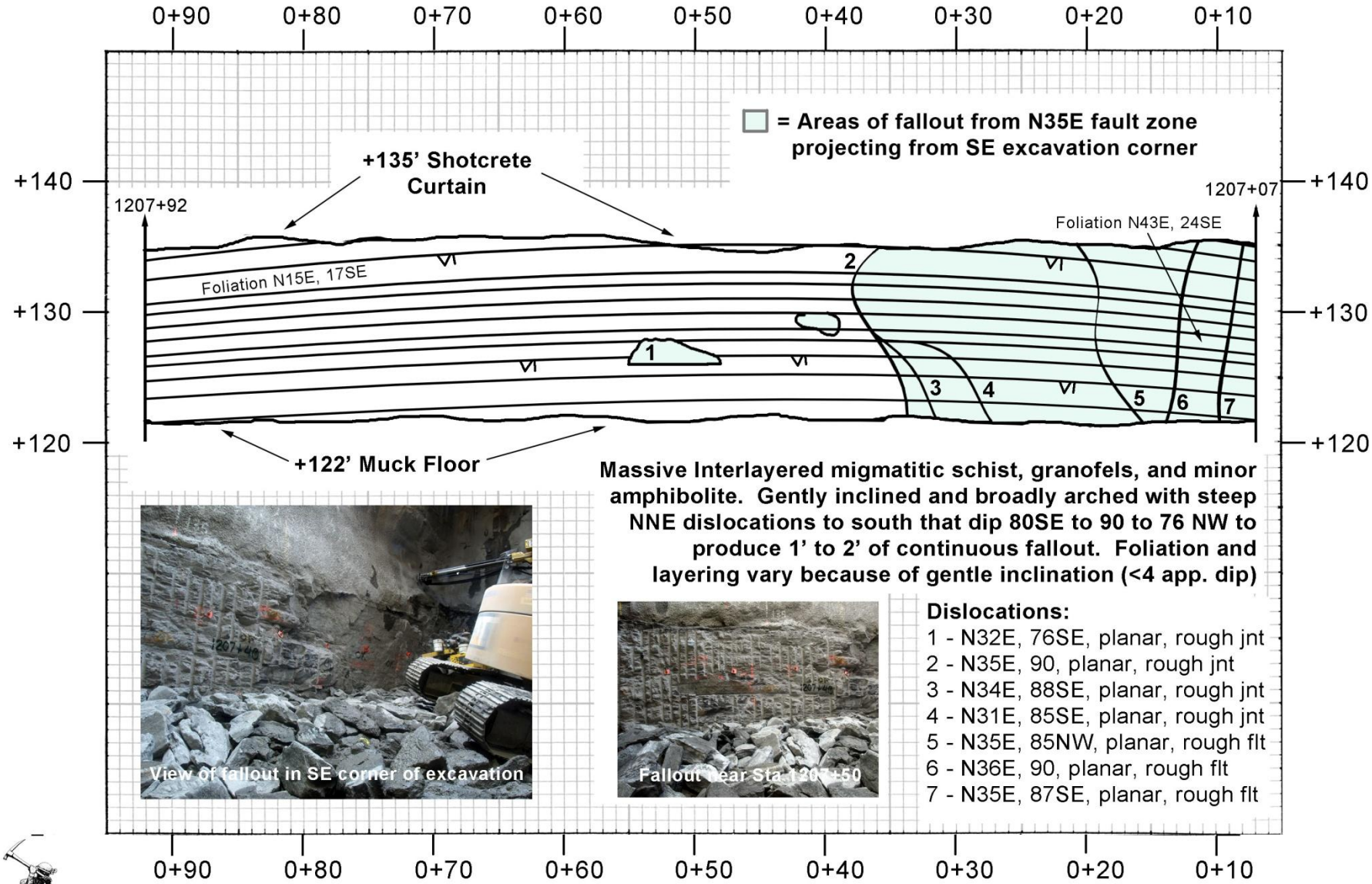
Second Avenue Subway - Ancillary #2 East Wall (Sta. 1207+07 to 1207+92); Elev. +135' to +122'



Massive Interlayered migmatitic schist, granofels, and minor amphibolite. Gently inclined and broadly arched with steep NNE dislocations to south that dip 80SE to 90 to 76 NW to produce 1' to 2' of continuous fallout. Foliation and layering vary because of gentle inclination (<4 app. dip)

View of fallout in SE corner of excavation

Fallout near Sta 1207+50

Dislocations:

1 - N32E, 76SE, planar, rough jnt
2 - N35E, 90, planar, rough jnt
3 - N34E, 88SE, planar, rough jnt
4 - N31E, 85SE, planar, rough jnt
5 - N35E, 85NW, planar, rough flt
6 - N36E, 90, planar, rough flt
7 - N35E, 87SE, planar, rough flt

0+90 0+80 0+70 0+60 0+50 0+40 0+30 0+20 0+10

Stationing in Feet North Along East Wall

(Map Drawn Parallel to Sta 0+50 West of Second Avenue Centerline)

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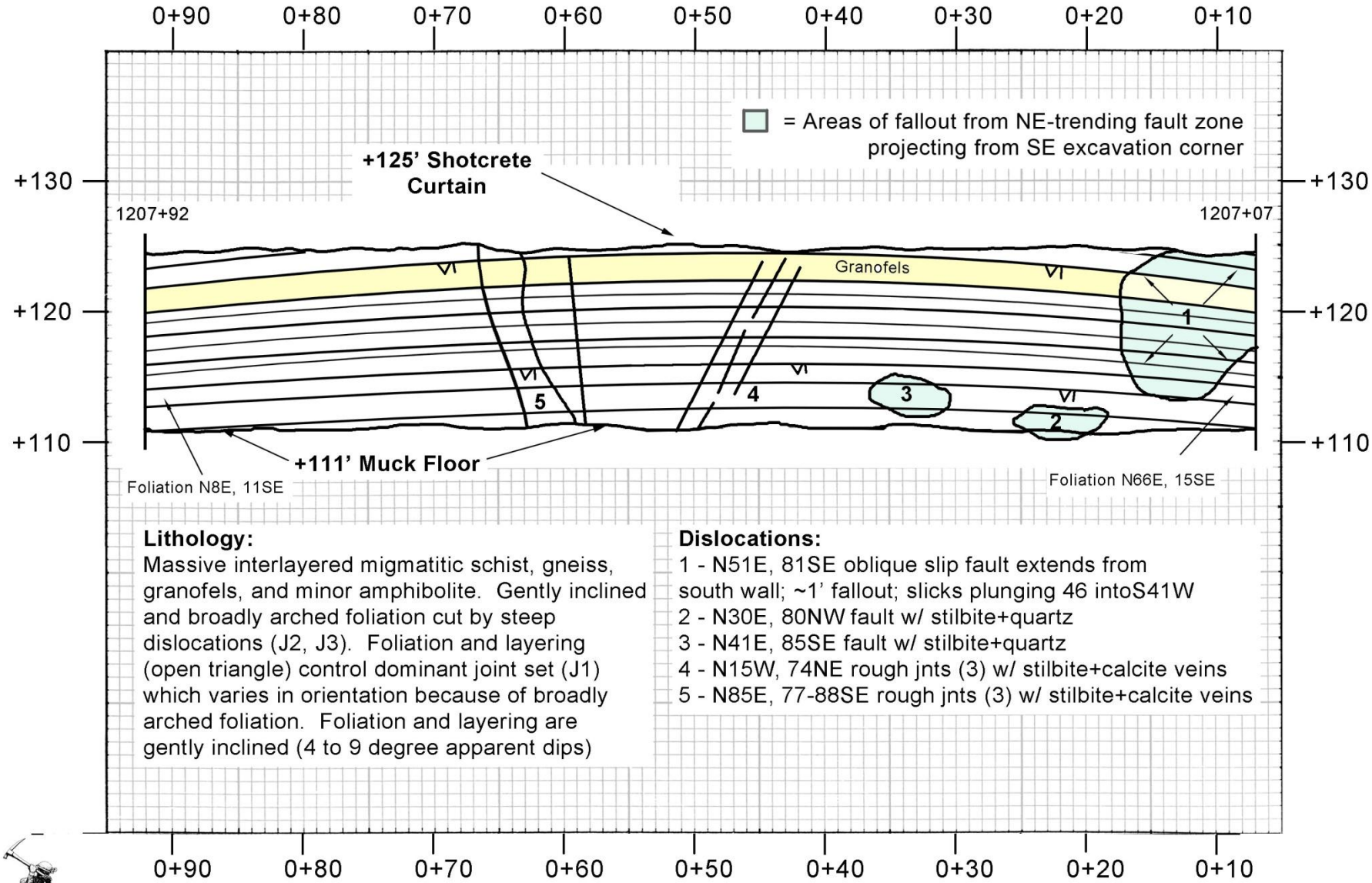
Mapped 21 November 2012

Second Avenue Subway - Ancillary #2 East Wall Sta. 1207+07 to 1207+92; Elev. +125' to +111'



Lithology:
Massive interlayered migmatitic schist, gneiss, granofels, and minor amphibolite. Gently inclined and broadly arched foliation cut by steep dislocations (J2, J3). Foliation and layering (open triangle) control dominant joint set (J1) which varies in orientation because of broadly arched foliation. Foliation and layering are gently inclined (4 to 9 degree apparent dips)

Dislocations:
1 - N51E, 81SE oblique slip fault extends from south wall; ~1' fallout; slicks plunging 46 intoS41W
2 - N30E, 80NW fault w/ stilbite+quartz
3 - N41E, 85SE fault w/ stilbite+quartz
4 - N15W, 74NE rough jnts (3) w/ stilbite+calcite veins
5 - N85E, 77-88SE rough jnts (3) w/ stilbite+calcite veins

Stationing in Feet North Along East Wall
(Map Drawn Parallel to Sta 0+50 West of Second Avenue Centerline)

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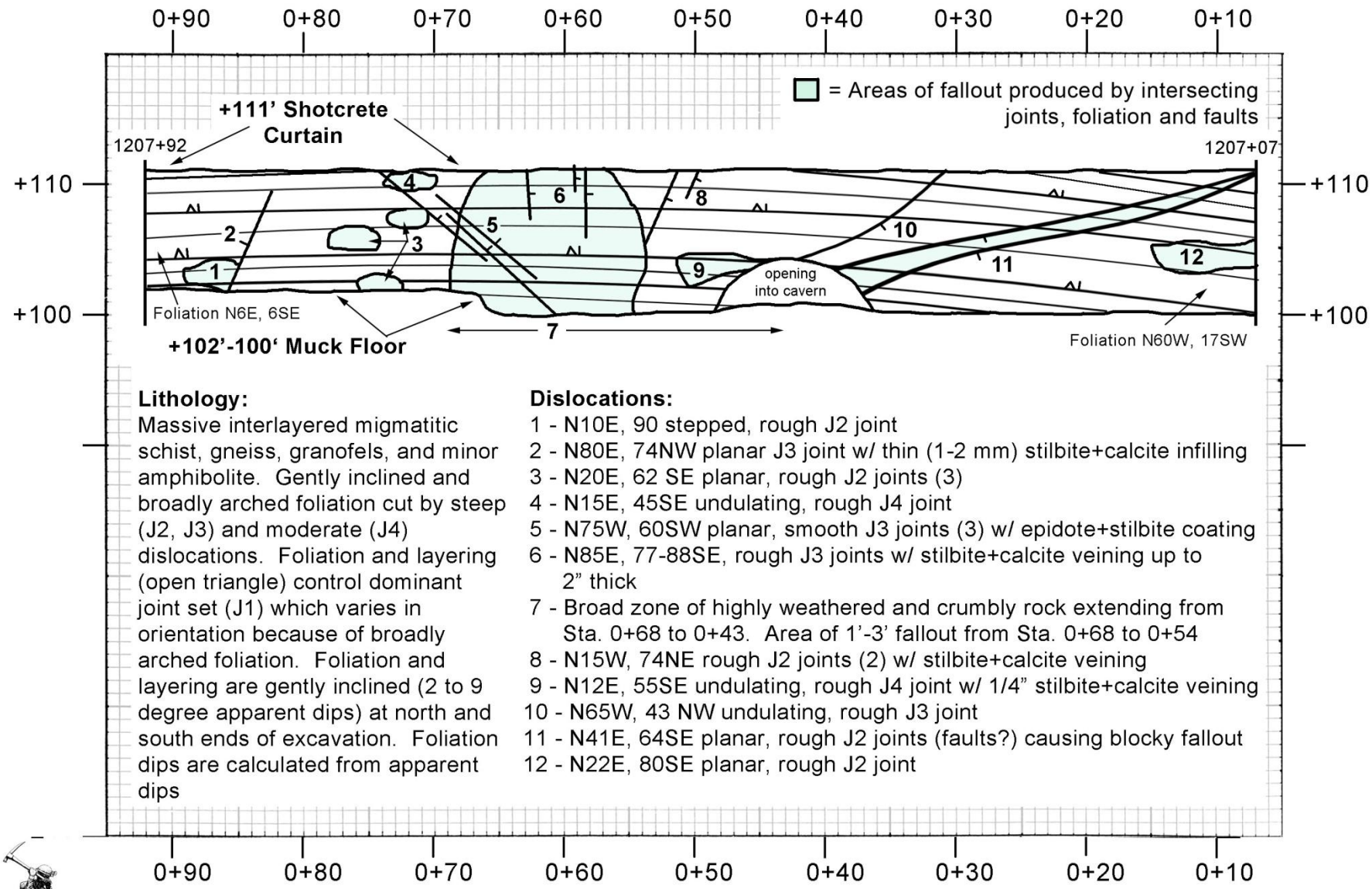
Mapped 15 January 2013

Second Avenue Subway - Ancillary #2 East Wall Sta. 1207+07 to 1207+92; Elev. +111' to +100'



Lithology:
Massive interlayered migmatitic schist, gneiss, granofels, and minor amphibolite. Gently inclined and broadly arched foliation cut by steep (J2, J3) and moderate (J4) dislocations. Foliation and layering (open triangle) control dominant joint set (J1) which varies in orientation because of broadly arched foliation. Foliation and layering are gently inclined (2 to 9 degree apparent dips) at north and south ends of excavation. Foliation dips are calculated from apparent dips

Dislocations:
1 - N10E, 90 stepped, rough J2 joint
2 - N80E, 74NW planar J3 joint w/ thin (1-2 mm) stilbite+calcite infilling
3 - N20E, 62 SE planar, rough J2 joints (3)
4 - N15E, 45SE undulating, rough J4 joint
5 - N75W, 60SW planar, smooth J3 joints (3) w/ epidote+stilbite coating
6 - N85E, 77-88SE, rough J3 joints w/ stilbite+calcite veining up to 2" thick
7 - Broad zone of highly weathered and crumbly rock extending from Sta. 0+68 to 0+43. Area of 1'-3' fallout from Sta. 0+68 to 0+54
8 - N15W, 74NE rough J2 joints (2) w/ stilbite+calcite veining
9 - N12E, 55SE undulating, rough J4 joint w/ 1/4" stilbite+calcite veining
10 - N65W, 43 NW undulating, rough J3 joint
11 - N41E, 64SE planar, rough J2 joints (faults?) causing blocky fallout
12 - N22E, 80SE planar, rough J2 joint

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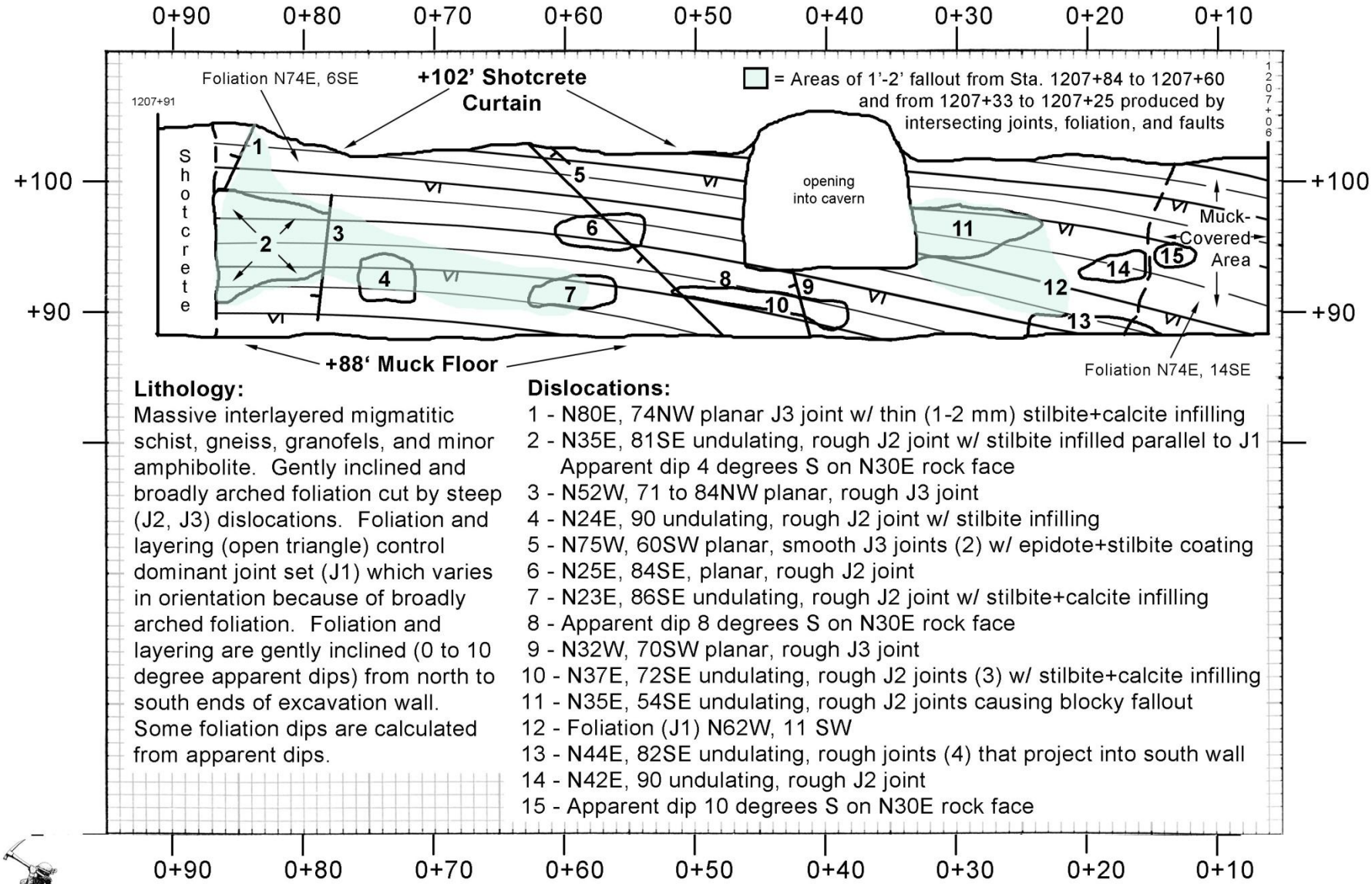
Stationing in Feet North Along East Wall
(Map Drawn Parallel to Sta 0+50 West of Second Avenue Centerline)

Mapped 06 February 2013

Second Avenue Subway - Ancillary #2 East Wall Sta. 1207+06 to 1207+91; Elev. +102' to +88'



Lithology:

Massive interlayered migmatitic schist, gneiss, granofels, and minor amphibolite. Gently inclined and broadly arched foliation cut by steep (J2, J3) dislocations. Foliation and layering (open triangle) control dominant joint set (J1) which varies in orientation because of broadly arched foliation. Foliation and layering are gently inclined (0 to 10 degree apparent dips) from north to south ends of excavation wall. Some foliation dips are calculated from apparent dips.

Dislocations:

1 - N80E, 74NW planar J3 joint w/ thin (1-2 mm) stilbite+calcite infilling
2 - N35E, 81SE undulating, rough J2 joint w/ stilbite infilled parallel to J1
Apparent dip 4 degrees S on N30E rock face
3 - N52W, 71 to 84NW planar, rough J3 joint
4 - N24E, 90 undulating, rough J2 joint w/ stilbite infilling
5 - N75W, 60SW planar, smooth J3 joints (2) w/ epidote+stilbite coating
6 - N25E, 84SE, planar, rough J2 joint
7 - N23E, 86SE undulating, rough J2 joint w/ stilbite+calcite infilling
8 - Apparent dip 8 degrees S on N30E rock face
9 - N32W, 70SW planar, rough J3 joint
10 - N37E, 72SE undulating, rough J2 joints (3) w/ stilbite+calcite infilling
11 - N35E, 54SE undulating, rough J2 joints causing blocky fallout
12 - Foliation (J1) N62W, 11 SW
13 - N44E, 82SE undulating, rough joints (4) that project into south wall
14 - N42E, 90 undulating, rough J2 joint
15 - Apparent dip 10 degrees S on N30E rock face

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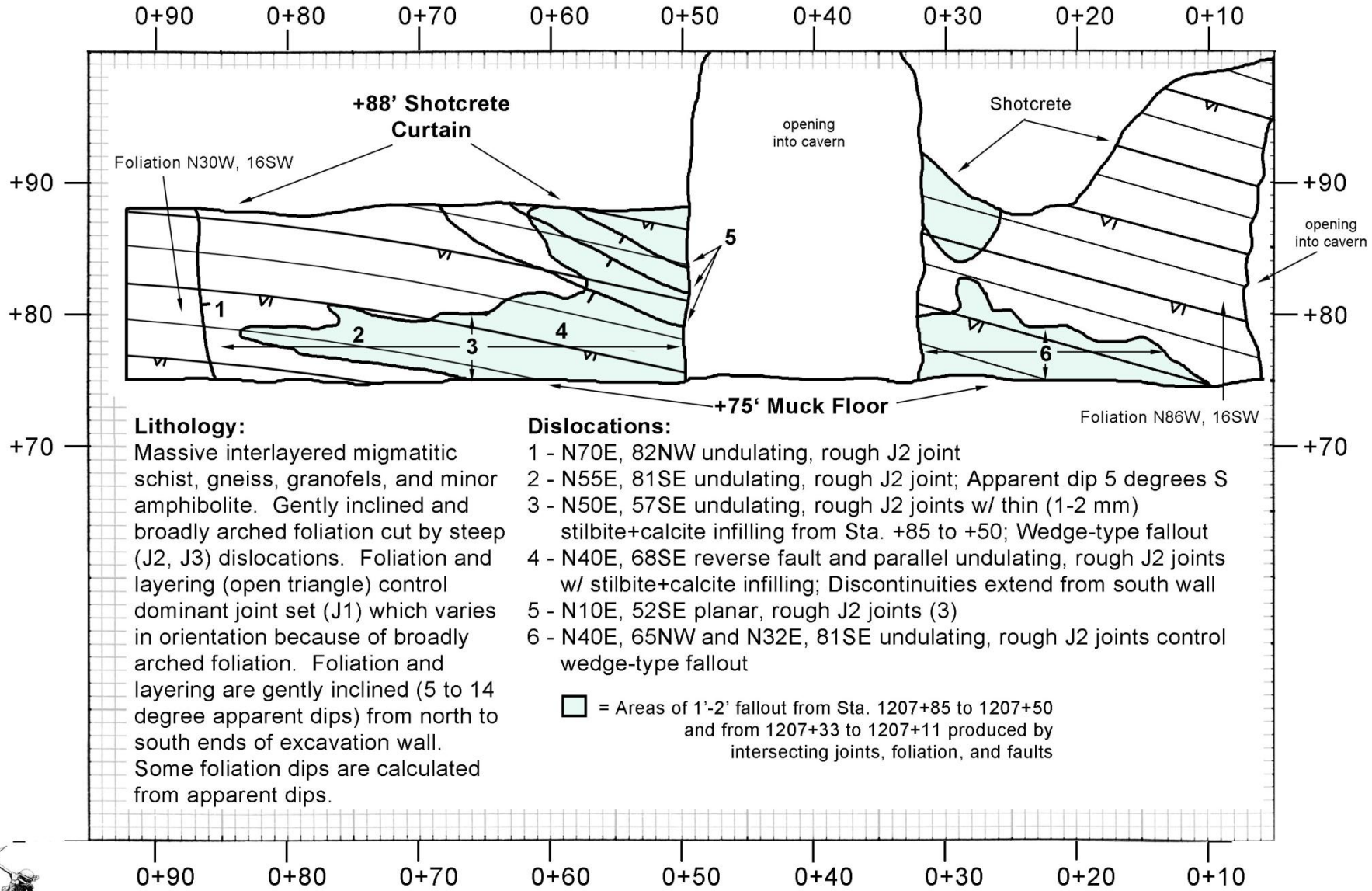
Stationing in Feet North Along East Wall

(Map Drawn Parallel to Sta 0+50 West of Second Avenue Centerline)

Mapped 05 March 2013

Second Avenue Subway - Ancillary #2 East Wall Sta. 1207+05 to 1207+92; Elev. +88' to +75'



Lithology:
Massive interlayered migmatitic schist, gneiss, granofels, and minor amphibolite. Gently inclined and broadly arched foliation cut by steep (J2, J3) dislocations. Foliation and layering (open triangle) control dominant joint set (J1) which varies in orientation because of broadly arched foliation. Foliation and layering are gently inclined (5 to 14 degree apparent dips) from north to south ends of excavation wall. Some foliation dips are calculated from apparent dips.

Dislocations:
1 - N70E, 82NW undulating, rough J2 joint
2 - N55E, 81SE undulating, rough J2 joint; Apparent dip 5 degrees S
3 - N50E, 57SE undulating, rough J2 joints w/ thin (1-2 mm) stilbite+calcite infilling from Sta. +85 to +50; Wedge-type fallout
4 - N40E, 68SE reverse fault and parallel undulating, rough J2 joints w/ stilbite+calcite infilling; Discontinuities extend from south wall
5 - N10E, 52SE planar, rough J2 joints (3)
6 - N40E, 65NW and N32E, 81SE undulating, rough J2 joints control wedge-type fallout

☐ = Areas of 1'-2' fallout from Sta. 1207+85 to 1207+50 and from 1207+33 to 1207+11 produced by intersecting joints, foliation, and faults

Stationing in Feet North Along East Wall
(Map Drawn Parallel to Sta 0+50 West of Second Avenue Centerline)

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Mapped 22 April 2013

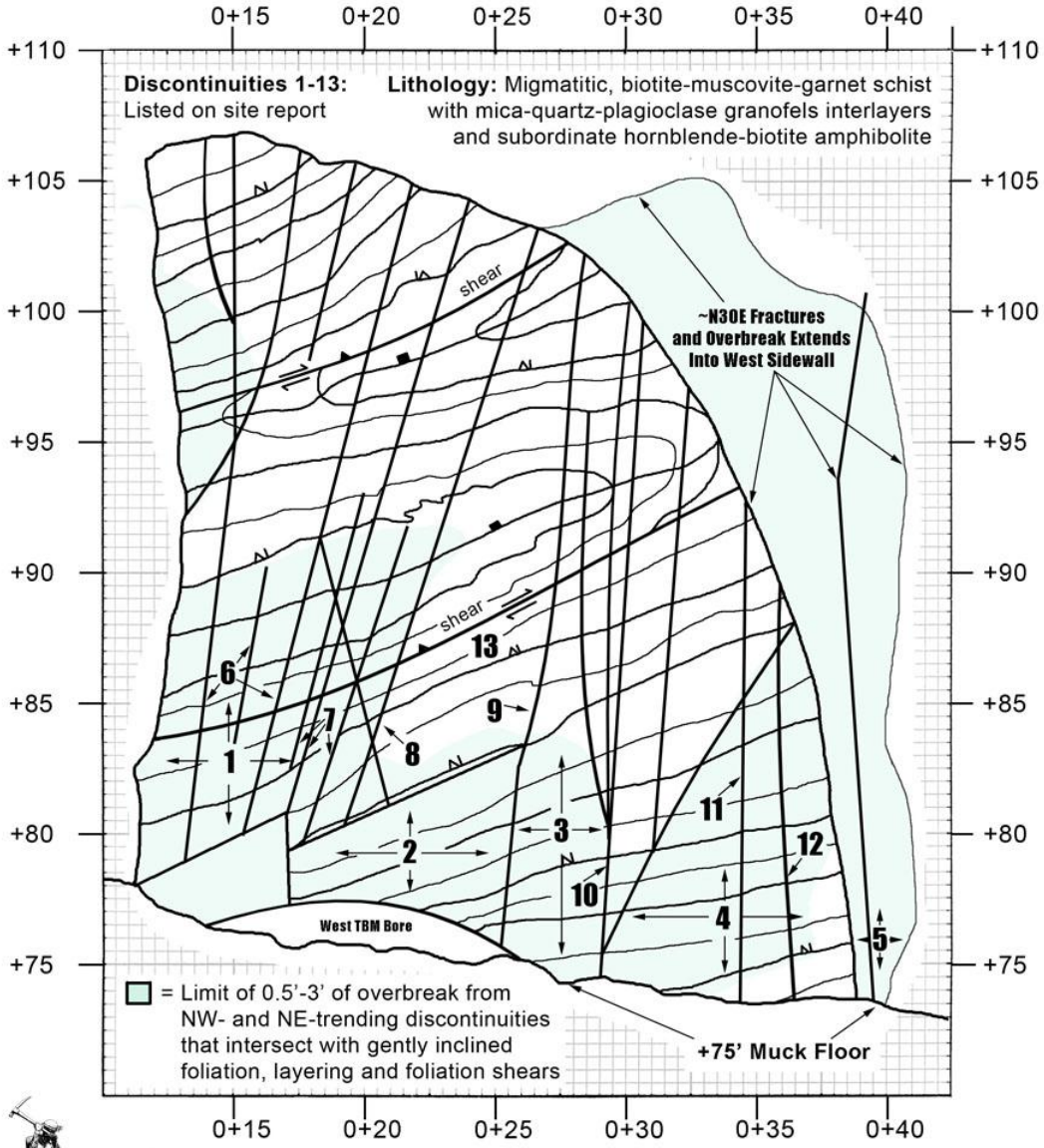
Hofstra Geology Club Visit – 23 April 2013

North Cavern – Sta. 1205+10
19 Dec 2012

North Cavern
North Slash
Sta. 1205+10

19 Dec 2012

Second Avenue Subway - North Cavern West Slash
Working Face at Sta. 1205+10; Elev. +75' to +105'



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Stationing in Feet West of Second Avenue Centerline →

Mapped 19 December 2012

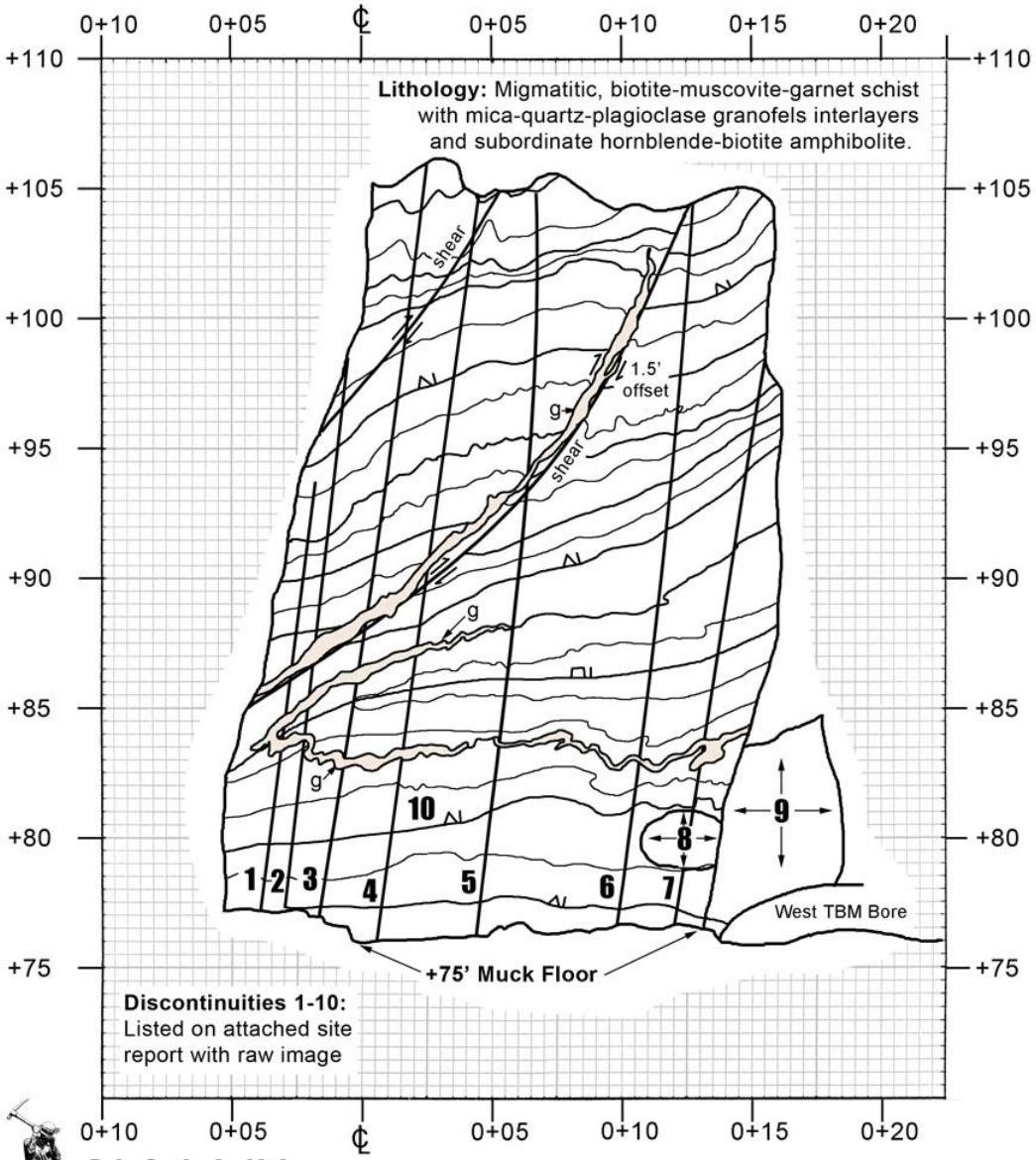
19 Dec 2012

North Cavern – Sta. 1205+10
19 Dec 2012

North Cavern Center Pilot Sta. 1204+90

19 Dec 2012

Second Avenue Subway - North Cavern Center Slash
Working Face at Sta. 1204+90; Elev. +75' to +108'



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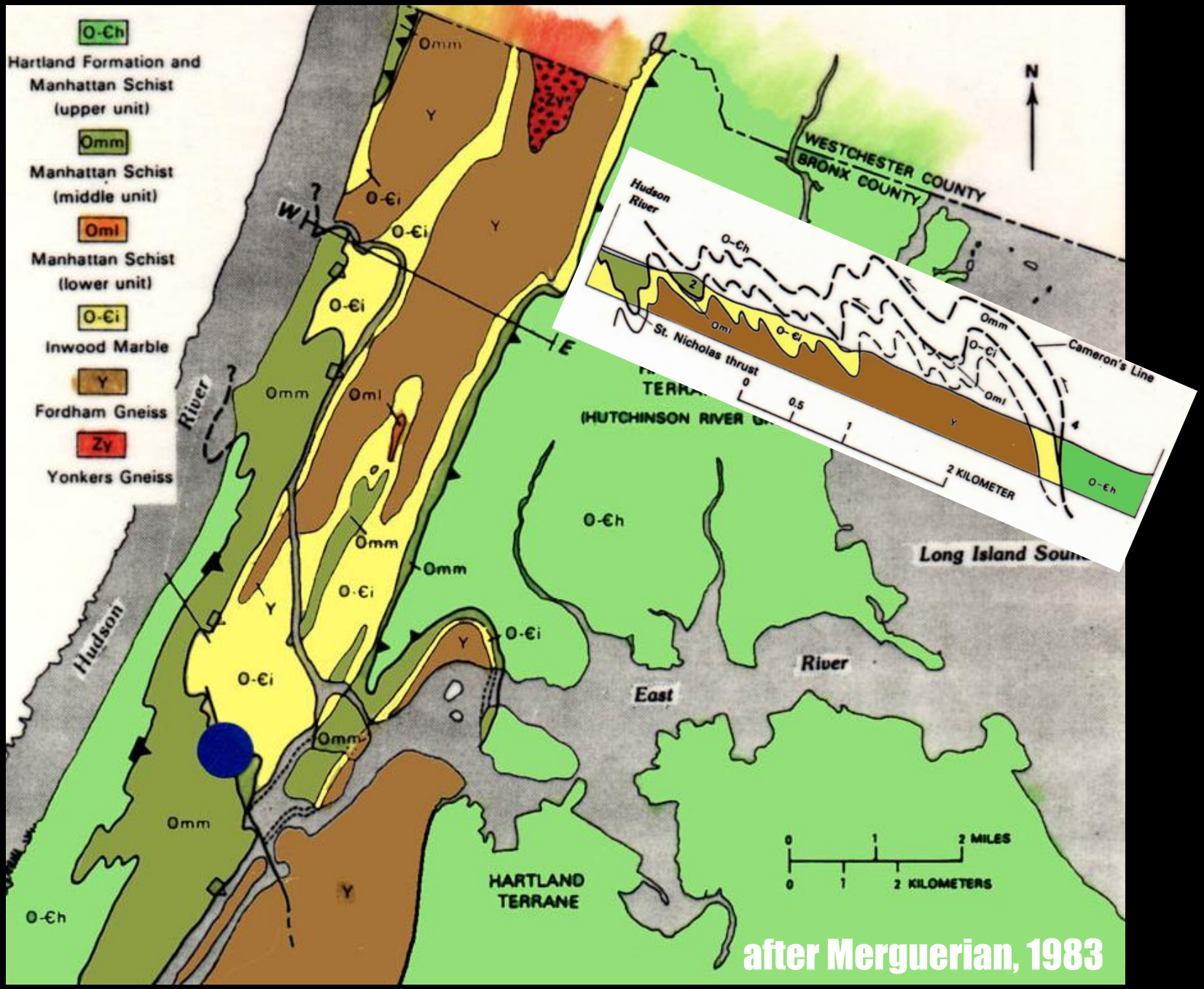
← Stationing East and West of Second Avenue Centerline →

Mapped 19 December 2012

19 Dec 2012


O-Ch
Hartland Formation and Manhattan Schist (upper unit)
Omm
Manhattan Schist (middle unit)
Oml
Manhattan Schist (lower unit)
O-Ci
Inwood Marble
Y
Fordham Gneiss
Zy
Yonkers Gneiss
N
WESTCHESTER COUNTY
BRONX COUNTY
Hudson River
O-Ch
Oml
O-Ci
Omm
Cameron's Line
St. Nicholas thrust
0
0.5
1
2 KILOMETER
O-Ch
Long Island Sound
Hudson
River
East
River
HARTLAND TERRANE
(HUTCHINSON RIVER
0
1
2 MILES
0
1
2 KILOMETERS
after Merguerian, 1983

OK, That's It! I've Heard Enough!
H. Manne

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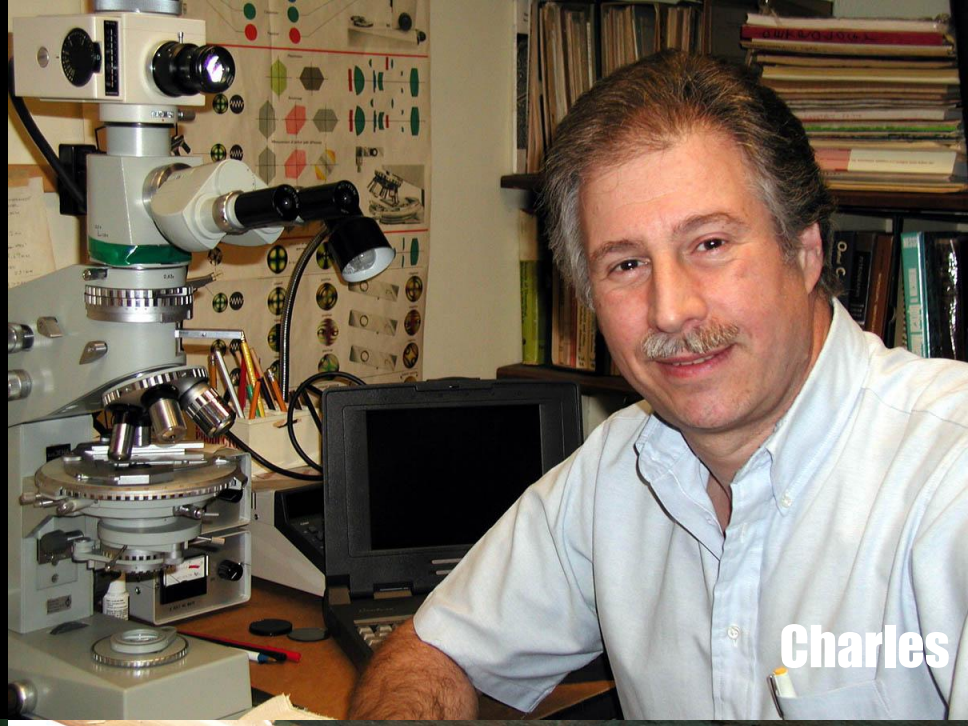

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What's That Noise?