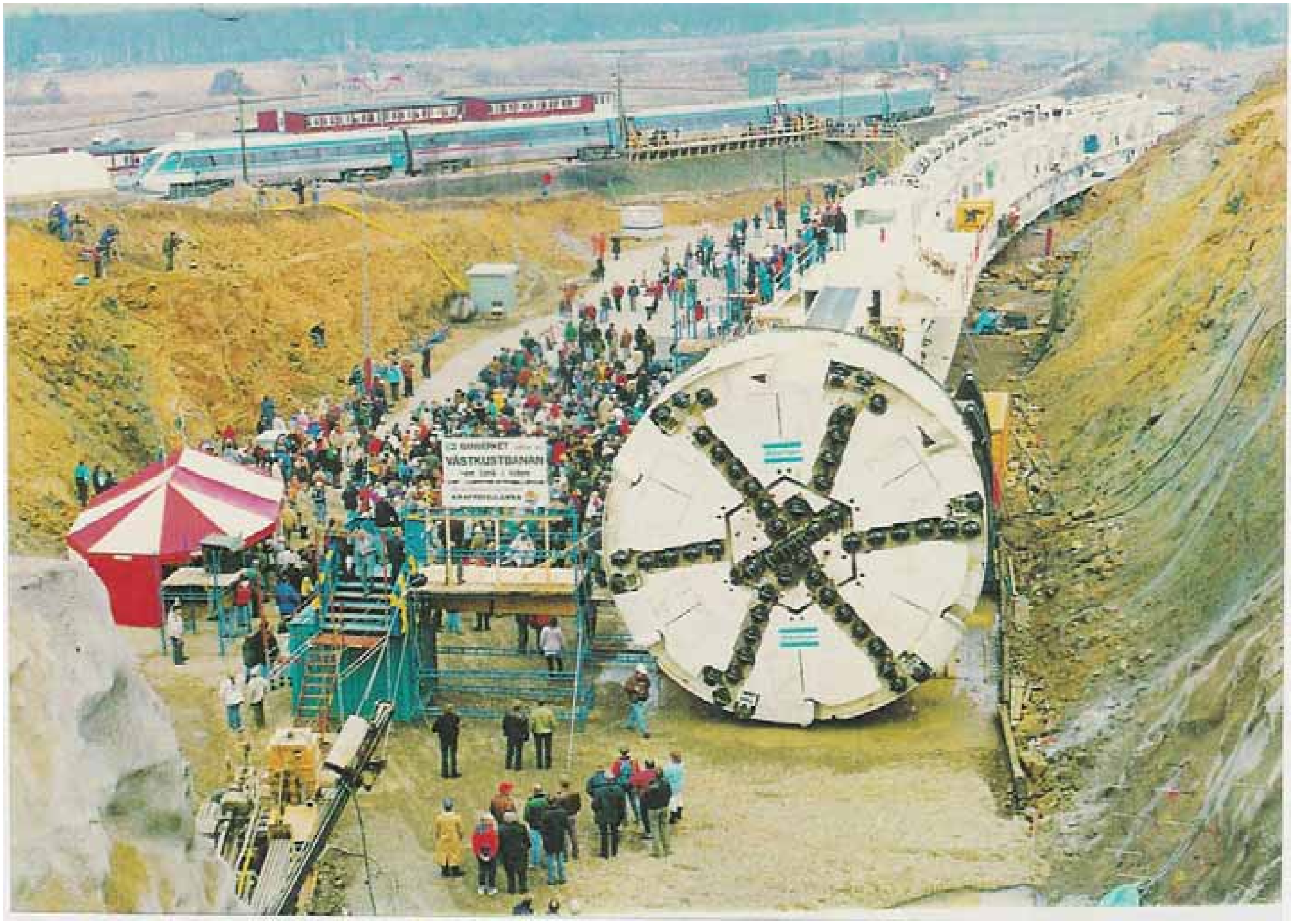
5. RISK TO TBM TUNNELLING FROM FAULTS



INTRODUCTION

- *After* a tunnel collapse or TBM cutter-head blockage in a tunnel, it is usually clear to the experienced tunnelling engineer what the cause(s) of the collapse or blockage were.

- *Before* the event it would often be necessary to be exceptionally pessimistic to have foreseen the ‘unthinkable’.

- *The ‘unthinkable’* is often the combination of several adverse factors, which separately are ‘expected’ though serious events, *but when combined are, quite logically, ‘unexpected events’.*

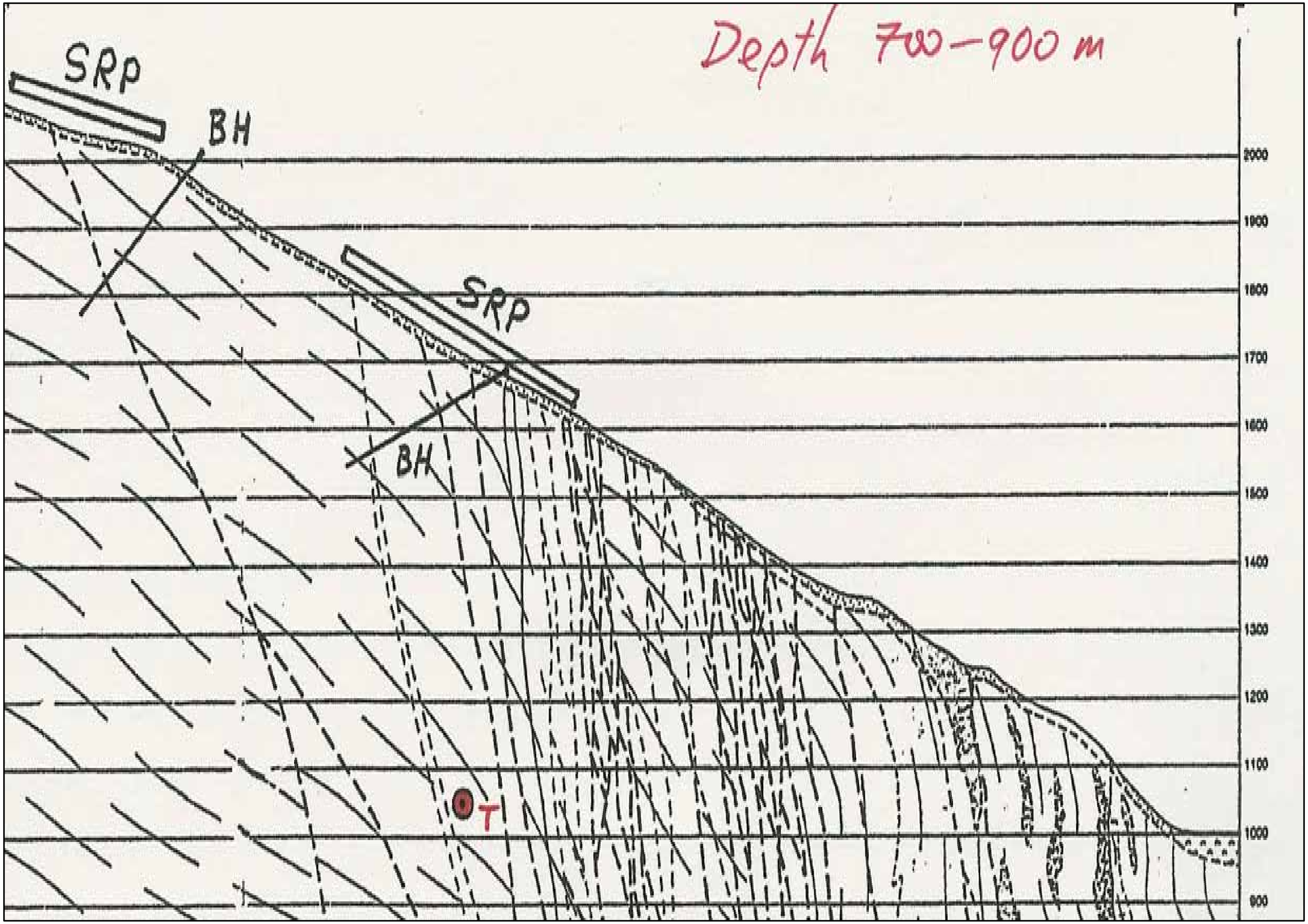
SOME OF THE (OBVIOUS) HIGH-RISK FACTORS

- ***significant fault zones***
- ***adversely oriented planar clay-coated joints***
- ***very weak rock, very hard massive rock***
- ***very abrasive rock***
- ***very low stress, very high stress***
- ***exceptional stress anisotropy***
- ***high volumes of stored water***
- ***high permeability***

A short list of TBM tunnels that suffered (catastrophically) from multiple unexpected events

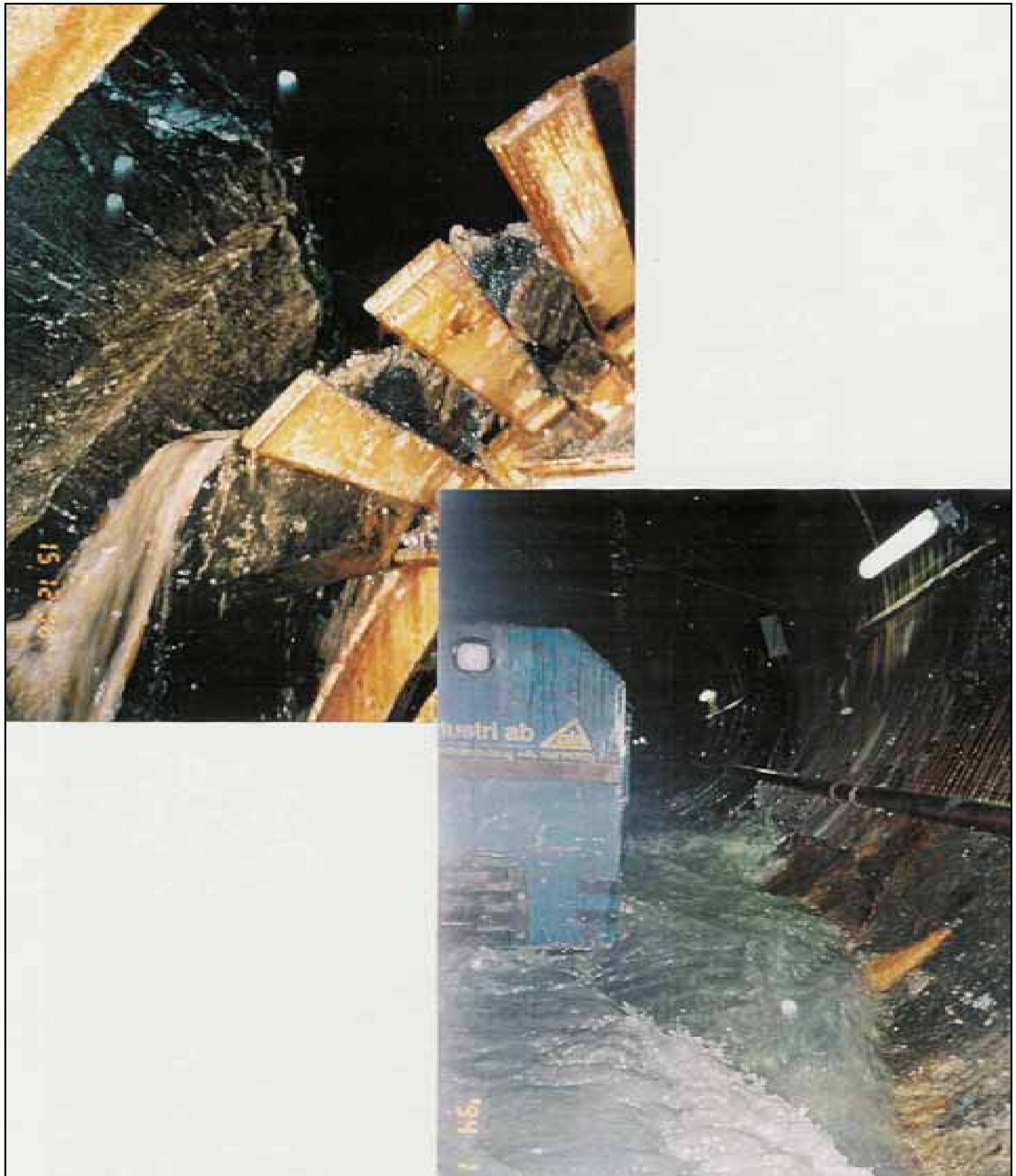
1. *Unpredicted fault swarm parallel to valley-side, together with very high (and fault-eroding) water pressures, at depths of 700-900m. TBM tunnel (diameter 5m) eventually ran sub-parallel to individual faults, causing delays of at least half a year for each 1m wide fault (AR ≈ 0.005m/hr). TBM finally abandoned; new contractor for D+B from other end of tunnel.*

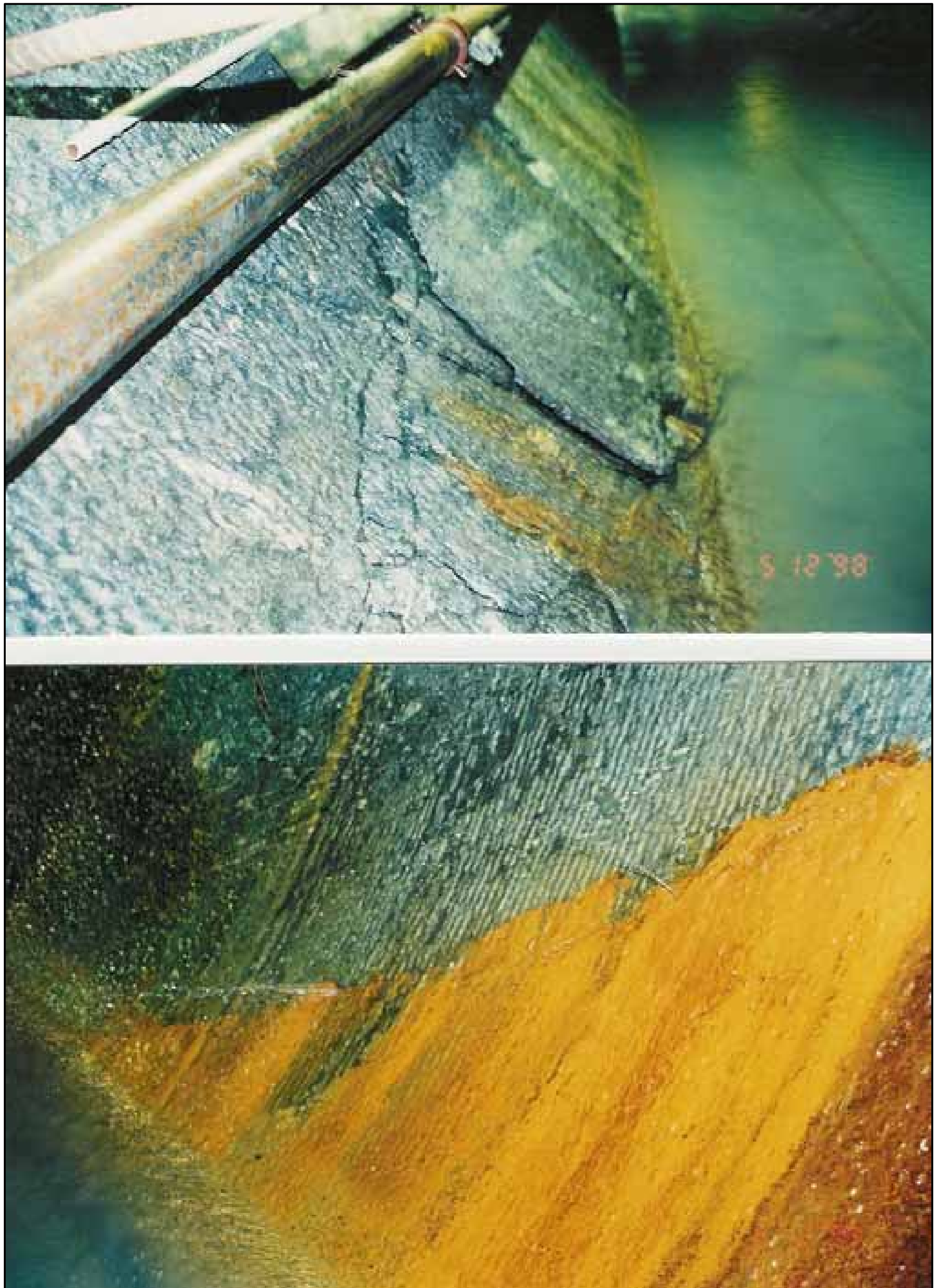
(Pont Ventoux HEP, N. Italy).



KEY FEATURES WERE MISSED IN THE SITE INVESTIGATION – BUT THE TUNNEL IS DEEP

FAULT ZONE STOPPAGES---AND MASSIVE WATER INFLOWS



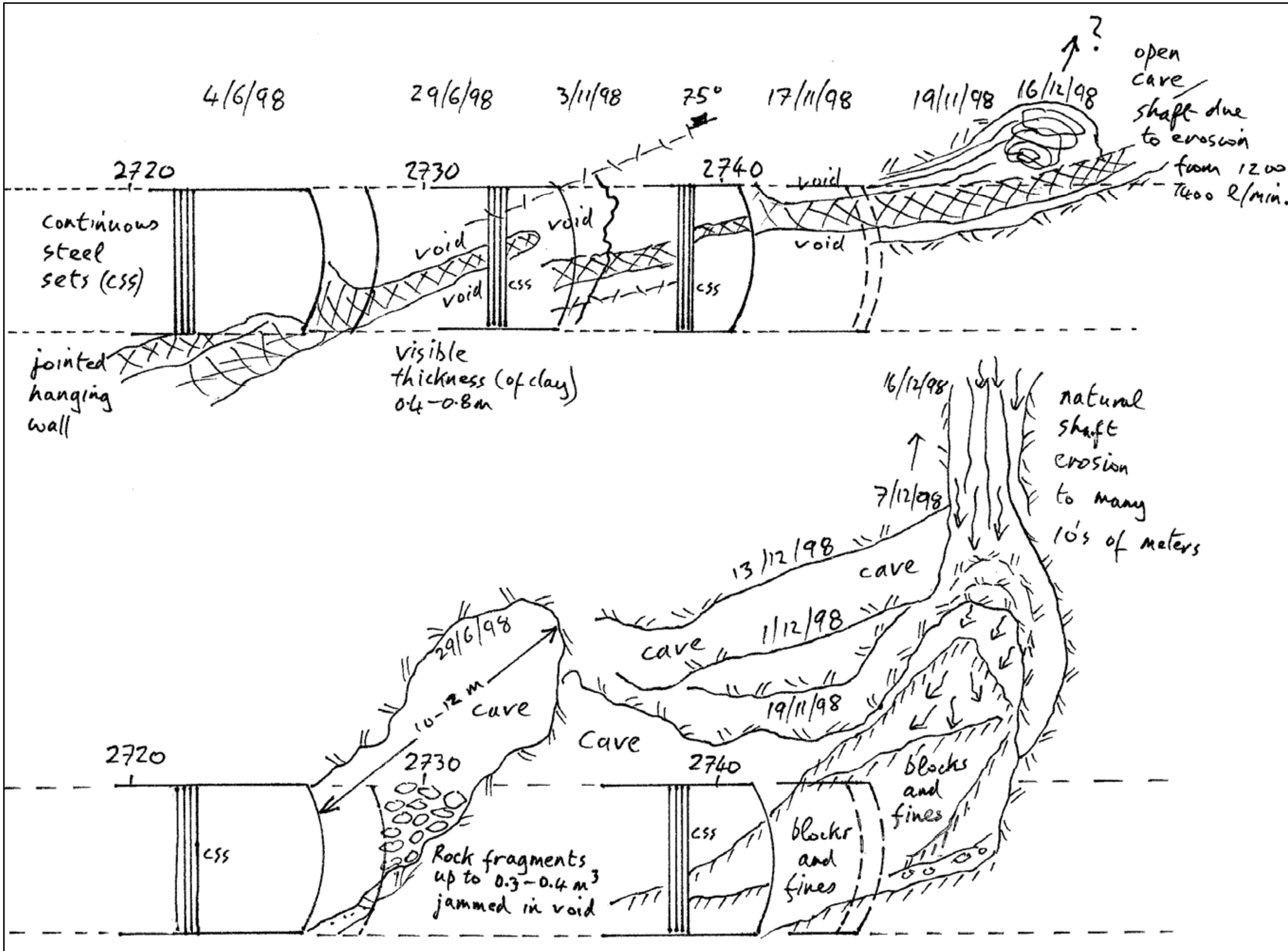


STRESS-SLABBING

HIGH WATER PRESSURES

(IN ADDITION TO FAULT ZONES)

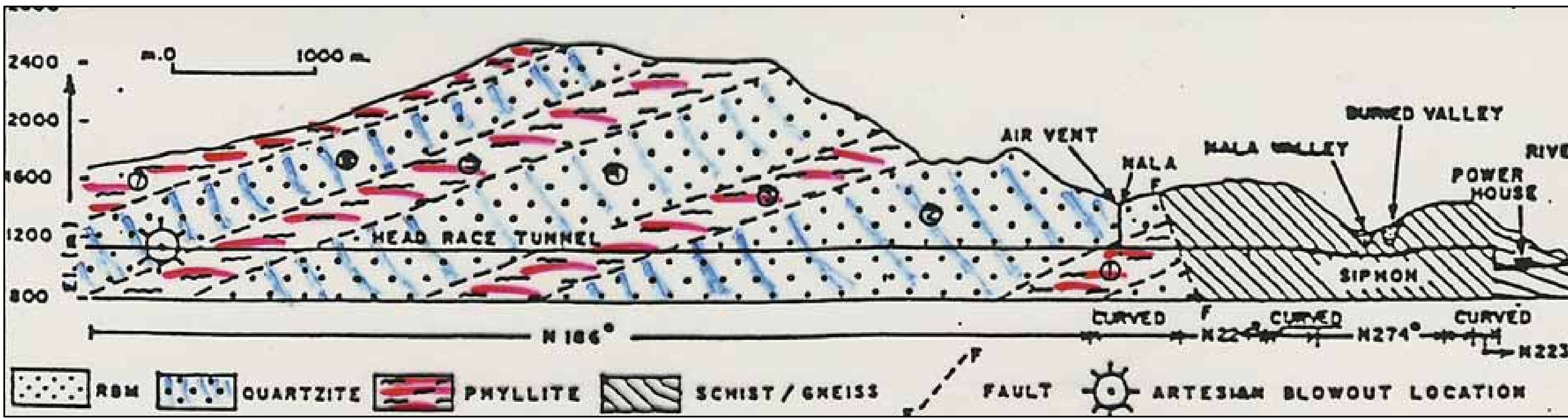
A SIX MONTH DELAY AT JUST ONE FAULT



1. *Alternating massive quartzite (minimum PR ≈ 0.2m/hr), talcy sheared phyllites (‘over-excavating’ and stand-up time limitations), and fractured quartzite ‘aquifer’. Early blow-out of 4000 m^3 rounded gravels at 750m depth and maximum 70 m^3/minute water in-rush. Eventual abandonment of the 8m diameter TBM in a fault zone; D+B from other end of tunnel after years of delay.*

(Dul Hasti HEP Kashmir).

THE ALTERNATING QUARTZITE AND PHYLLITE



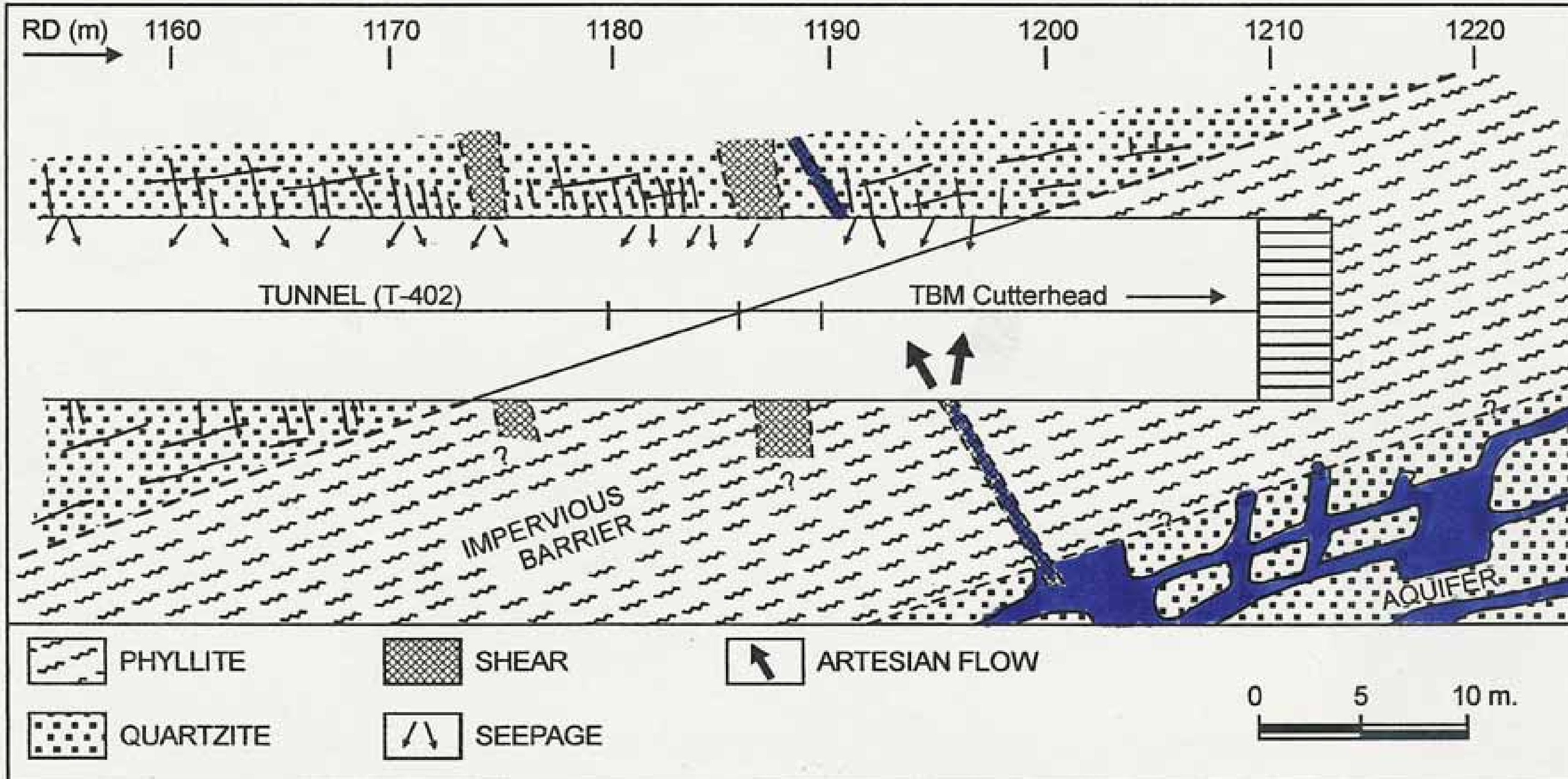


Fig. 41 Blow-out location for 4000 m^3 of sands and gravels and peak water inflows of 70 m^3/min at Dul Hasti HEP, Kashmir. Deva et al., 1994.

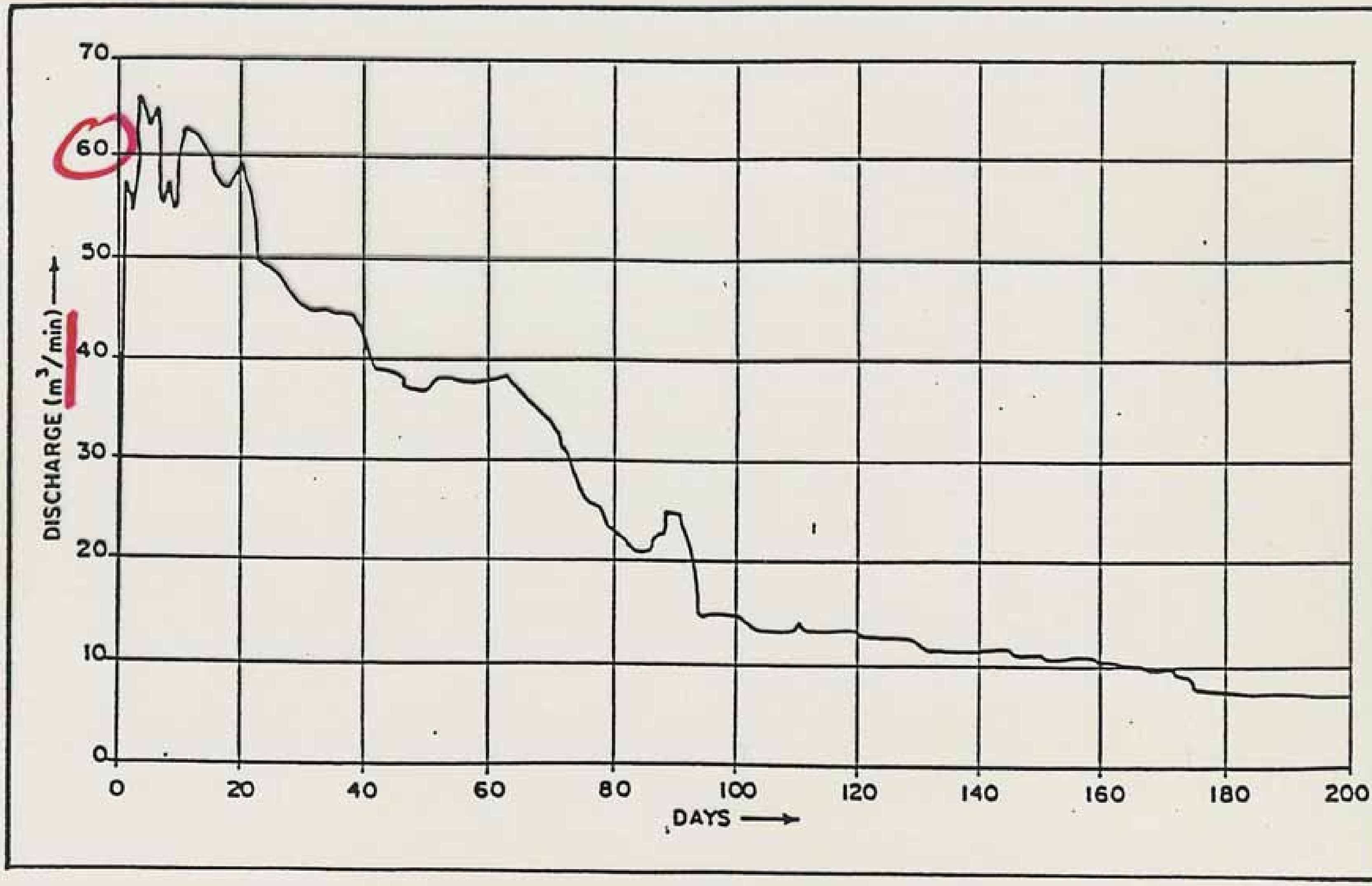


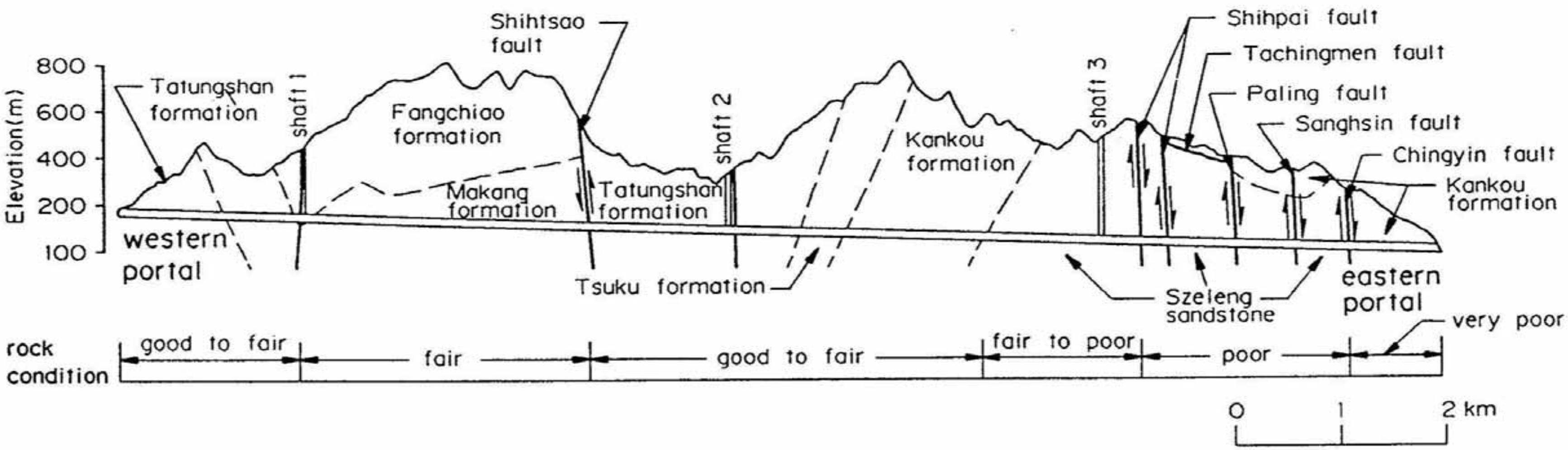
Figure 18 Deva et al. (1994) recordings of pressure decay in 8.4 m TBM tunnel driven in fractured quartzite and phyllite

THE SITE OF THE BLOW-OUT….SOME YEARS LATER….
NOW A NEW CONTRACTOR

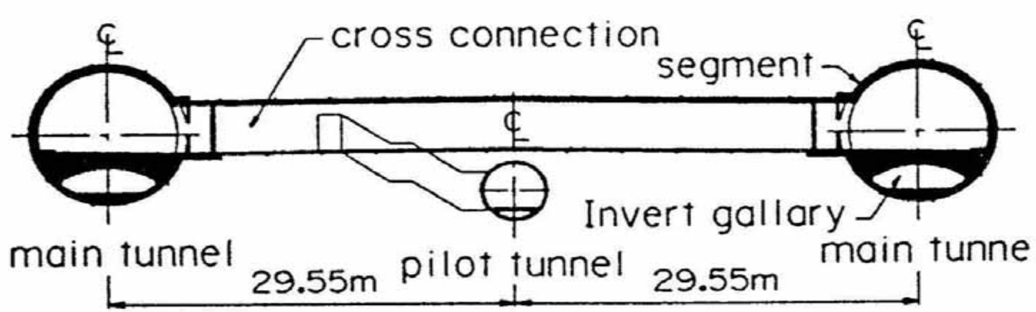
TBM BLOCKED IN THE PHYLLITE…..OVER-EXCAVATION DUE TO SHORT STAND-UP TIME

1. *‘Unexpected’ combination of fault zones, abrasive quartzites and meta-sandstones, clay-coated joint sets and exceptional water pressures and inflows. At least twelve D+B by-passes of TBM pilot tunnel during 10 years of delays. Squeezing deformation of pilot tunnel from 26m distant main (11.7m) TBM. Fault zone collapse destroyed one 11.7m TBM, other used to mine invert, needing D+B cutter-head releases and D+B mining and support of top-heading. Great difficulties to drill pre-injection holes. Eventual completion (after 12 years) by mainly D+B from other end of tunnel.*

(Pinglin Tunnels, Taiwan).



Geologic profile along the Pingline Tunnel



Cross-sectional layout of Pinglin tunnels

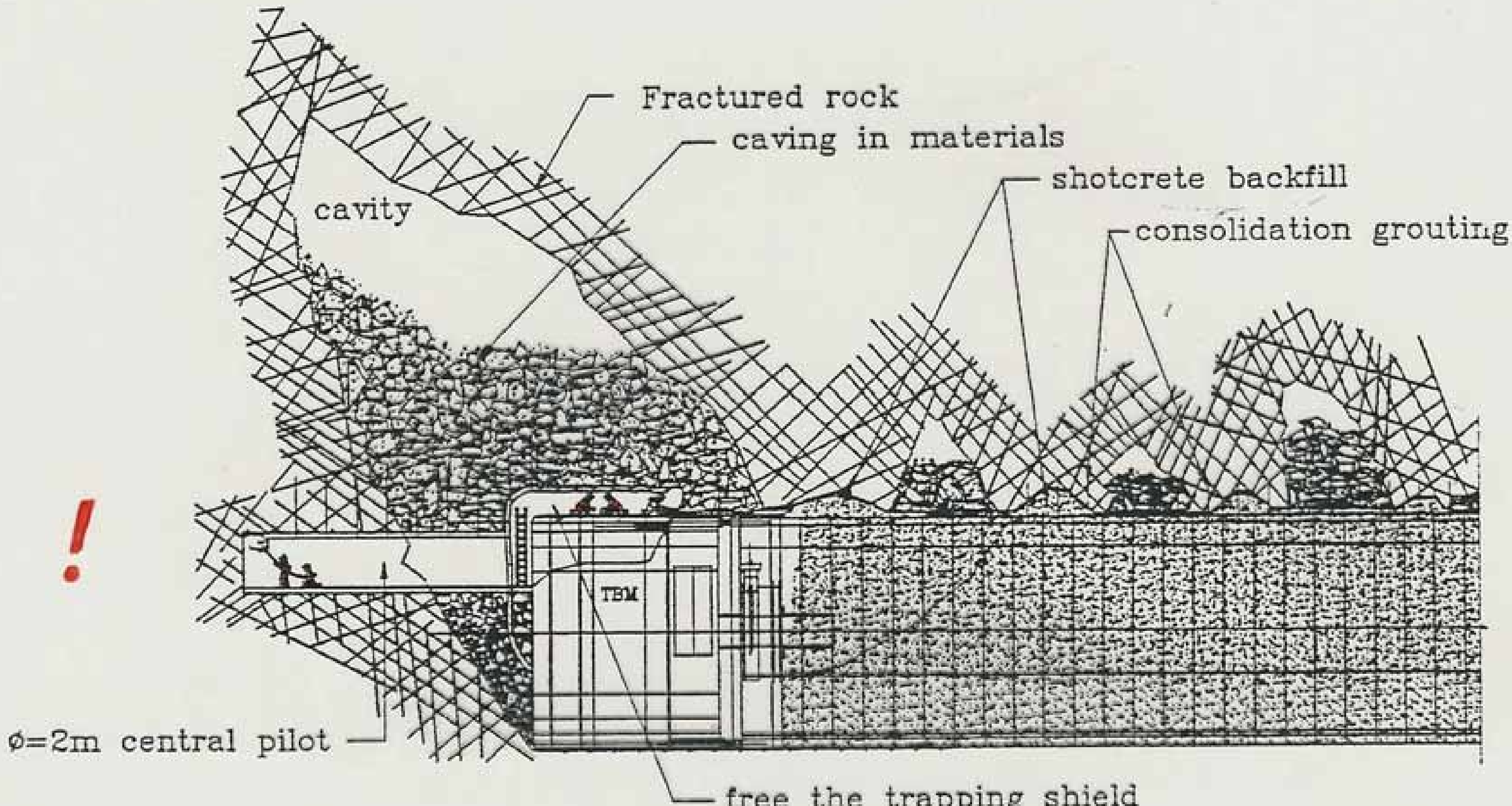
WIRTH
WIRTH HOWDEN
T U N N E L L I N G

TUNNELLING MACHINES TO SUIT ALL GROUND CONDITIONS

The 12th by-pass of the pilot TBM to release the cutter-head, after 10 years of tunnelling problems (2002).

BY-PASS SITUATION FOR THE DOUBLE-SHIELD (11.7m) TBM

PINGLIN LARGE TBM



Shows risky means to free TBM cutter head or shield

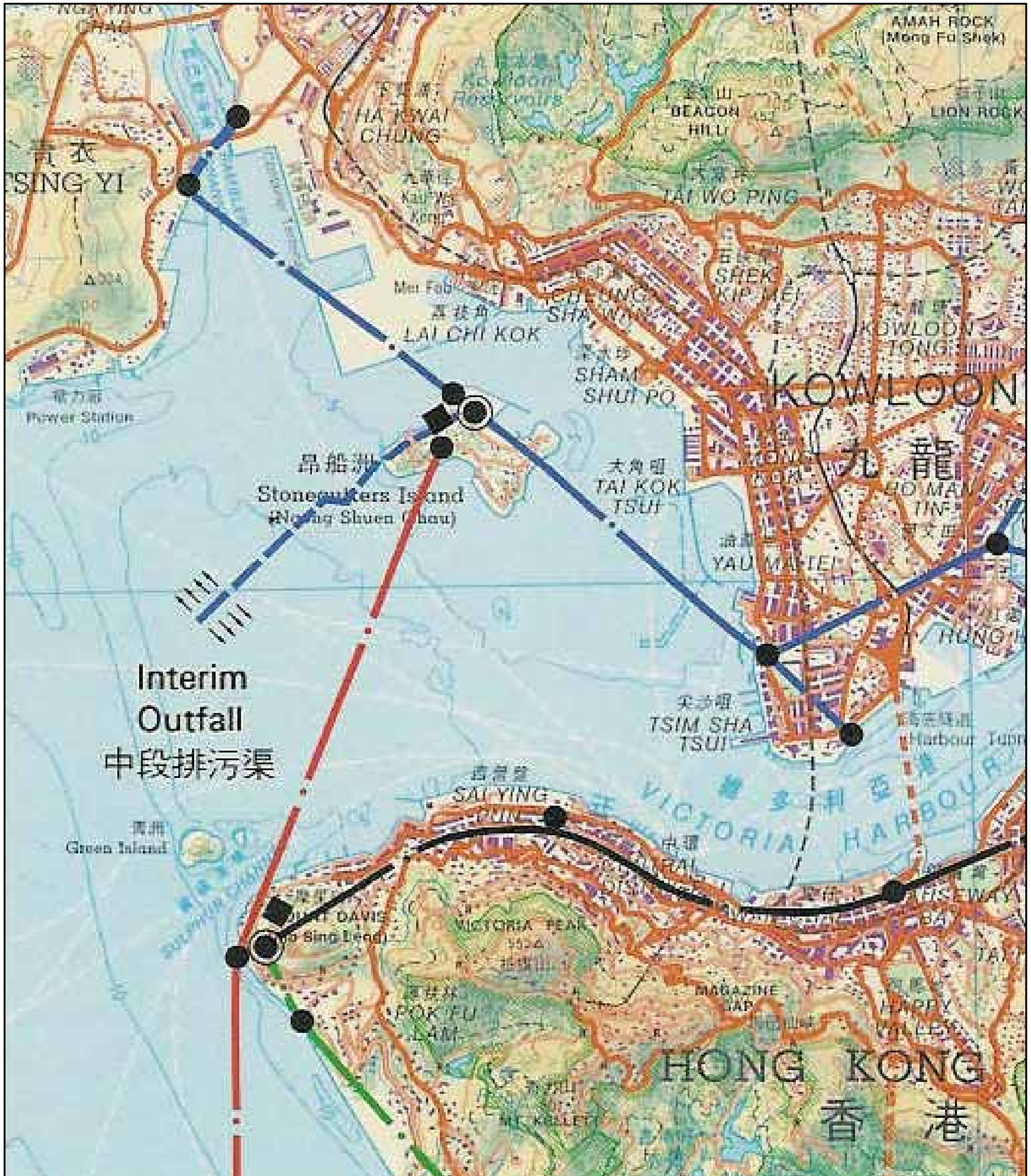
Shen et al. 1999

ONE 11.7m TBM IS REMAINING, ONE IS DESTROYED (2002)

1. *Unexpectedly high water inflows and unexplored regional fault zone due to limited access for marine seismic at container port. Sub-sea TBM of 3.3m diameter took three times longer than contracted, even after abandonment by first contractor.*

(Tunnel F, SSDS, Hong Kong).

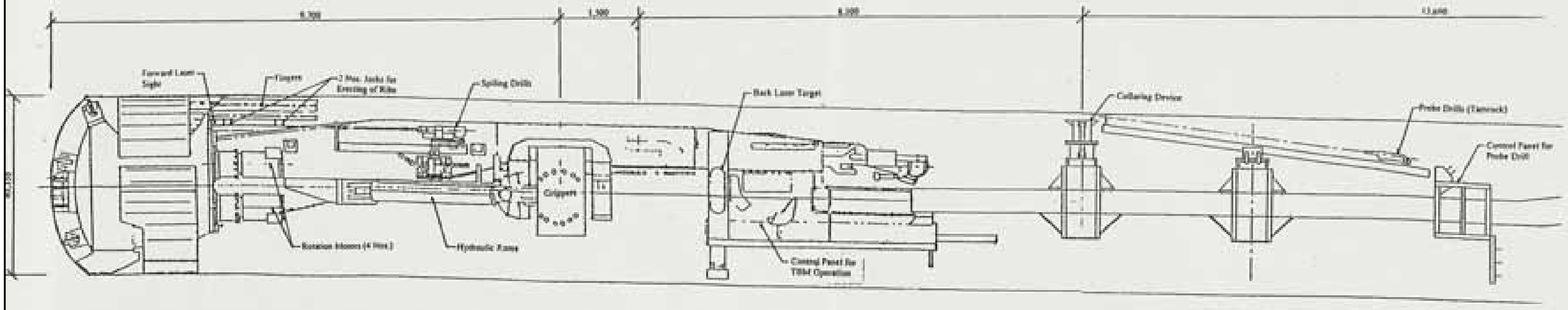
STRATEGIC SEWAGE DISPOSAL SCHEME FOR HONG KONG



NOTE CONTAINER PORT (white area)

SEE REGIONAL FAULT ZONE

NOTE DIFFICULT PRE-GROUTING ‘GEOMETRY’



ITEM	METRIC	COMMENTS
Cutters: Cutter Diameter Max. Cutter Loading No. of Discs	 432mm 250kN 26	
Cutterhead: Thrust (Max. recommended) Thrust (Max. available) Power Rotation Speed Torque Hyd. Start & Jog Motors	 648 tonnes 698 tonnes 748kW 13.2 rpm 55,010 kg-m 1	 At 4,330 psi (300 bar) At 4,300 psi (300 bar) 4 water cooled motors
Boring Stroke:	1.52 meters	
Machine Configuration:	Two Horizontal Grippers	
Gripper Assemblies: Force of Horizontal Grippers Grip to Thrust Ratio	 3,414 Tonne 2.8 : 1	 At 4,500 psi (262 bar)
System Electric Power:	30kW	

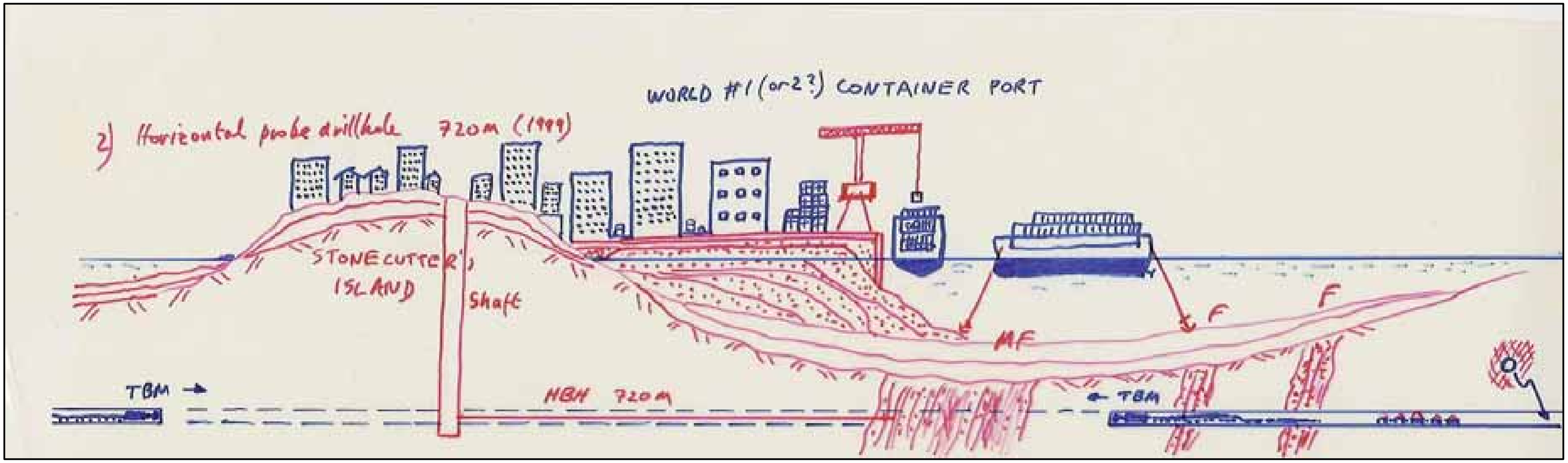
TOTAL LENGTH OF TBM + BACKUP = 117.1m

Fig. 36. *The unfavourable position of the Tamrock drills, and measures used to collar closer to the face. (Skanska photos)*

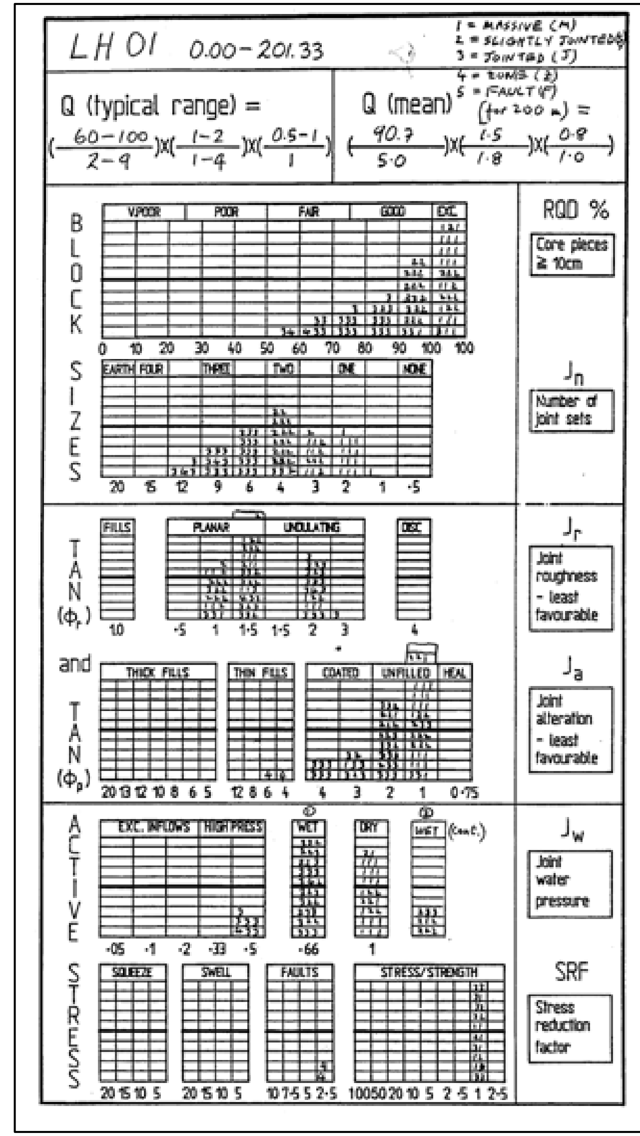
Nick Barton and Associates

Rock Engineering

SKETCH OF REGIONAL FAULT ZONE and 'pilot' borehole drilled backwards from forward shaft

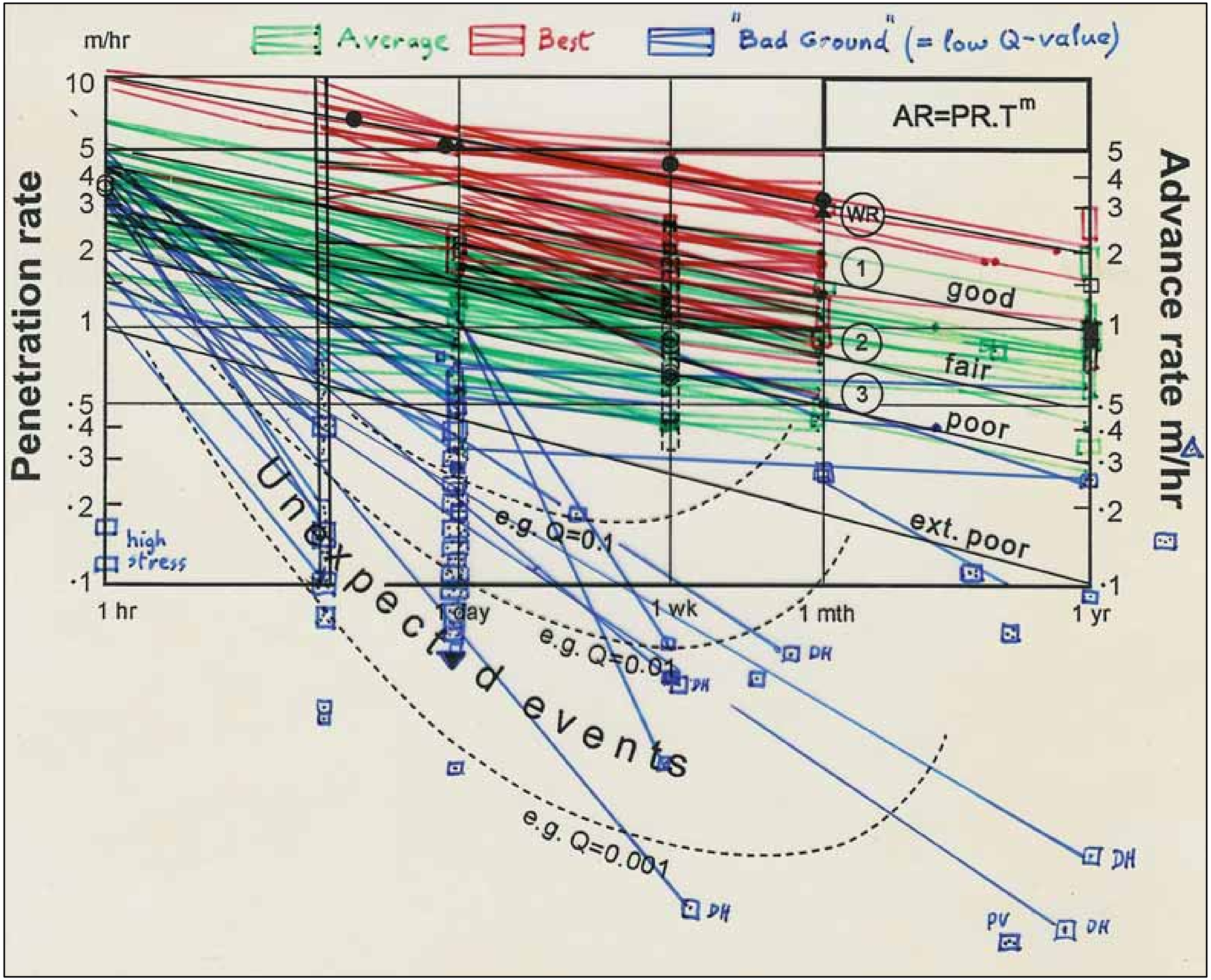


THE 730m OF CORE WAS Q-HISTOGRAM LOGGED TO PRODUCE STATISTICS OF *FIVE ROCK CLASSES*

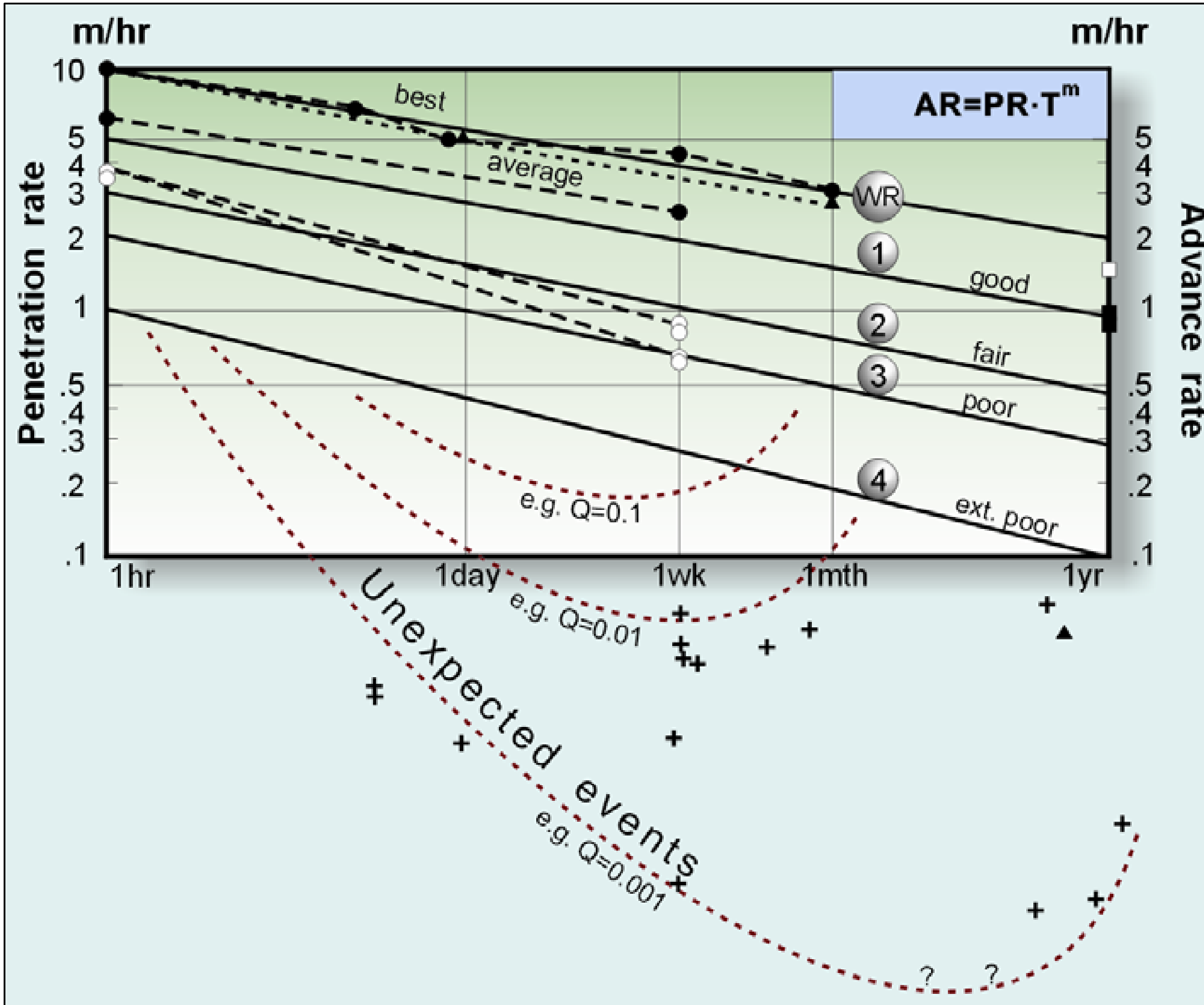


EXAMPLES OF FIVE ROCK CLASSES **and their Q-parameter statistics**

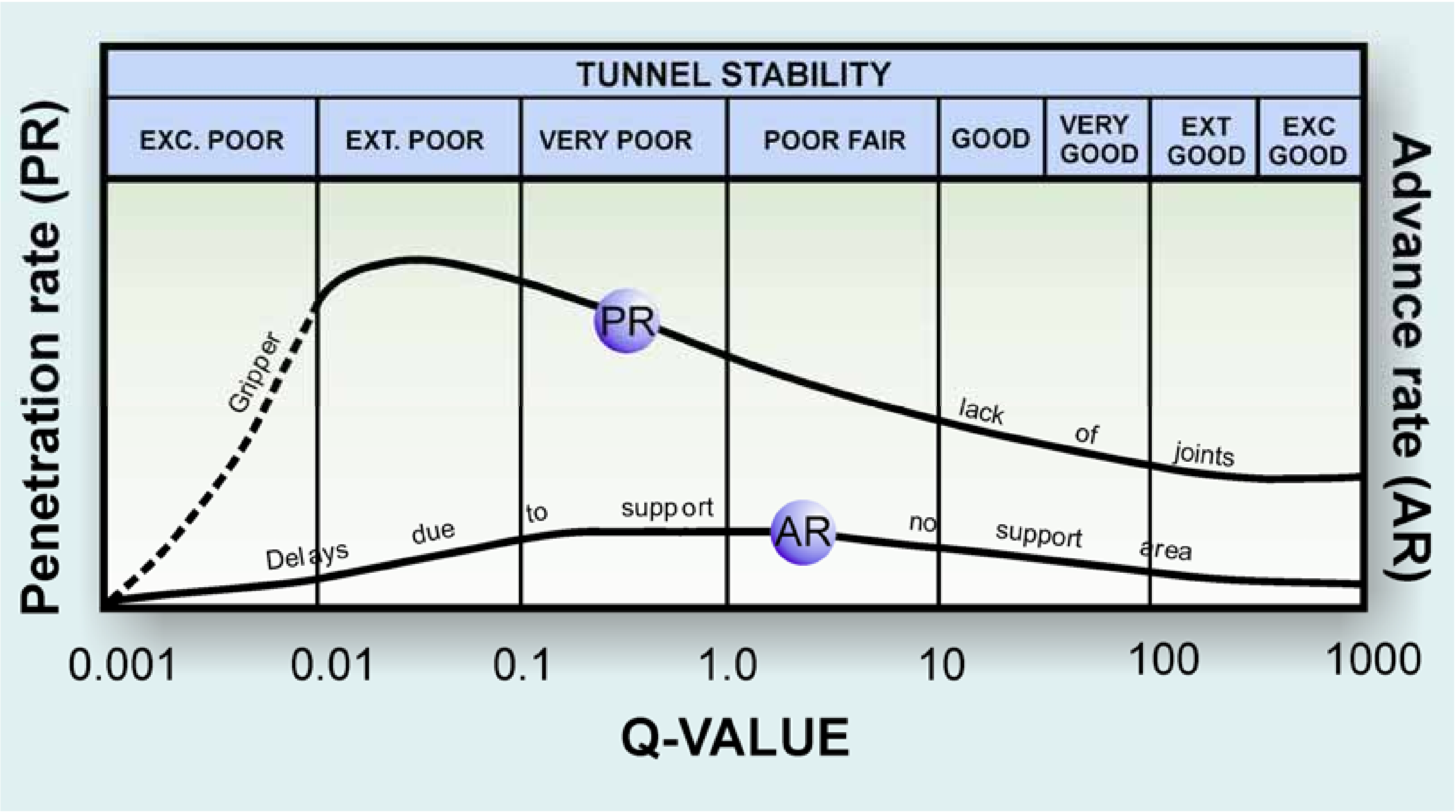
CASE RECORD DATA FROM 140 TBM (Barton, 2000).



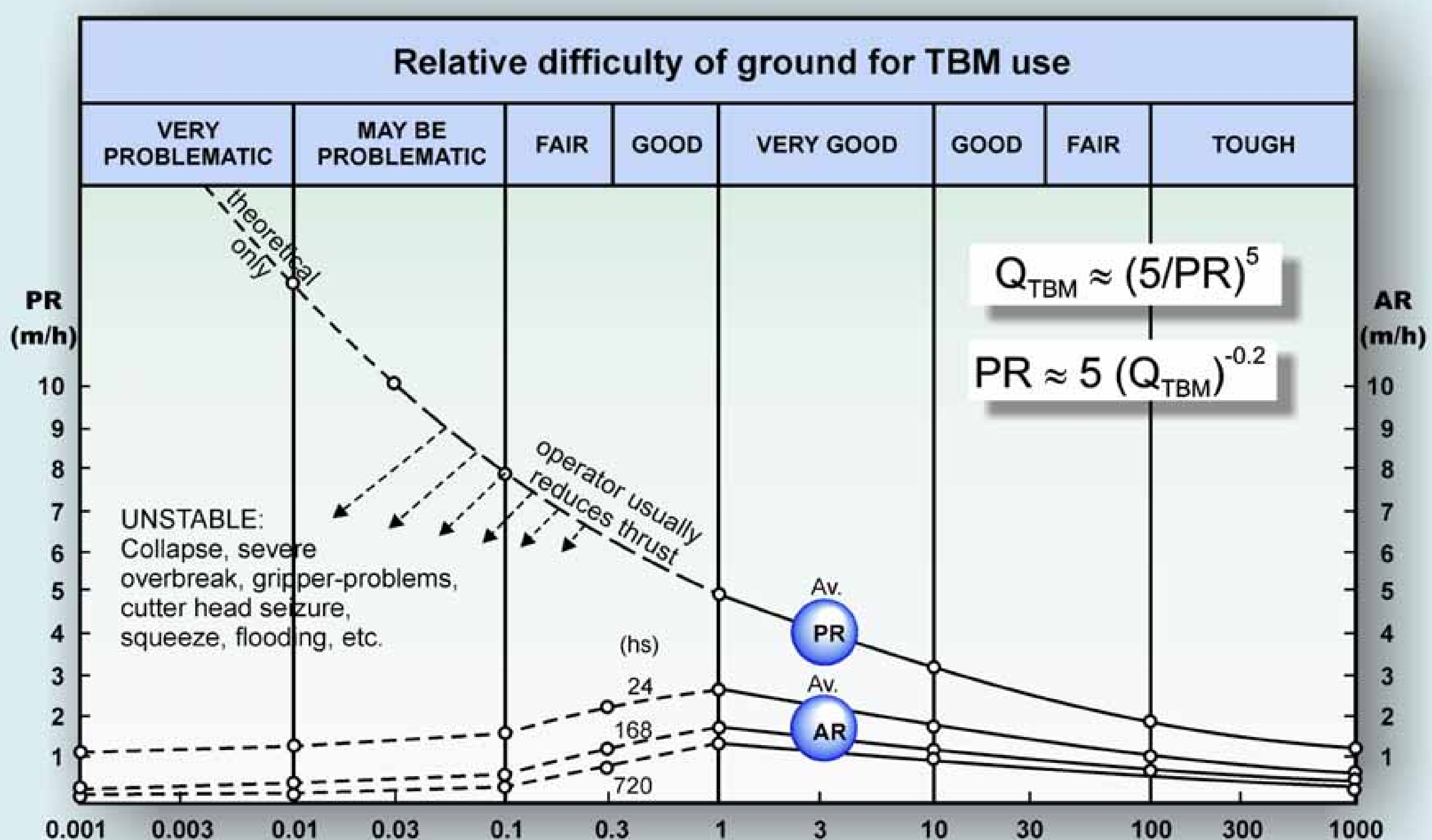
THE GENERAL TRENDS OF DECELERATION WITH LENGTH



NOTE 'UNEXPECTED' EVENTS!



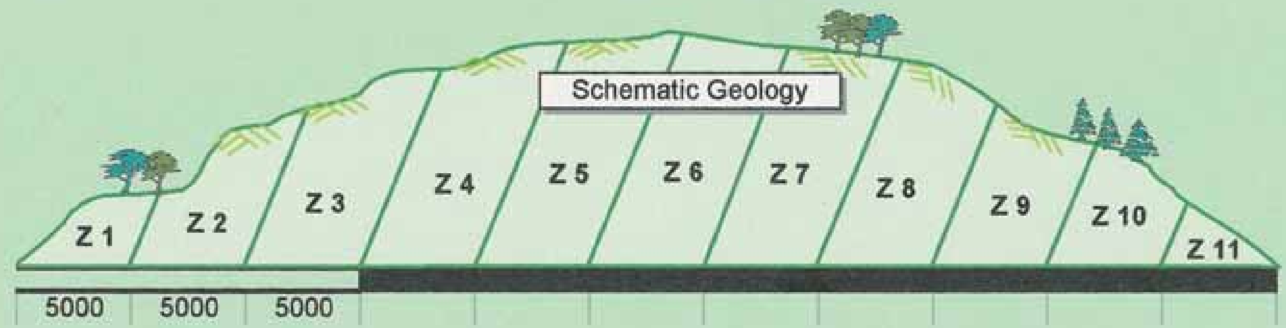
TUNNEL STABILITY
EXC. POOR
EXT. POOR
VERY POOR
POOR FAIR
GOOD
VERY GOOD
EXT GOOD
EXC GOOD
Penetration rate (PR)
Advance rate (AR)
PR
AR
Gripper
lack of joints
Delays due to support
no support area
0.001
0.01
0.1
1.0
10
100
1000
Q-VALUE



$$Q_{TBM} = \frac{RQD_O}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

Nick Barton & Associates

Q TBM



ZONE	3	LITHOLOGY	*basalt*	ZONE LENGTH	*5000*

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)
						-0.18		2.7

V_P (km/s)
5

β^o	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	153		22	26	1	25	5.15	2

Date	*01/Apr/2001*

Contract	*LHWP Phase 1B*	Site	*Mohale Tunnel Example 4*

USE OF Q_{TBM} METHOD TO ESTIMATE PROGRESS WITHOUT INJECTION

Fig. 4. Prognoses for 731 m of tunnel, without any pre-injection.

USE OF Q_{TBM} METHOD TO ESTIMATE PROGRESS WITH INJECTION

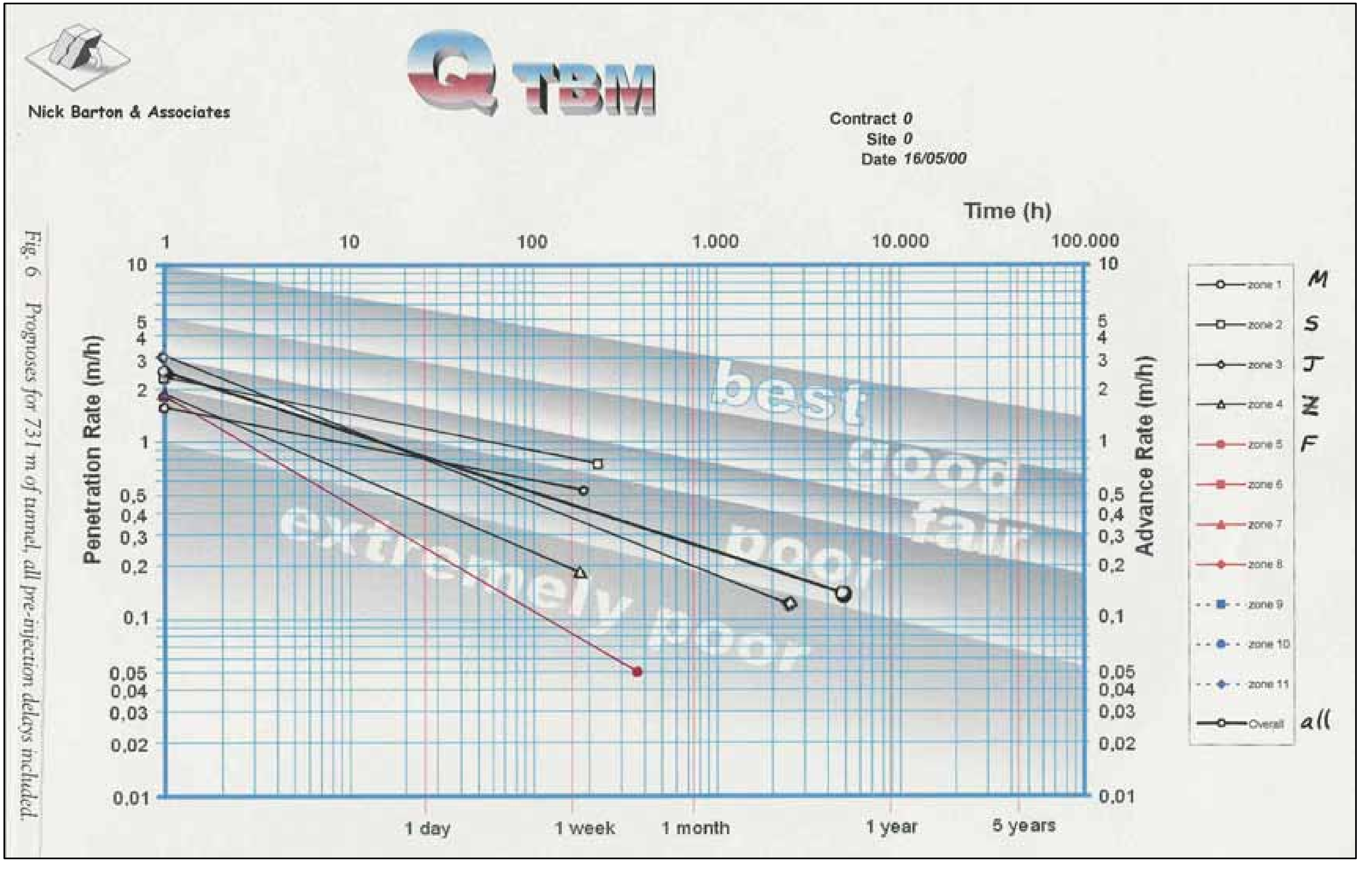


Fig. 7. Samples of the edge of the Tolo Channel Fault Zone, at end of LH01.

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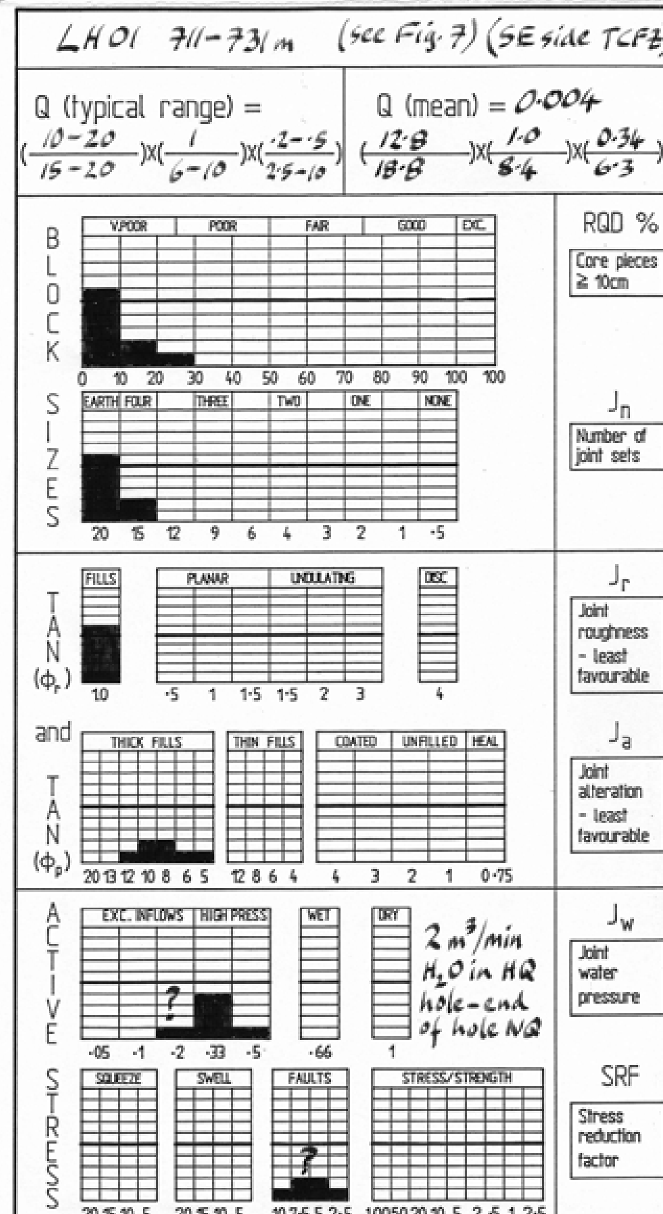
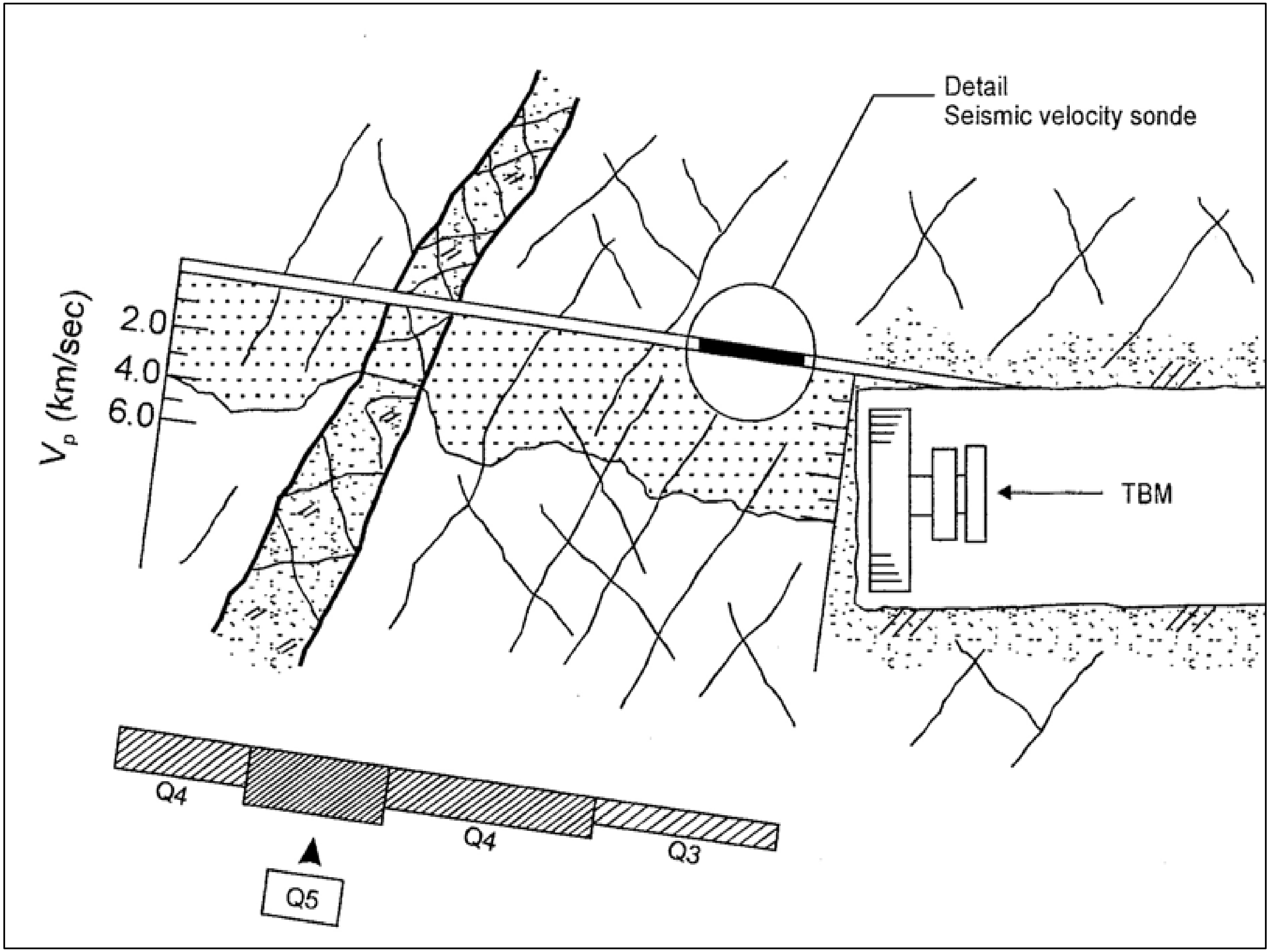
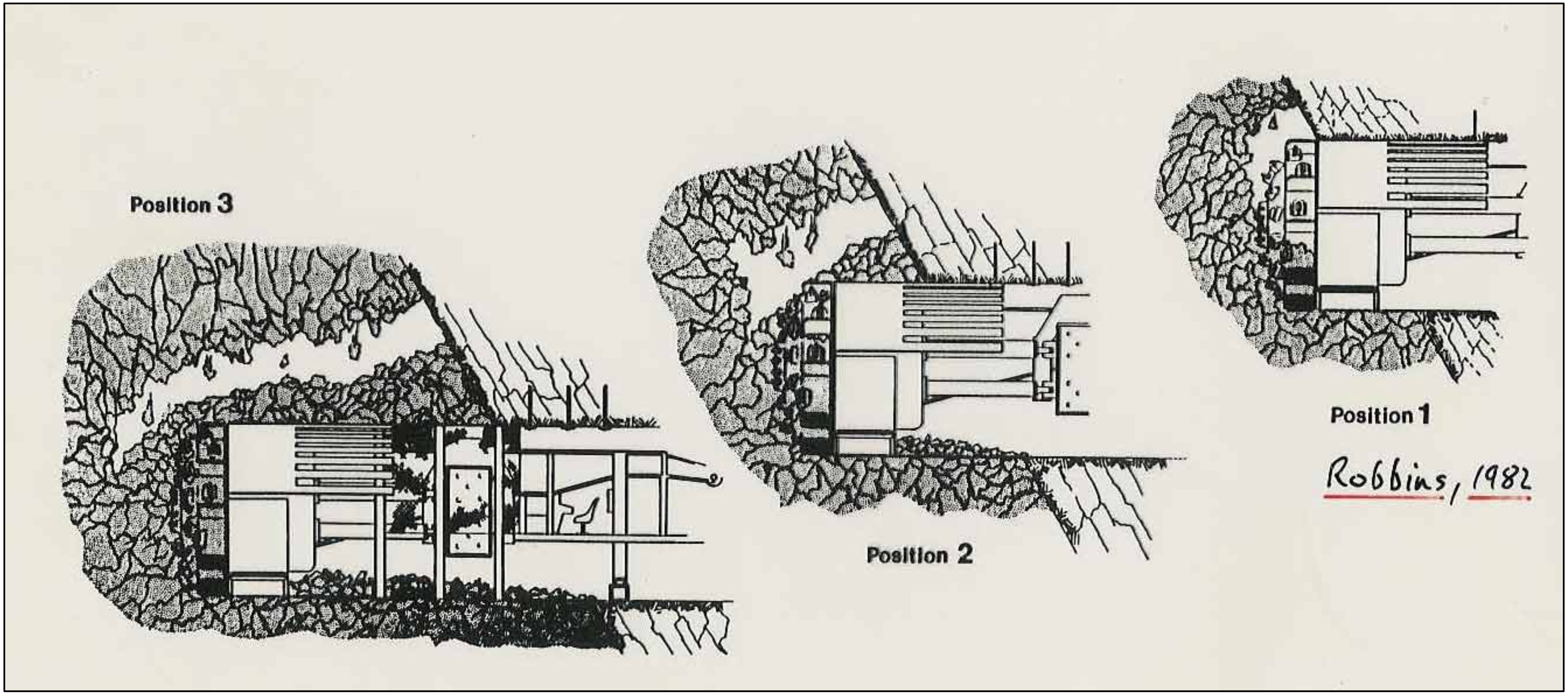


Fig. 8. Q-parameter log of TCFZ material, ch. 711–731, LH01.



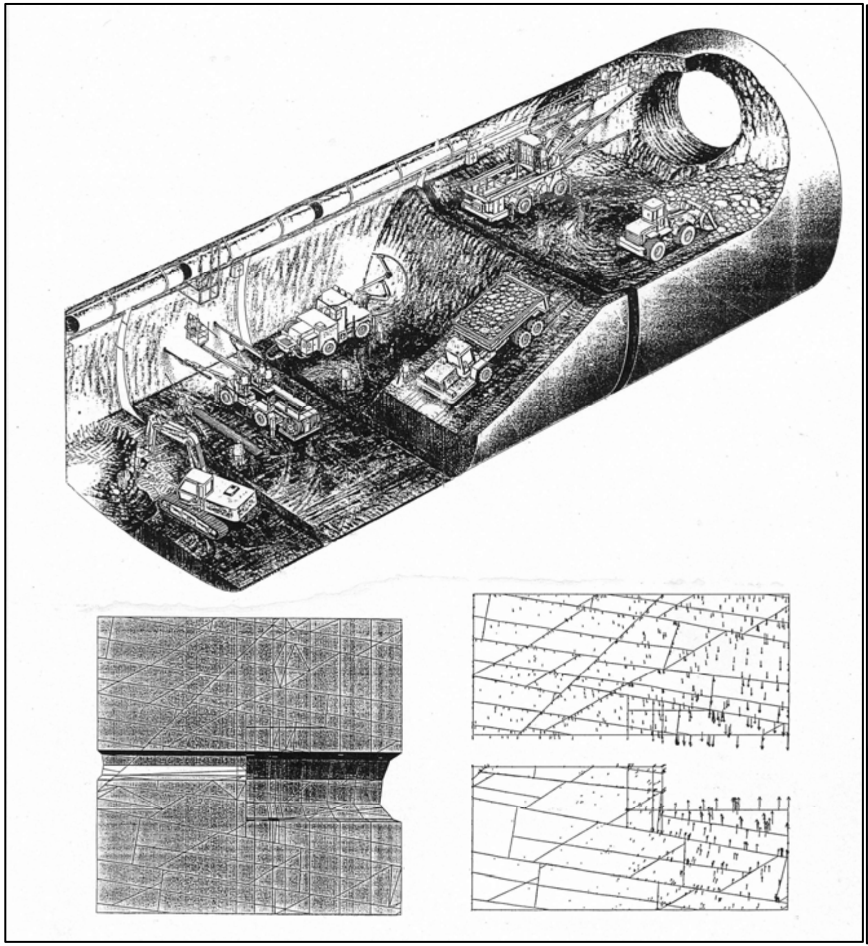
AN IDEAL GOAL…. V_p and Q-value …… recording these before going too far with the TBM !

IN OTHER WORDS-----AVOIDANCE OF THESE TYPES OF DELAYS (which reduce AR, and increase the negative gradient (-)m of deceleration)



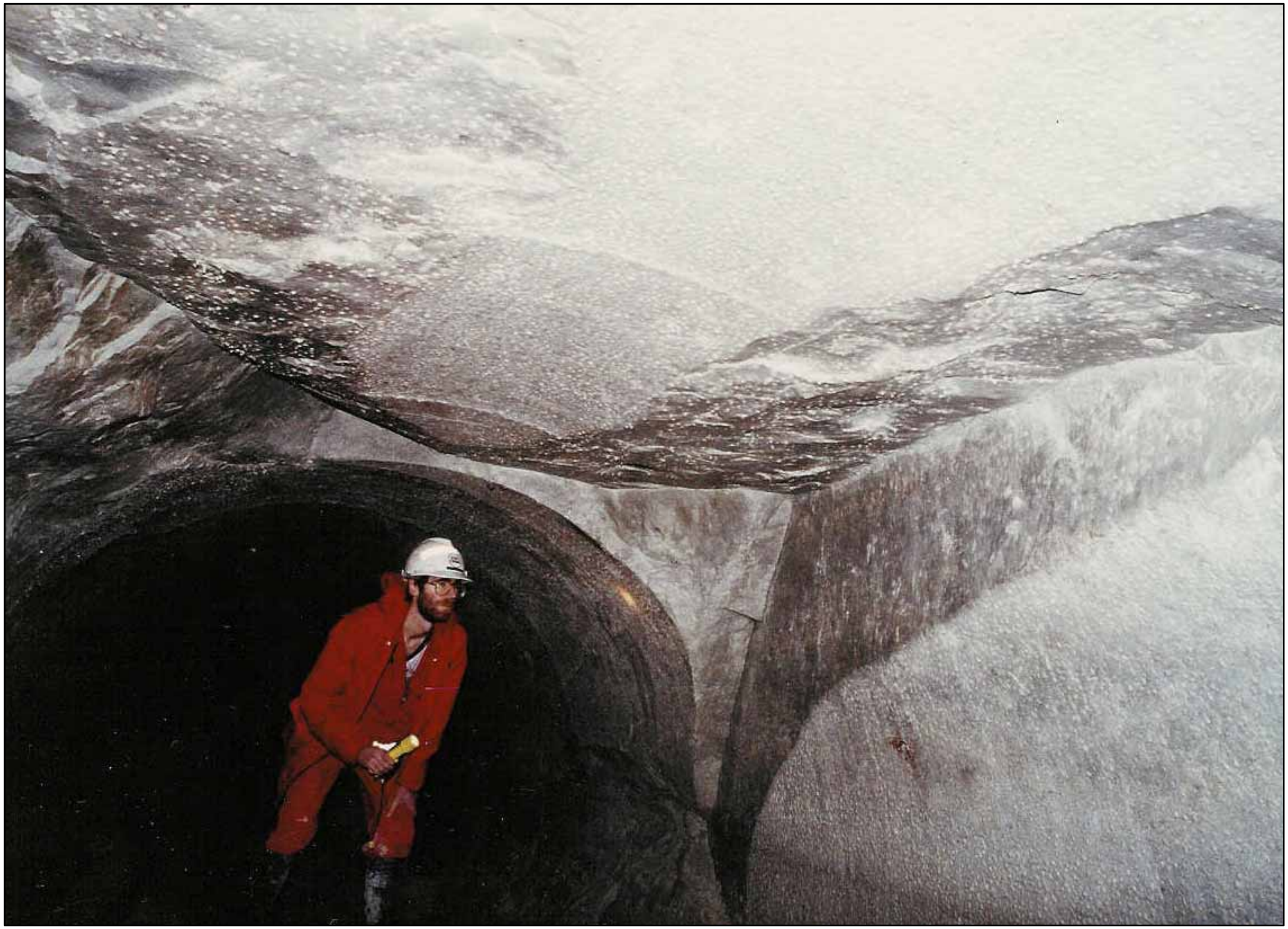
EARLIER IN THE TUNNEL, THIS TBM WAS BREAKING RECORDS IN SHALE

BUT SOMETIMES THE TBM IS THE PILOT HOLE !

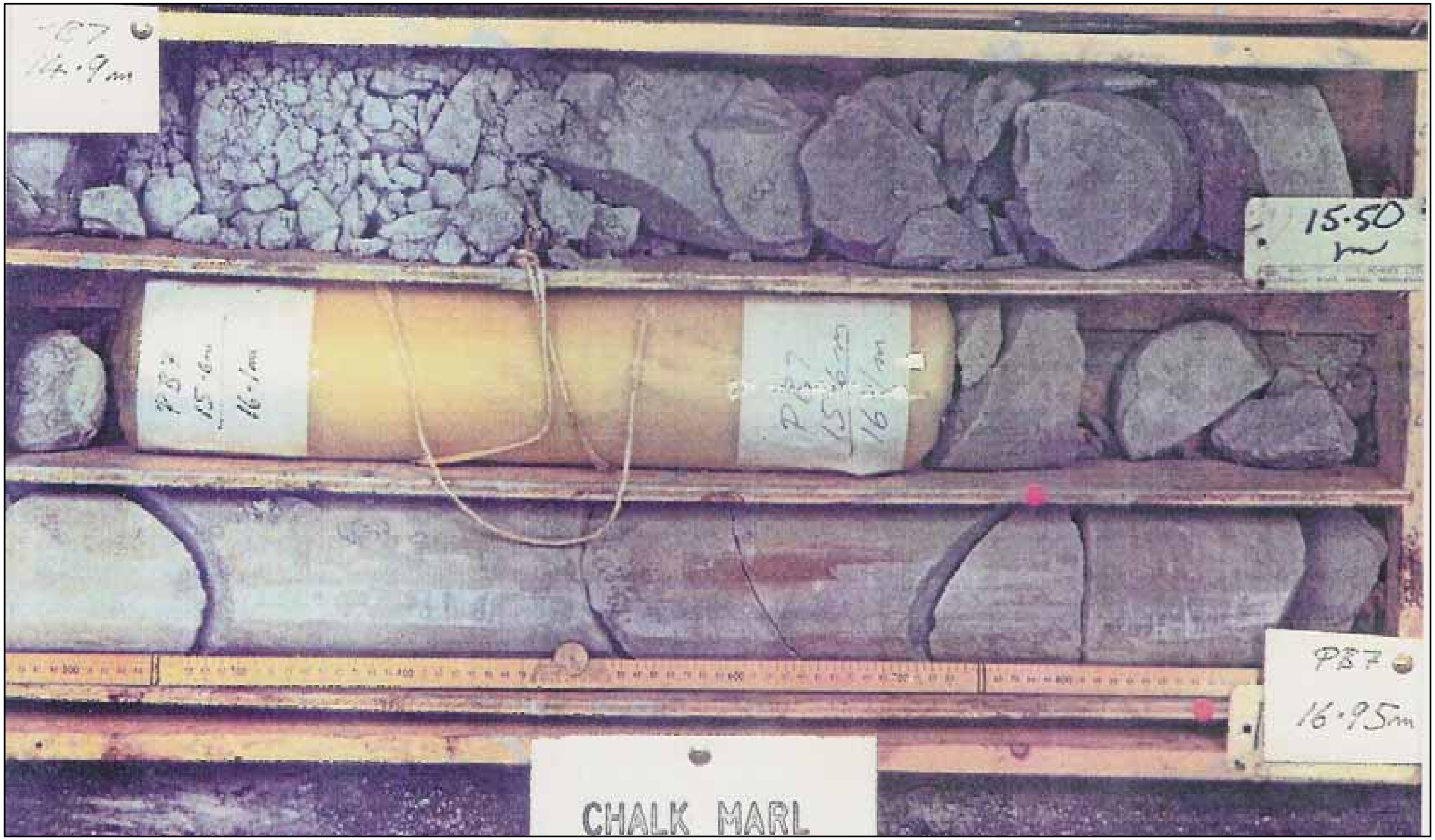


SHIMIZU 3, TOMEI 2, JAPAN

1880 (!) PILOT TBM in *chalk marl* (σ_c = 4 to 9 MPa)

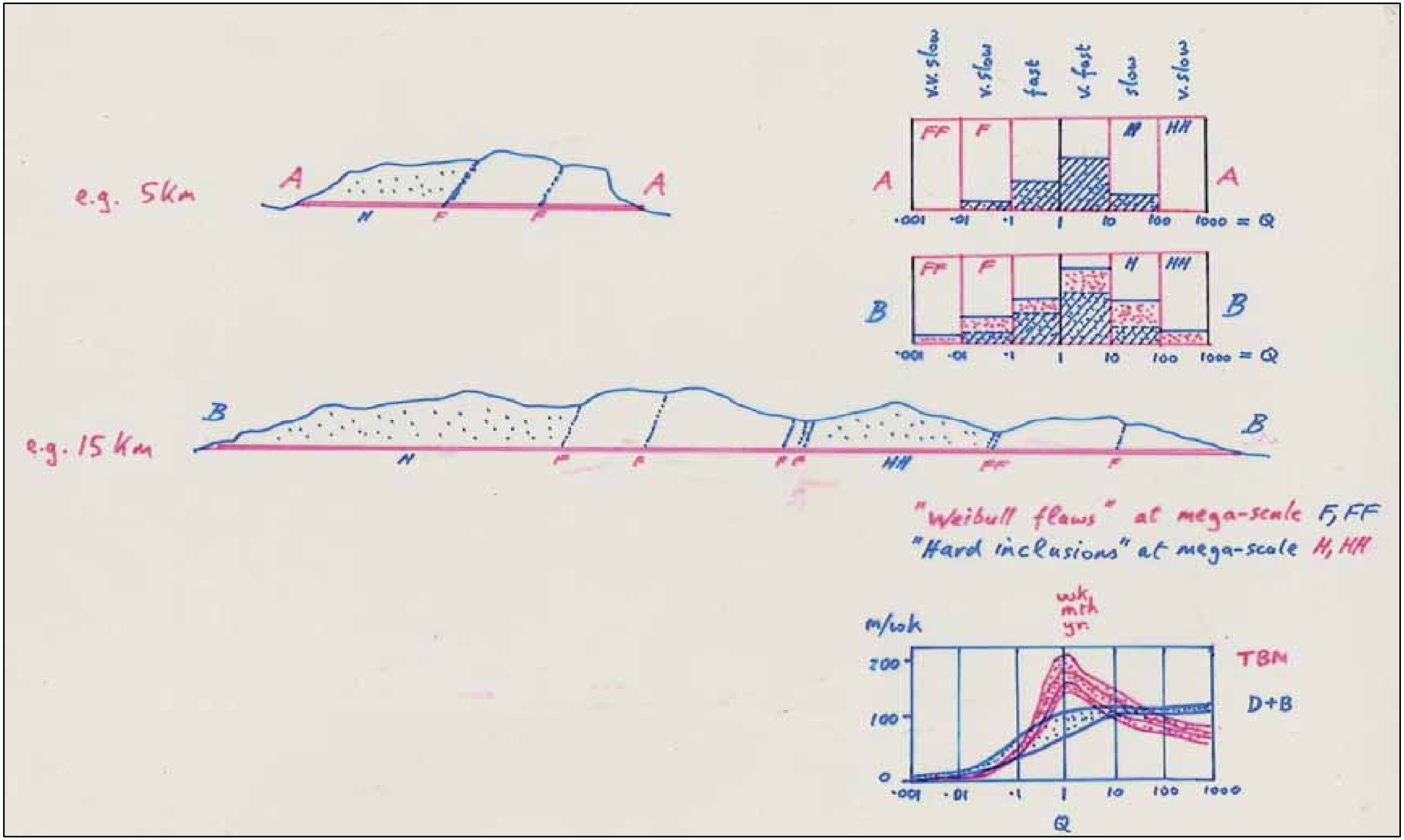


THE *CHALK MARL* WAS NOT EXPECTED TO BE JOINTED !

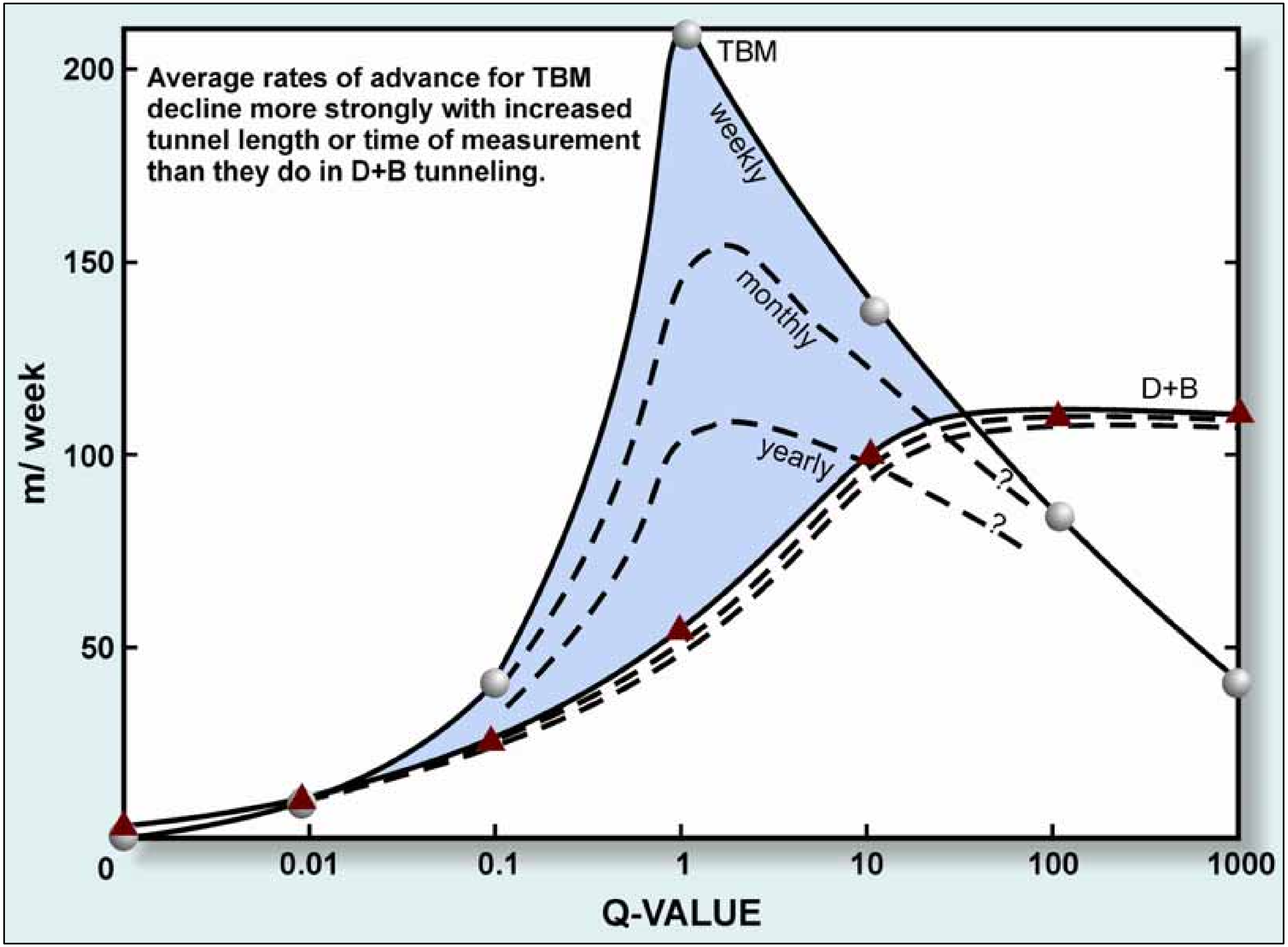


THE TBM HAD GREAT DIFFICULTIES IN THE EARLY KILOMETERS, DUE TO SUCH JOINTS (weathering and water pressure and salt water and block-falls ….. all added risk

DON'T AUTOMATICALLY ASSUME THAT LONG TUNNELS NEED TBM – this will also reduce risk !



ONE MUST BE CLEAR ABOUT THE ROCK QUALITY STATISTICS….



BEFORE CHOOSING THE TBM ALTERNATIVE…..FOR THE WHOLE TUNNEL

BAD FOR TBM TUNNELLING !

Q = 100/0.5 x 4/0.75 x 1/1

Q = 1000 (or better)

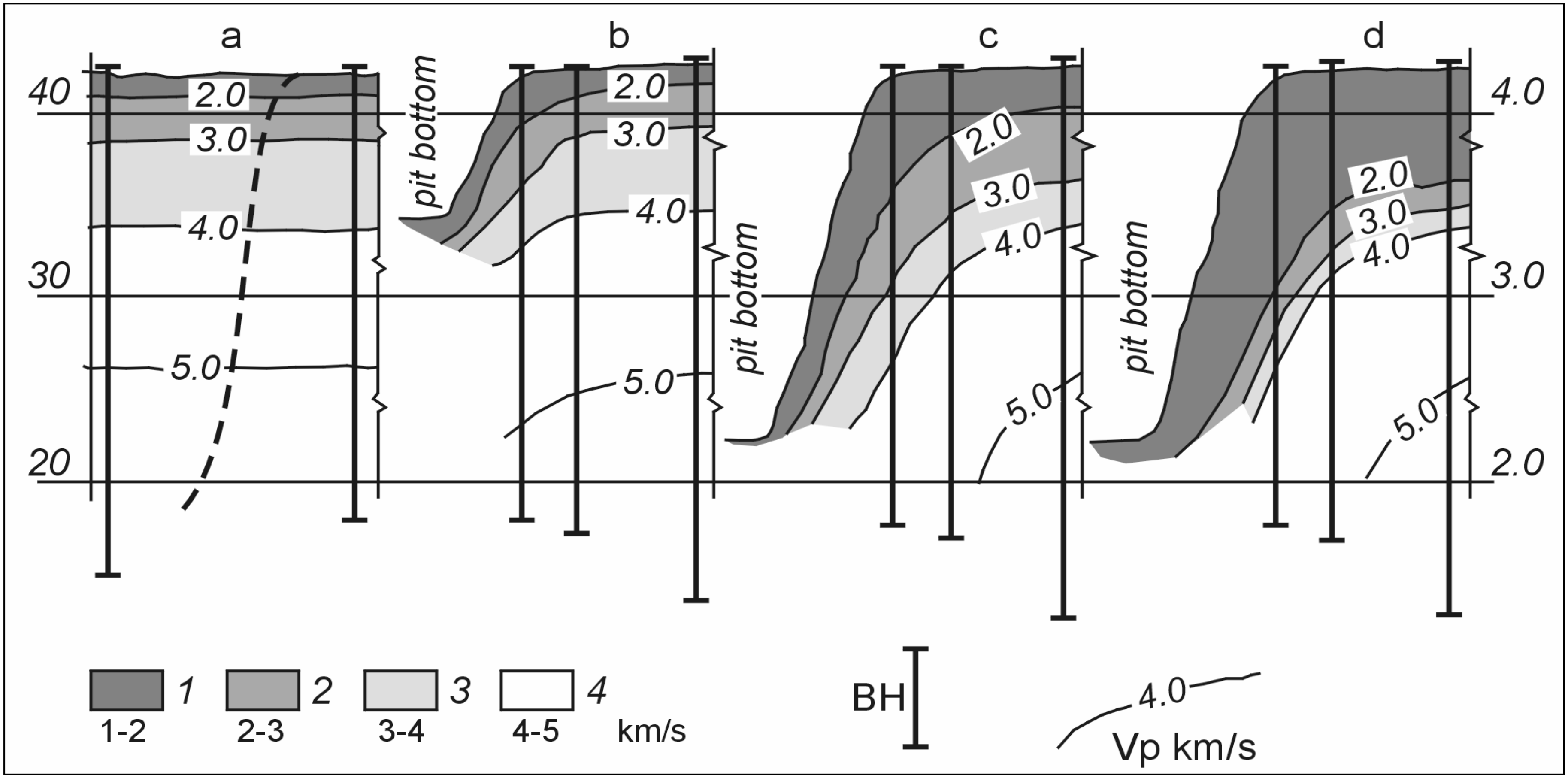
BAD FOR D+B and TBM TUNNELLING !

Q = 10/20 x 1/8 x 0.5/ 20

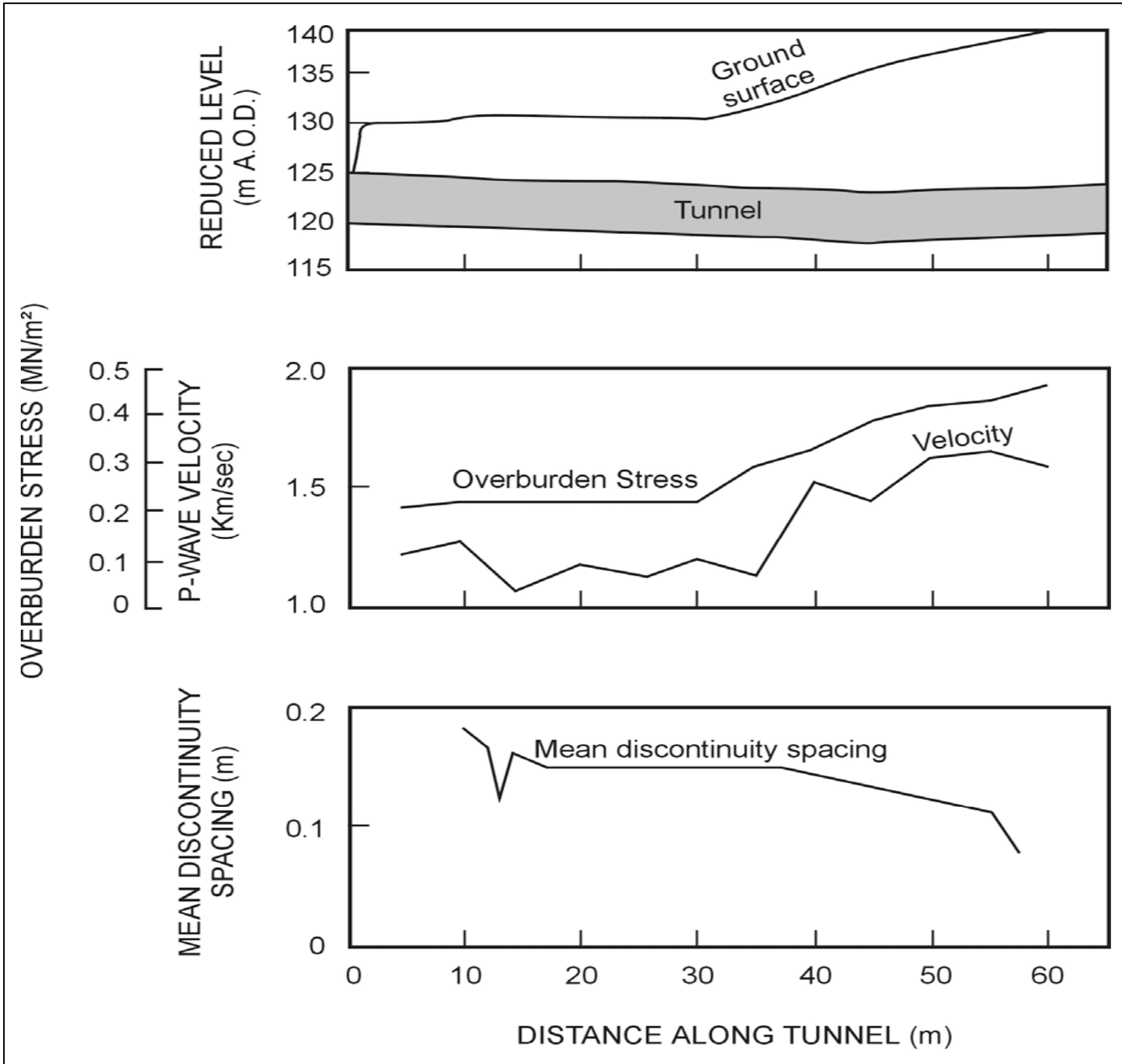
Q = 0.001 (or worse)

SEISMIC MEASUREMENTS FOR REDUCING RISK….

EFFECT OF TIME, INSUFFICIENT SUPPORT, DEPTH on V_P



(Is the deeper rock better quality…..or just more highly stressed?)

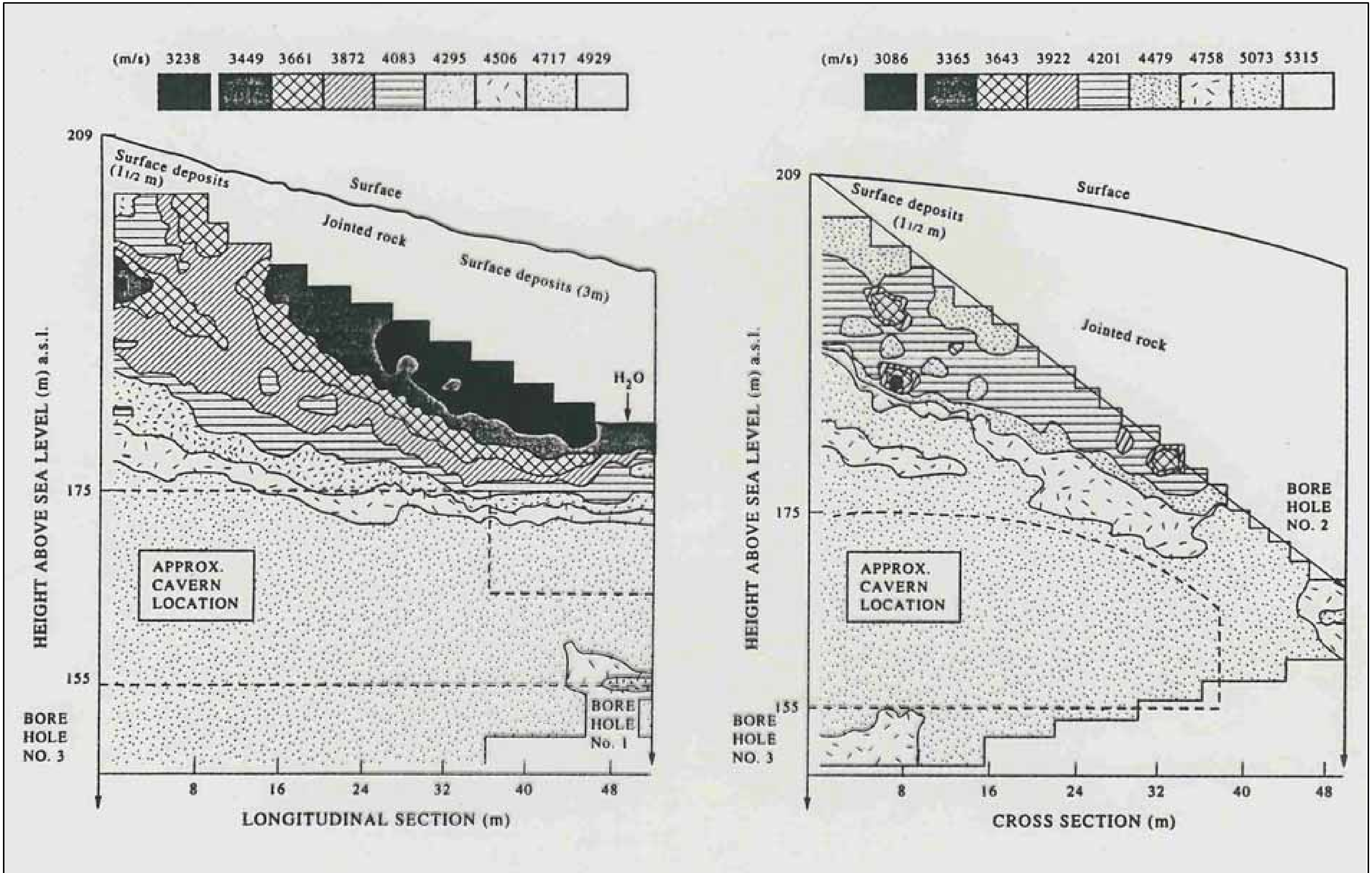


140
135
130
125
120
115
REDUCED LEVEL
(m A.O.D.)
Ground surface
Tunnel
OVERBURDEN STRESS (MN/m²)
0.5
0.4
0.3
0.2
0.1
0
P-WAVE VELOCITY
(Km/sec)
2.0
1.5
1.0
Overburden Stress
Velocity
MEAN DISCONTINUITY
SPACING (m)
0.2
0.1
0
Mean discontinuity spacing
0
10
20
30
40
50
60
DISTANCE ALONG TUNNEL (m)

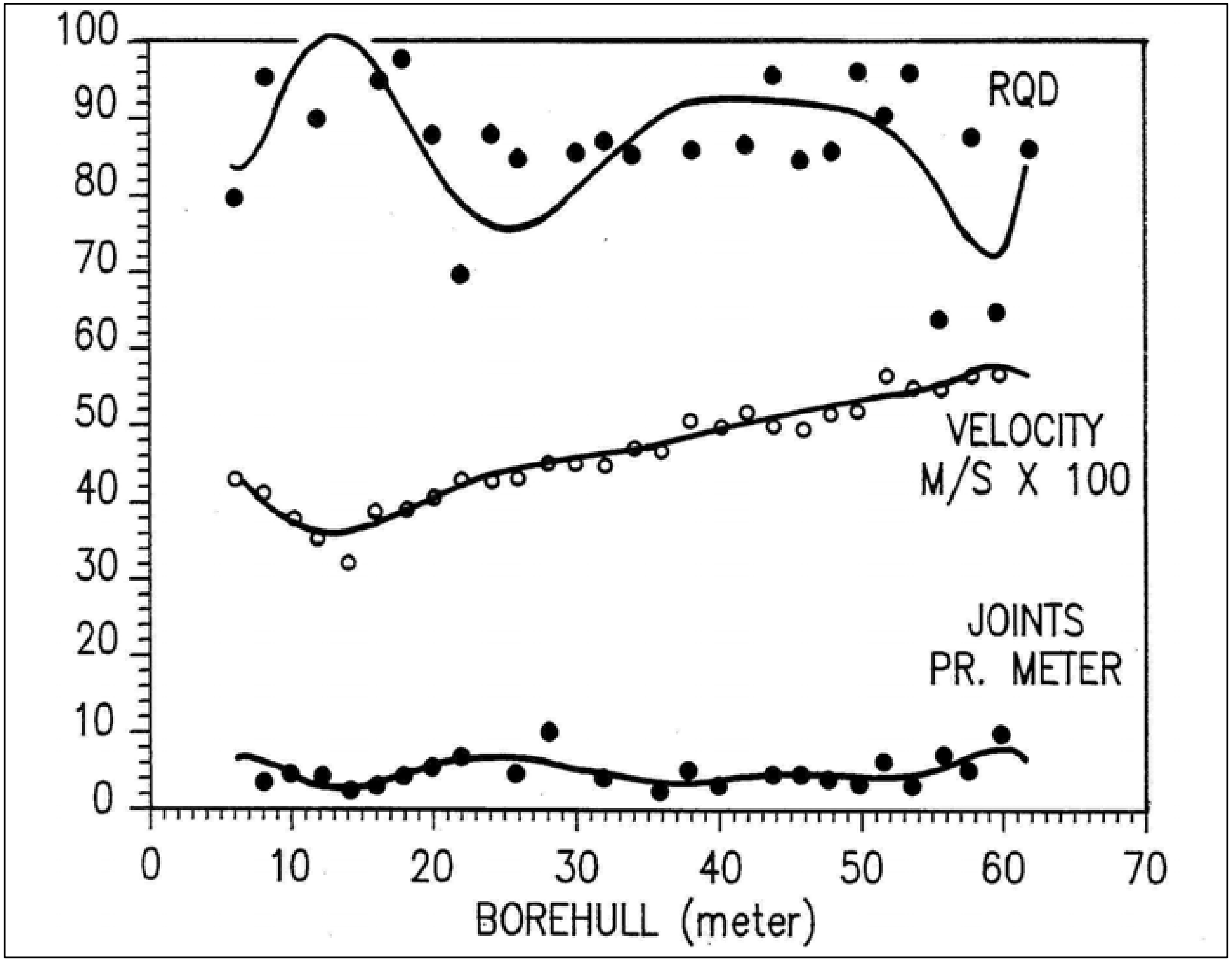
Gjøvik Olympic cavern…..see pre-investigations

(Photo from Veidekke A/S, one of the contractors)

Cores were logged from either side of the seismic cross-hole tomography profiles (NGI, Barton et al. 1991)

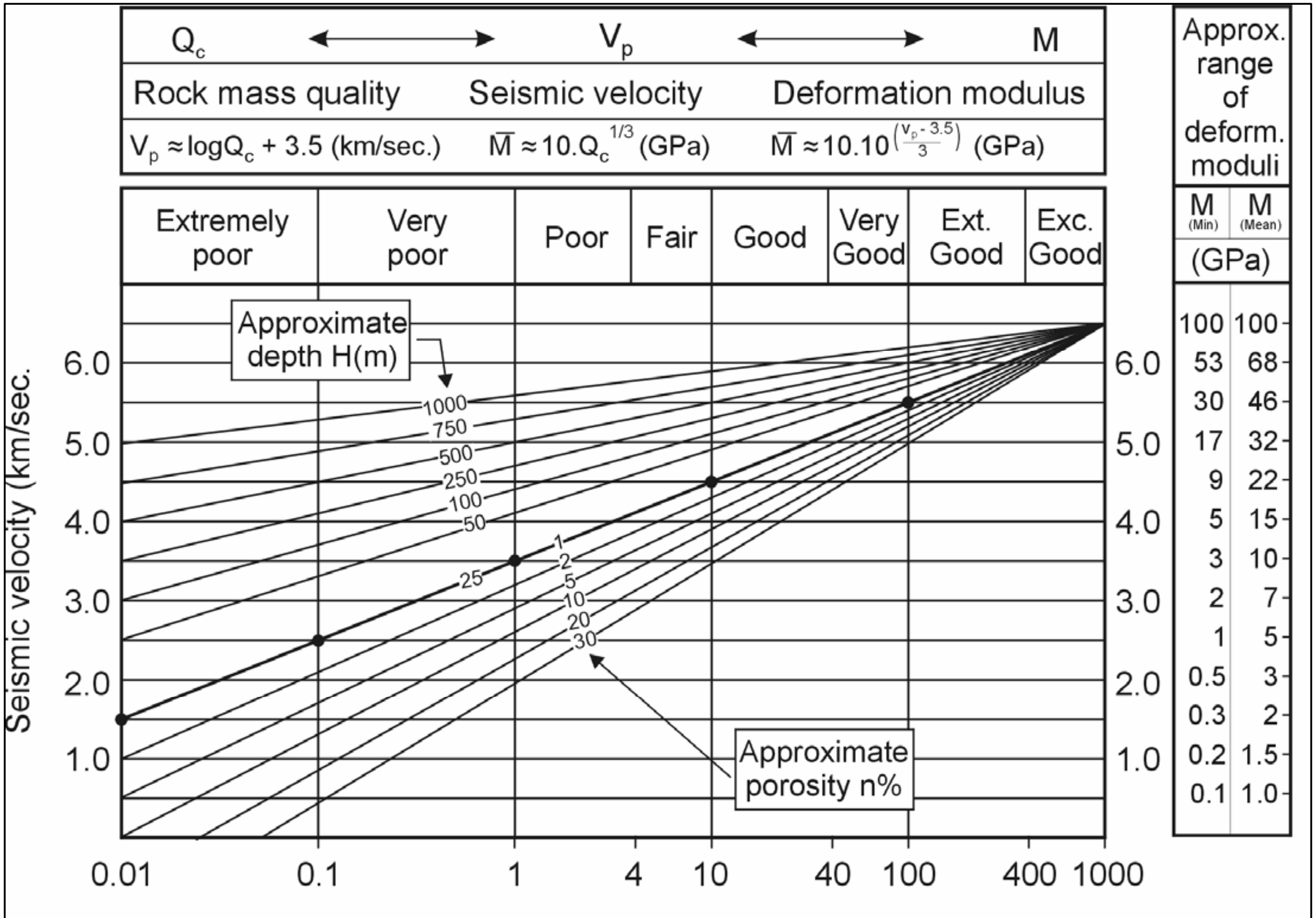


Despite no trend for improved RQD, F m^{-1} or Q with depth……



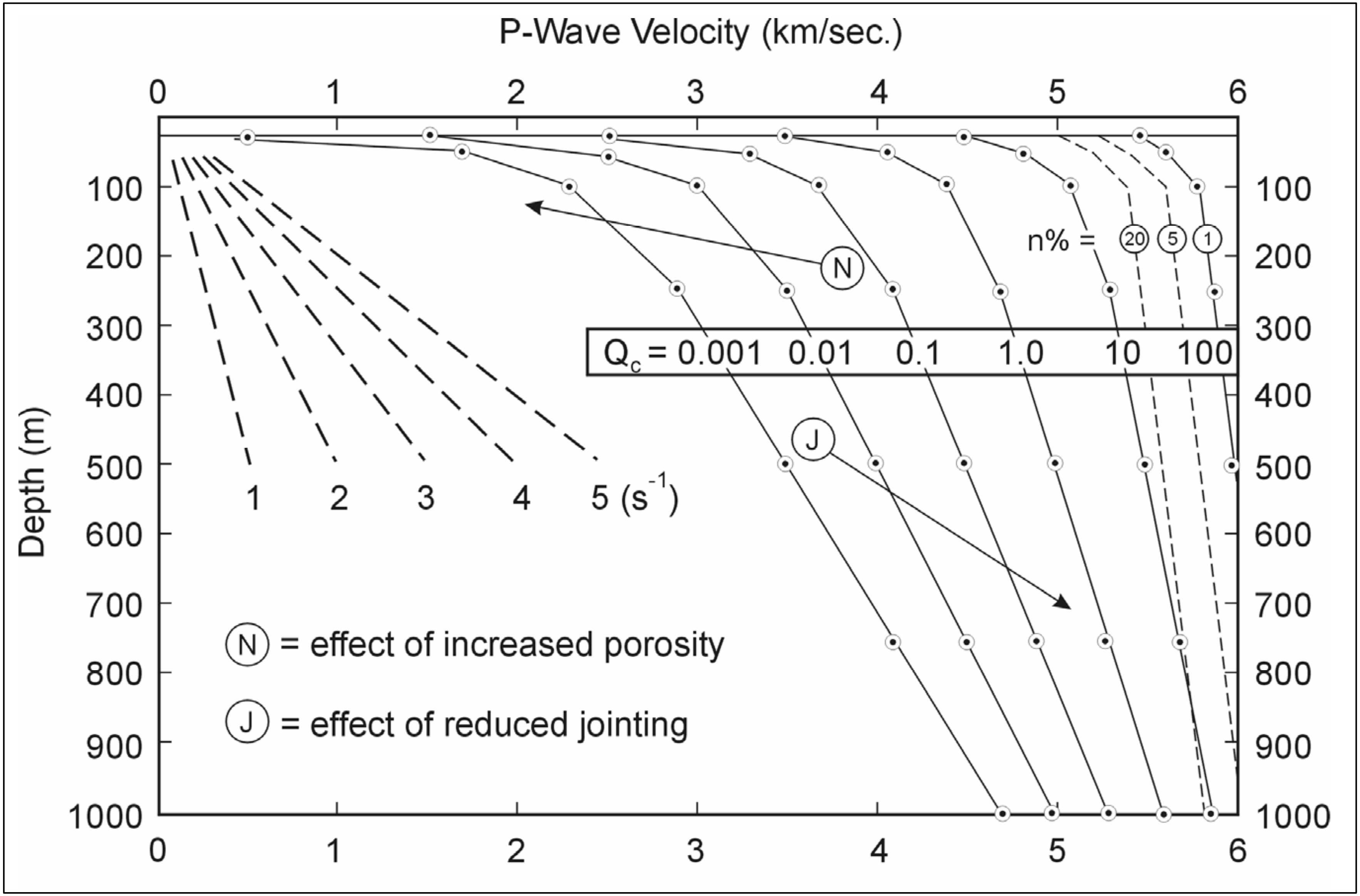
the velocity next to the boreholes was increasing…..up to 2 km/s

An empirical model for interpreting depth effects



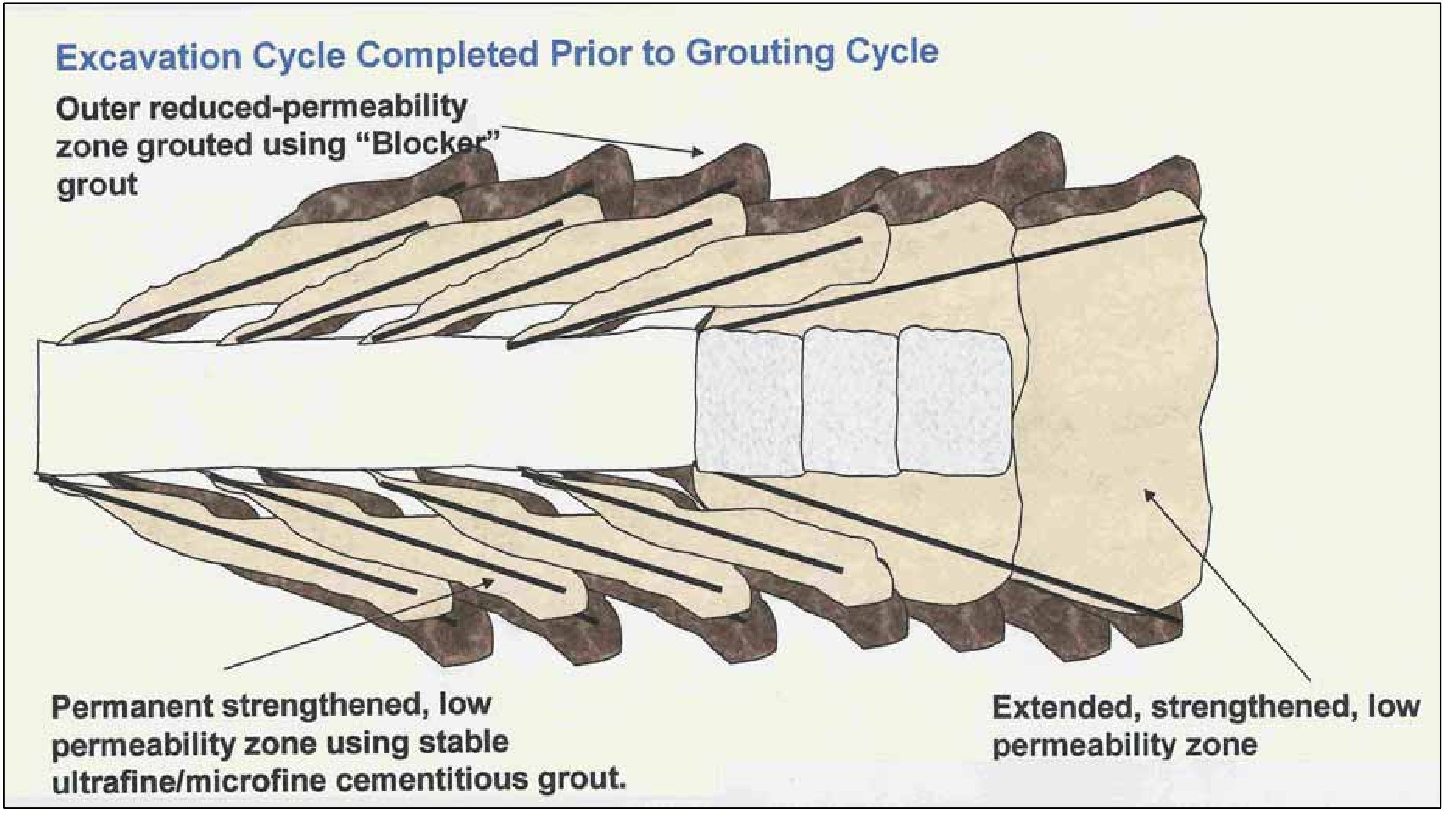
$$Q_c = \left[\frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}\right] \frac{\sigma_c}{100}$$

(Q_c is the Q-value normalized by UCS/100)



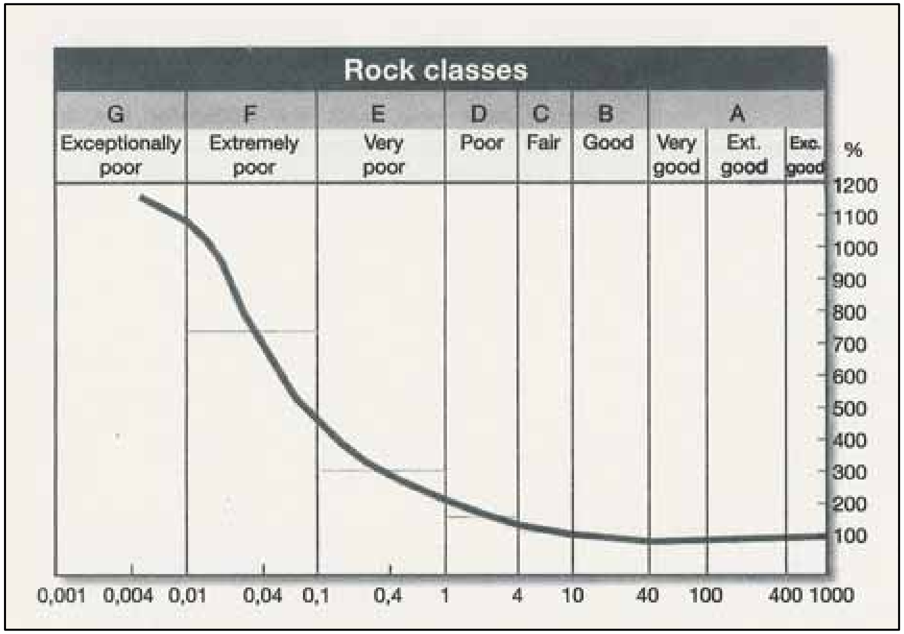
Velocities are 'all' predicted to be high at depth, but different rock qualities are differentiated to a degree that should still be useful

PRE-GROUTING……FOR REDUCING RISK



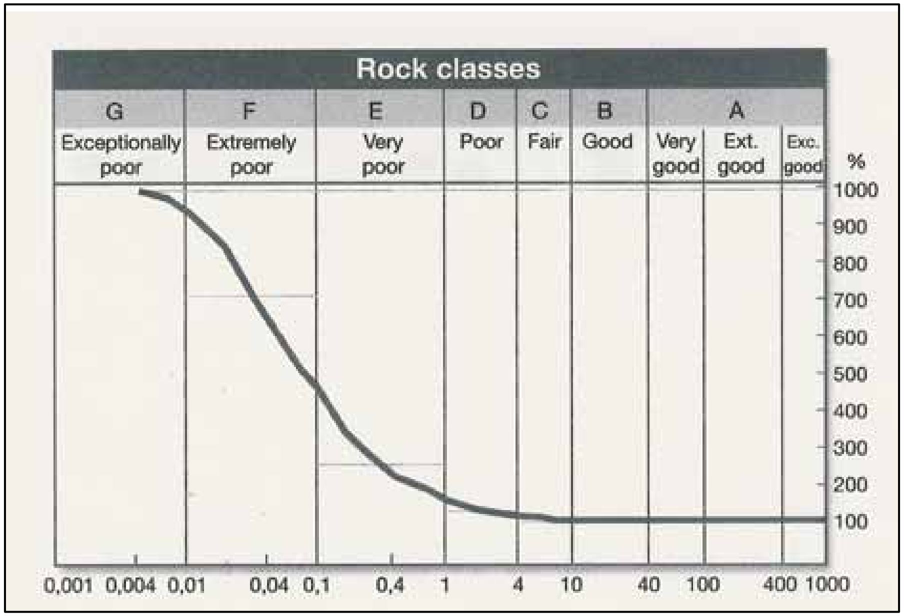
(One of ELKEM's Multigrout concepts)

REDUCING RISK BY PRE-INJECTION MEASURES….INCREASE Q ???



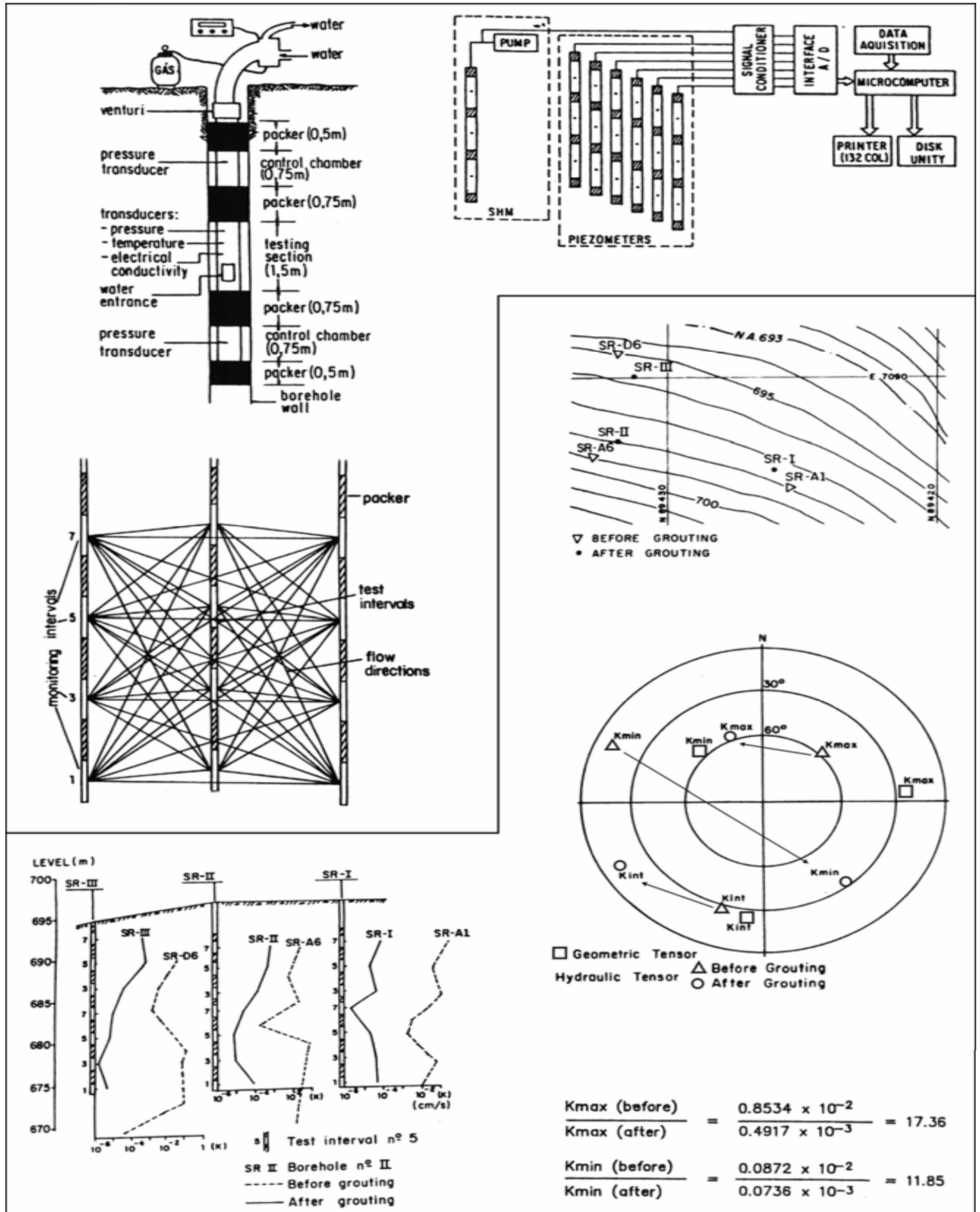
RELATIVE **TIME** FOR TUNNELLING

SO IF WE COULD ***DETECT Q*** *BEFORE TUNNELLING…….*



RELATIVE **COST** OF TUNNELLING

SO IF WE COULD ***IMPROVE Q*** *DURING TUNNELLING*



IPT multi-probe-multi-hole measurement of grouting
(Quadros and Correa Filho, 1995)

effective	RQD	increases	e.g.	30 to 50%	
effective	J_n	reduces	e.g.	9 to 6	
	J_r	increases	e.g.	1 to 2	(changed set)*
	J_a	reduces	e.g.	2 to 1	(changed set)*
	J_w	increases	e.g.	0.5 to 0.66	(perhaps Jw = 1 is achieved)

Before pre-grouting $Q \approx \frac{30}{9} \times \frac{1}{2} \times \frac{0.5}{2,5}$

≈ 0.3

After pre-grouting $Q \approx \frac{50}{6} \times \frac{2}{1} \times \frac{0.66}{1 \text{or} 2.5}$

≈ 11 (or 4·4)

Before pre-grouting	*After pre-grouting*	*(alternative)*
Q ≈ 0.3	Q ≈ 11	(Q ≈ 4·4)
V_p ≈ 3.0 km/sec	Vp ≈ 4.5 km/sec	(V_p ≈ 4·1) km/sec
L ≈ 3 ($3x10^{-7}$ m/s	L ≈ 0·1 (10^{-8} m/s)	(L ≈ 0·2) 2 x 10^{-8} m/s
M ≈ 7 GPa	M ≈ 22 GPa	(M ≈ 16) GPa
P_r ≈14 tnf/m^2	Pr ≈ 4·5 tnf/m^2	(P_r ≈ 6·1) tnf/m^2
Δ ≈ 33 mm	Δ ≈ 0·9 mm	(Δ ≈ 2·3) mm

Without pre-grouting	*With pre-grouting*	*(alternative)*
B 1·5 m/sec	B 2·4 m c/c	B 2·1 m c/c
S (fr) 12 cm	S (fr) 4 cm	S (fr) 5 cm

SOME OF THE EMPIRICAL EQUATIONS RELATING Q-value and rock mass property estimates

$$Q_c = Q \times \sigma_c / 100$$

(km/s) $V_p \approx \log Q_c + 3.5$ (+ depth effect)

(GPa) $E_{mass} \approx 10\, Q_c^{1/3}$ (+ depth)

$SIGMA_{cm} = 5\gamma\, Q_c^{1/3}$ (MPa)

$P_r \approx 0.1\, Q^{-1/3} \approx \frac{10^{-3}}{E_{mass}}$ (MPa)

$$L \approx 1/Q_c$$

$K \approx 10^{-7} \times L$ (m/s)

$$\Delta_{mm} \approx SPAN(m)/Q$$

$$FC = \tan^{-1}(J_r/J_a \times J_w)^\circ$$

$CC = RQD/J_n \times 1/SRF \times \sigma_c/100$ MPa

CONCLUSIONS

- ***High risk factors are often combined in an 'unexpected' combination when TBM get stuck***

- ***Risk can be reduced by appropriate use of standard techniques (geological logging and rock mass characterization, core logging, hydraulic testing, seismic profiles between holes)***

- ***When tunnel depth is great each of the above require 'extrapolation' and risk increases, making probe drilling (even) more important***

- ***The assumption that TBM go faster than drilling-and-blasting in long tunnels introduce several increased risks:***

  a) adverse rock quality statistics (extreme-value problem)

  b) need 'central' rock qualities to improve TBM deceleration (-)m

c) *less favourable 'problem solving' conditions for the contractor in TBM tunnel*

- ***Seismic velocity probing needs careful correction for stress/compaction effects as V_P may increase without rock quality improvements***

- ***A way to improve effective rock quality and control water, and therefore to reduce risk, is to (try to) perform pre-injection ahead of the face***