SESSION TWO: MOUNTAIN TUNNELS
1400 hrs *TOPIC ONE*

TBM Tunnel Collapses in Difficult Mountain Areas : Possible Avoidance and Prognosis

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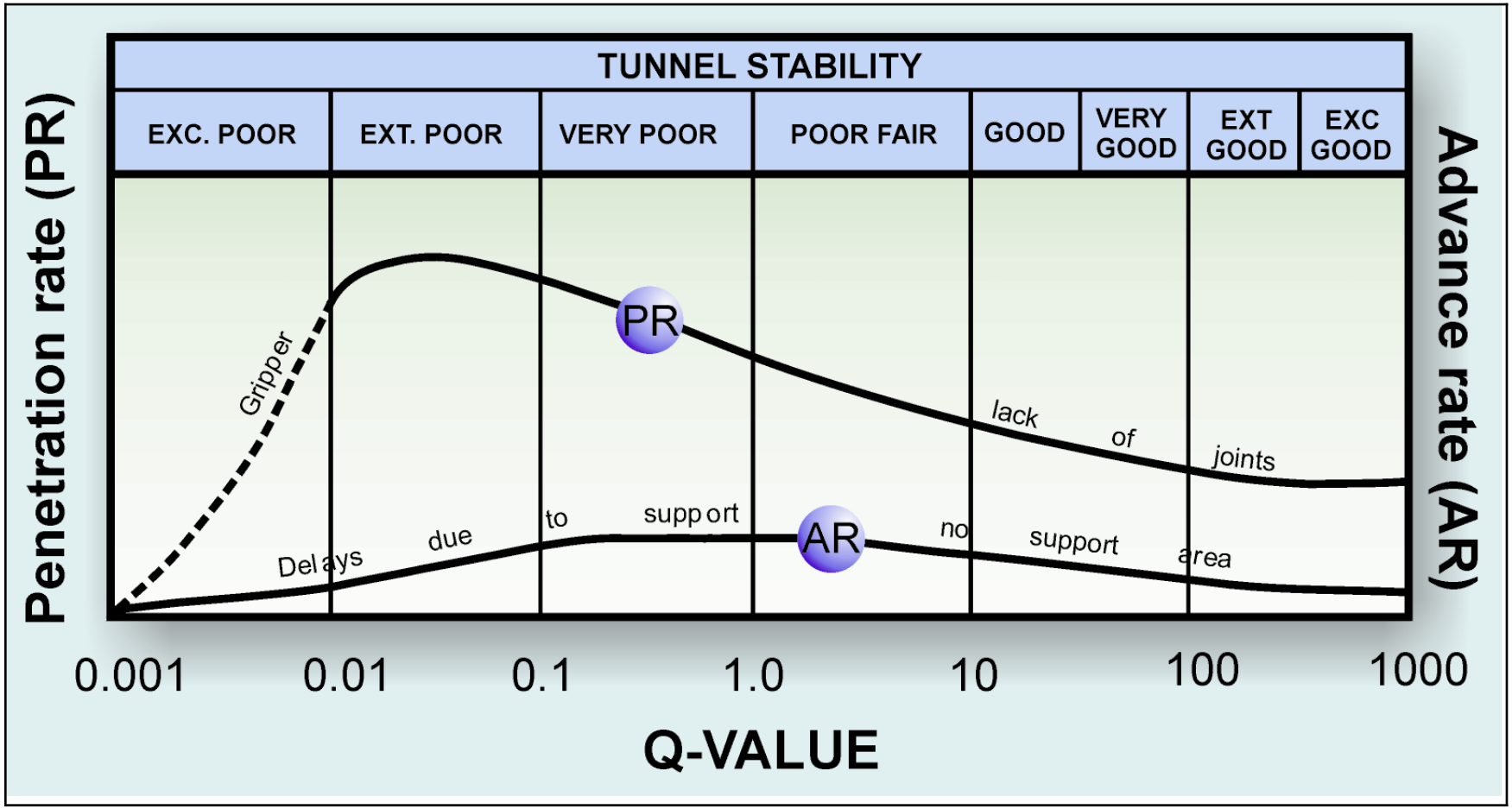
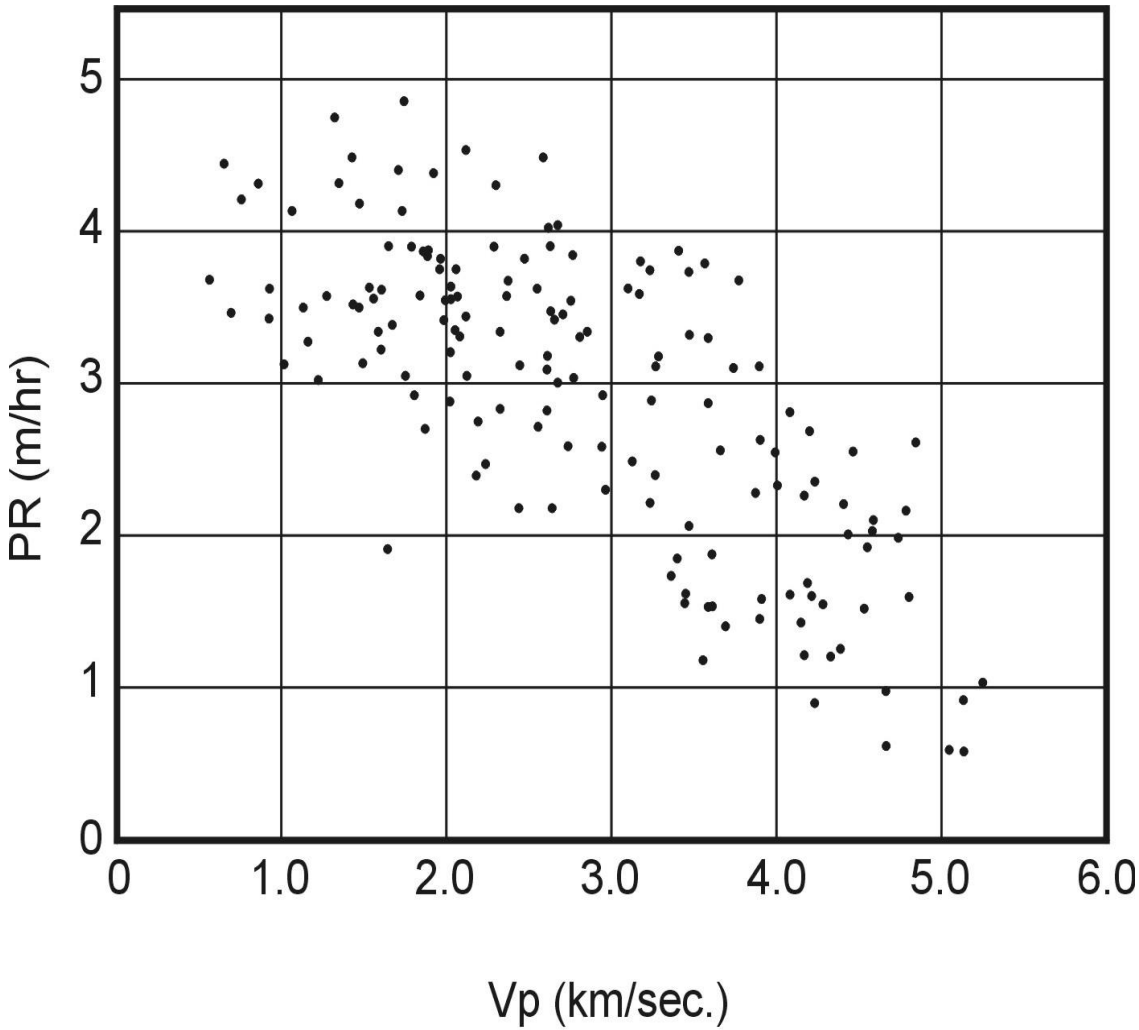
TBM Tunnel Collapses in Difficult Mountain Areas – Possible Avoidance and Prognosis

- Long and deep tunnels increase the hydro- and geological risk.
- Some illustrative cases with hydro- & geological hazards.
- Deceleration of advance rate is usually higher for *open-gripper TBM* than for *double-shield TBM* with push-off-liner capability: nevertheless choice of machine may be critical.
- Probe-drilling, seismic, and pre-injection can be of benefit. A case record.
- Demonstration of *QTBM* prognosis modelling for various cases of *mountain tunnels, including faults and high stress*.

The standard 'Q-system' adjectives (with drill-and blast logic) need to be modified for TBM.

« Lack of joints » also means need for more thrust, and more cutter change if *abrasive* hard rock, etc.





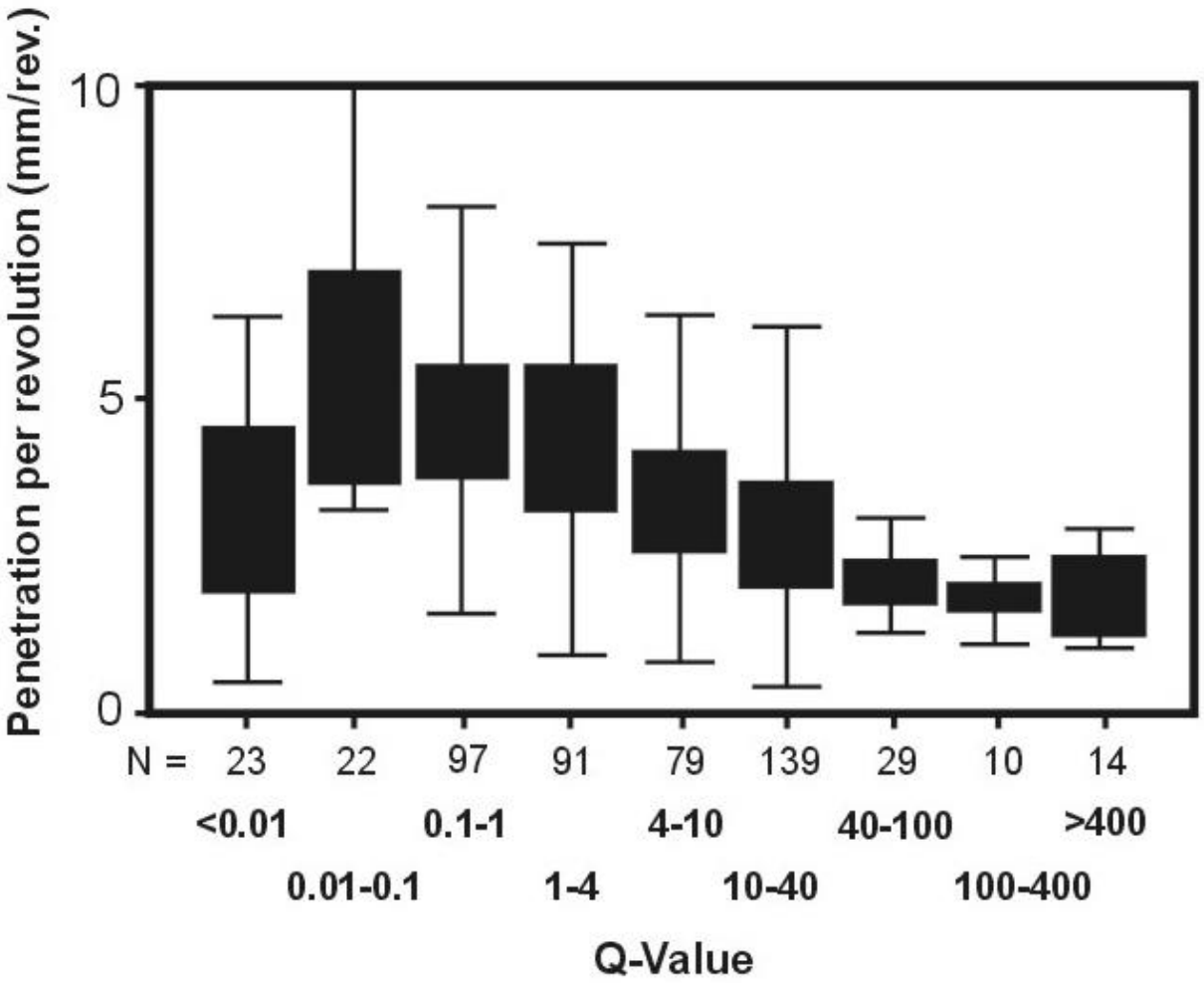
Effect of high Vp giving low PR also seems a reverse of standard logic.

***PR* is best with low V_p**
(in *theory*, if gripper-thrust is possible)

(but AR may be prejudiced by low V_P)

Data from a TBM in granites, Malaysia.

(Sundaram and Rafek, 1998)

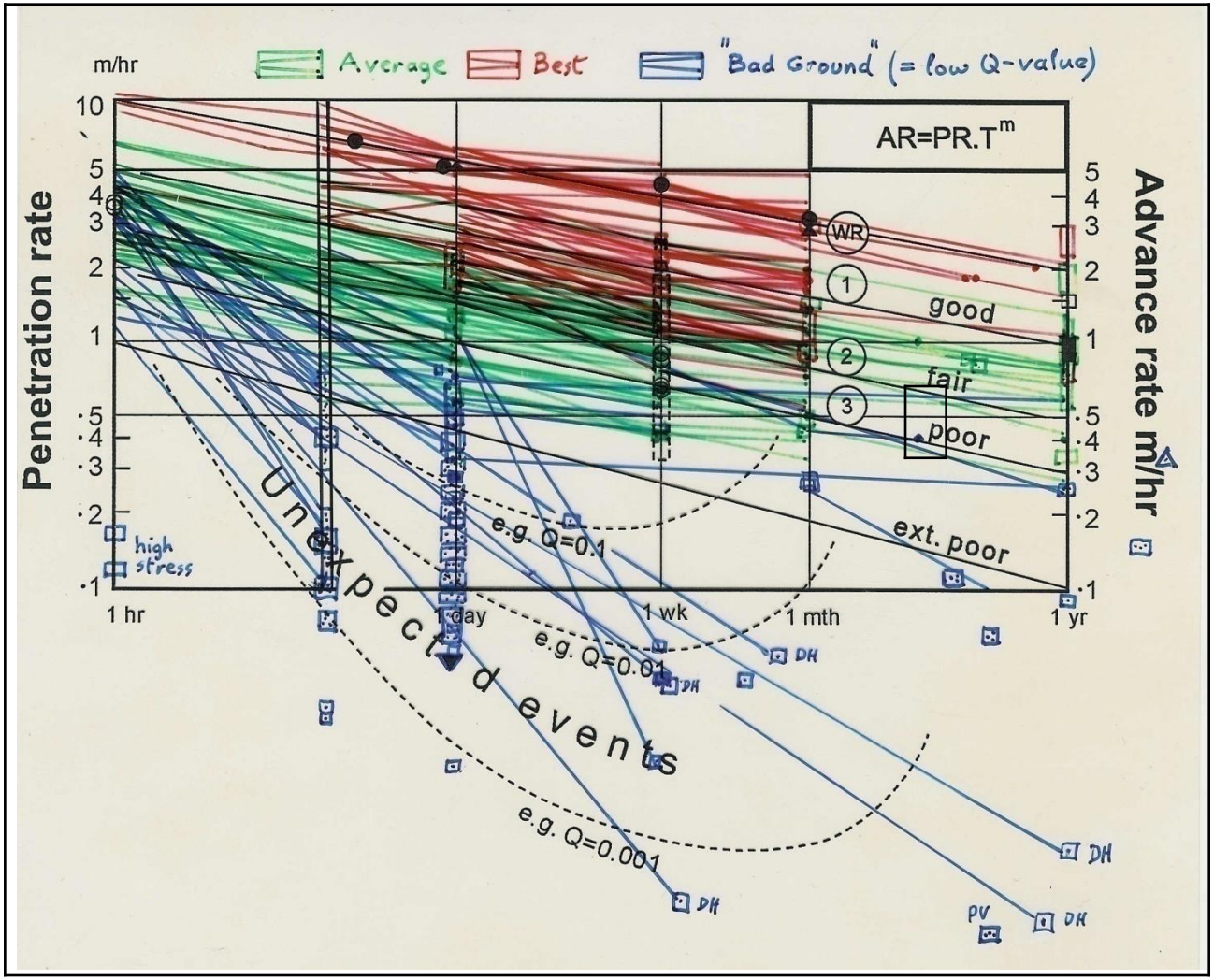


A survey of 145 TBM tunnels

GREAT MAJORITY OPEN GRIPPER TBM

(WHERE ROCK CONDITIONS COULD BE DESCRIBED MORE ACCURATELY)

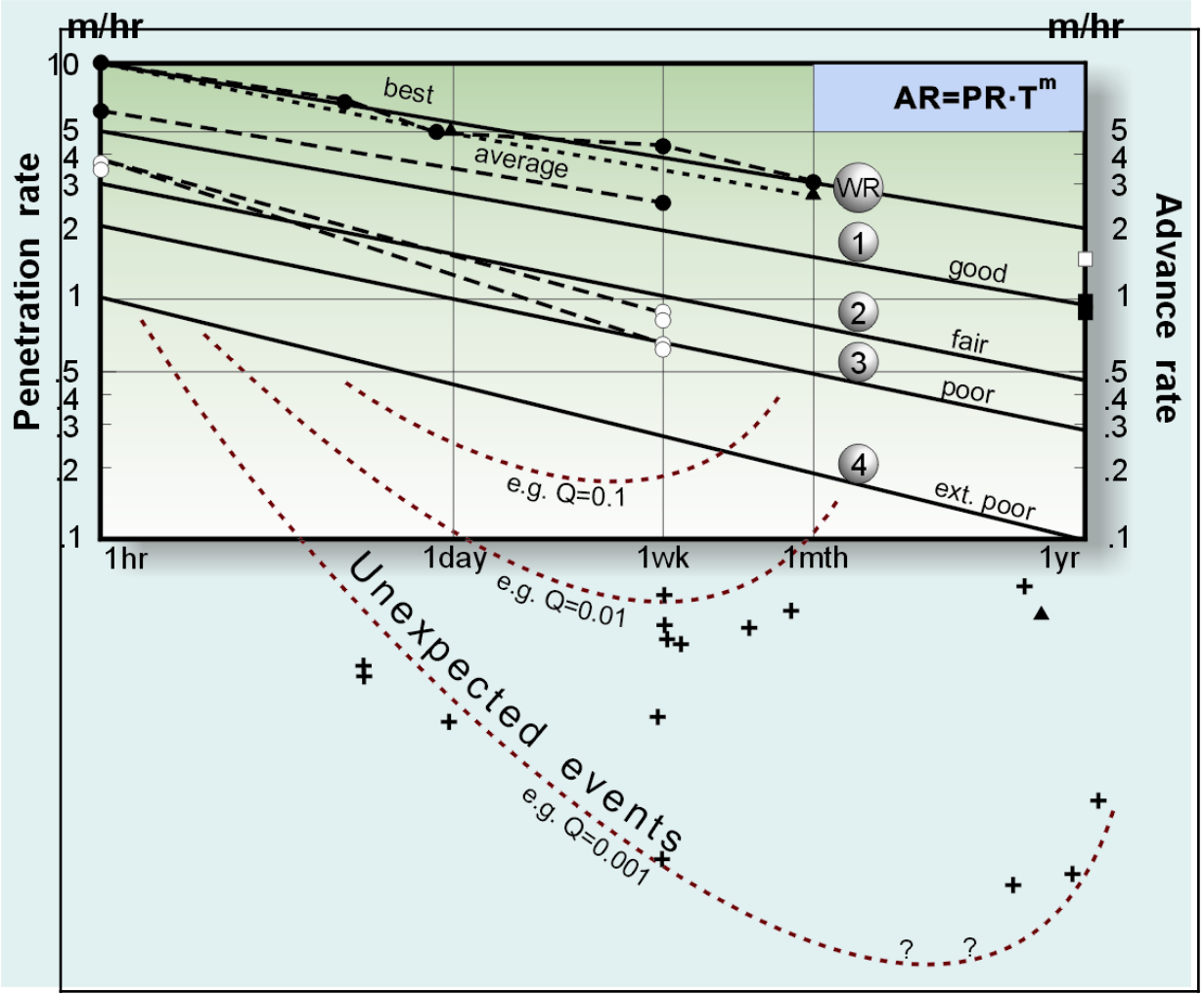
145 case-RECORDS SHOWED THE FOLLOWING ‘BEST’, ‘AVERAGE’, ‘BAD-GROUND’ PERFORMANCE….on a log PR – log T – log AR graph (Barton, 2000).

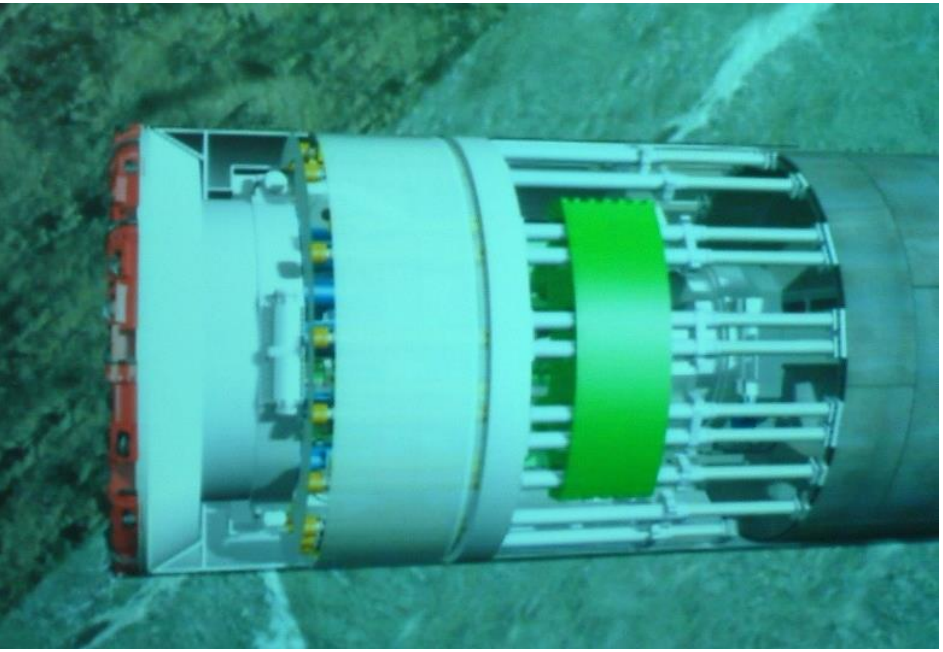


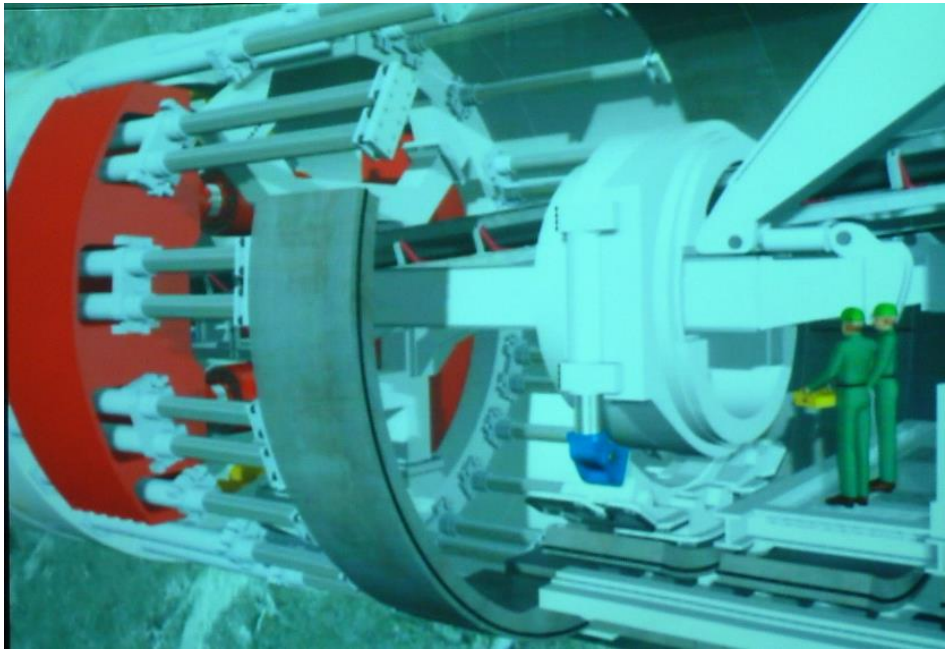
CONVENTIONAL TBM EQUATION: **AR = PR X *U*** ***U = T^m***

UTILIZATION =U gradually declines with increased tunnel length.....*if all time, even down-time*, is included. Gradient *(-)m* is deceleration.

These trends are very important for mountain tunnels!

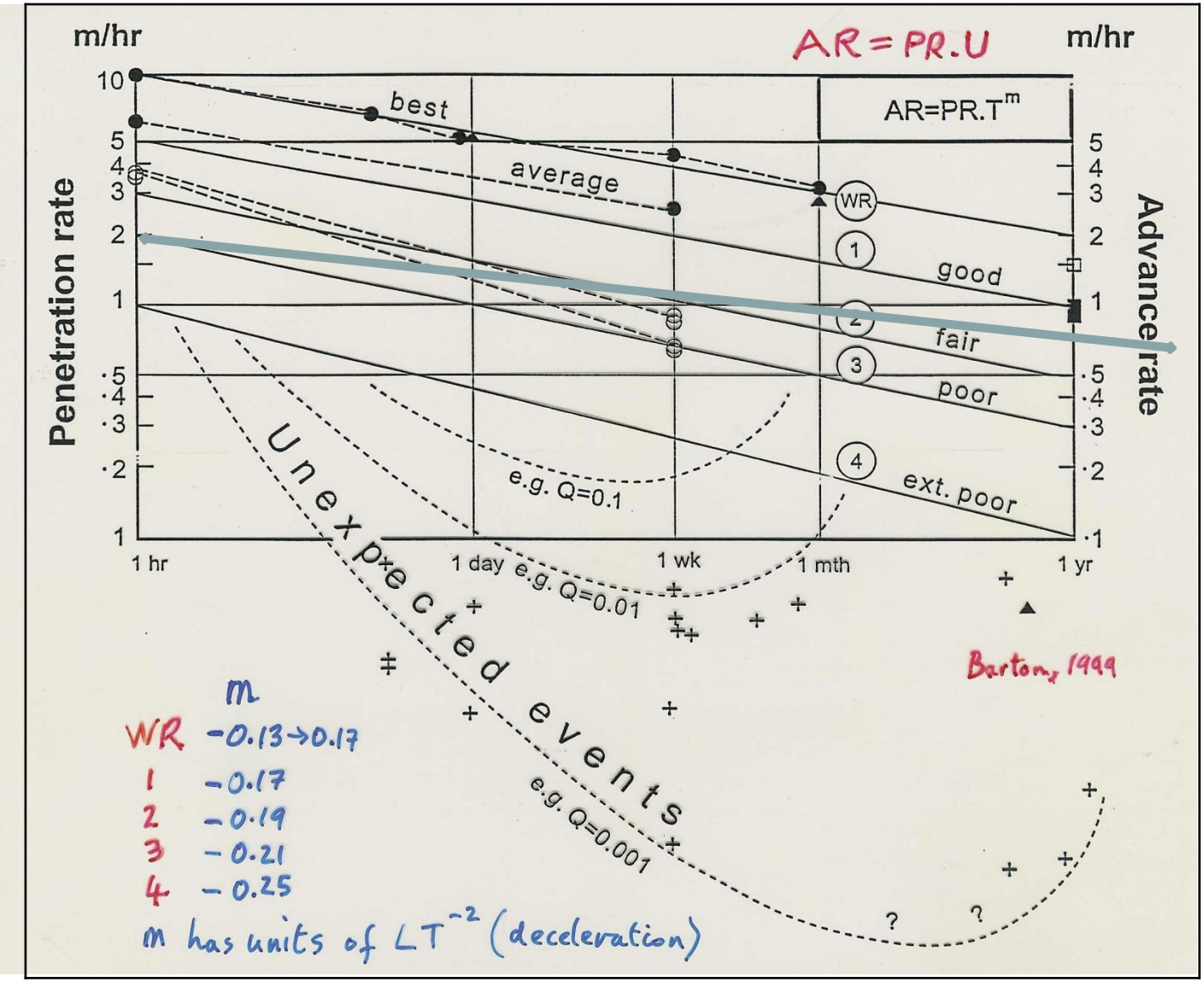






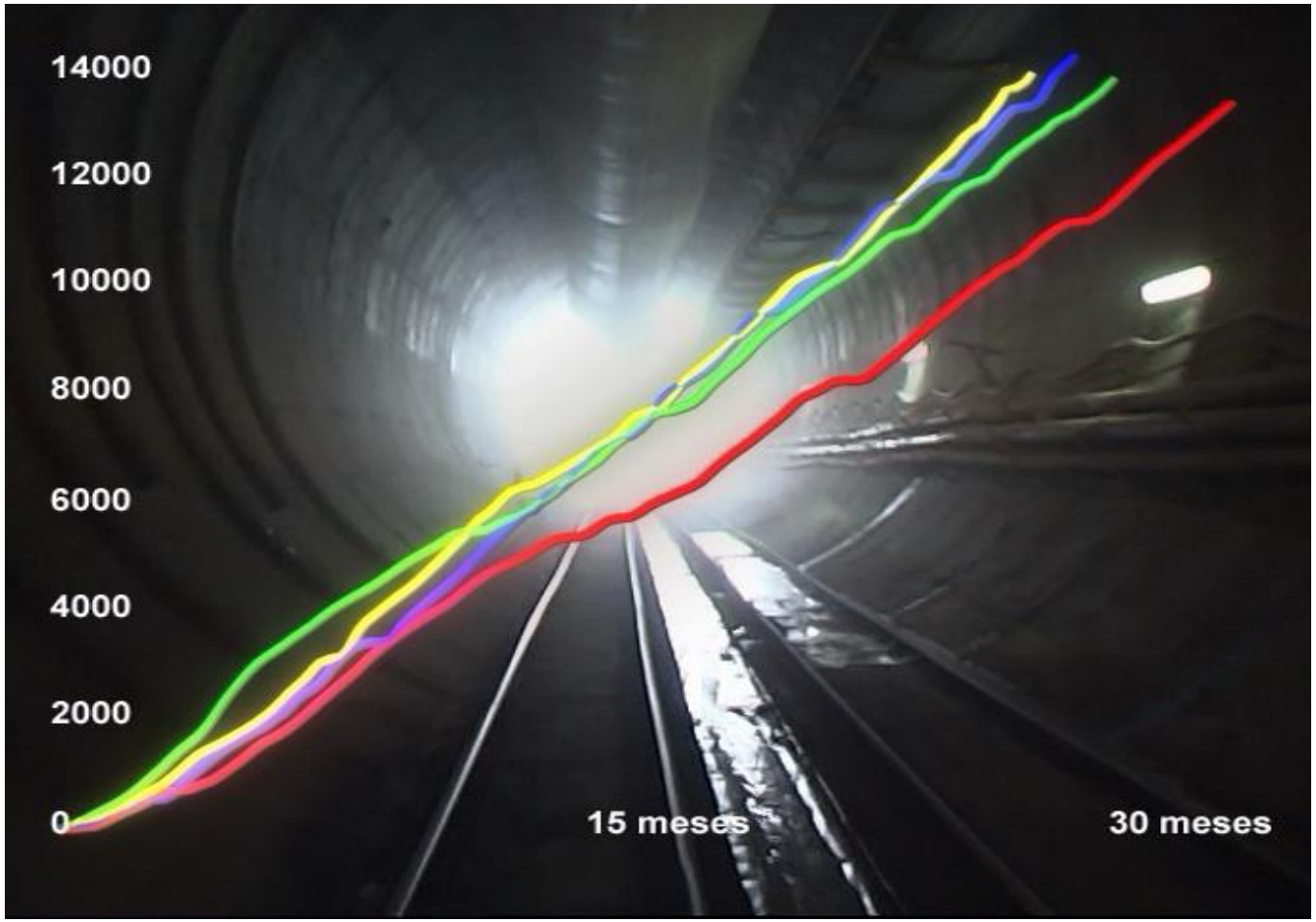
3065 VM

Double-shield machines with liner-element automation, formed very few of these 145 case records . Rock quality can be described only approximately when *seen with difficulty* during e.g.cutter change. SEE BLUE ARROW!



Guadarrama Base Tunnel
2 x 28 km…….14 km by each TBM

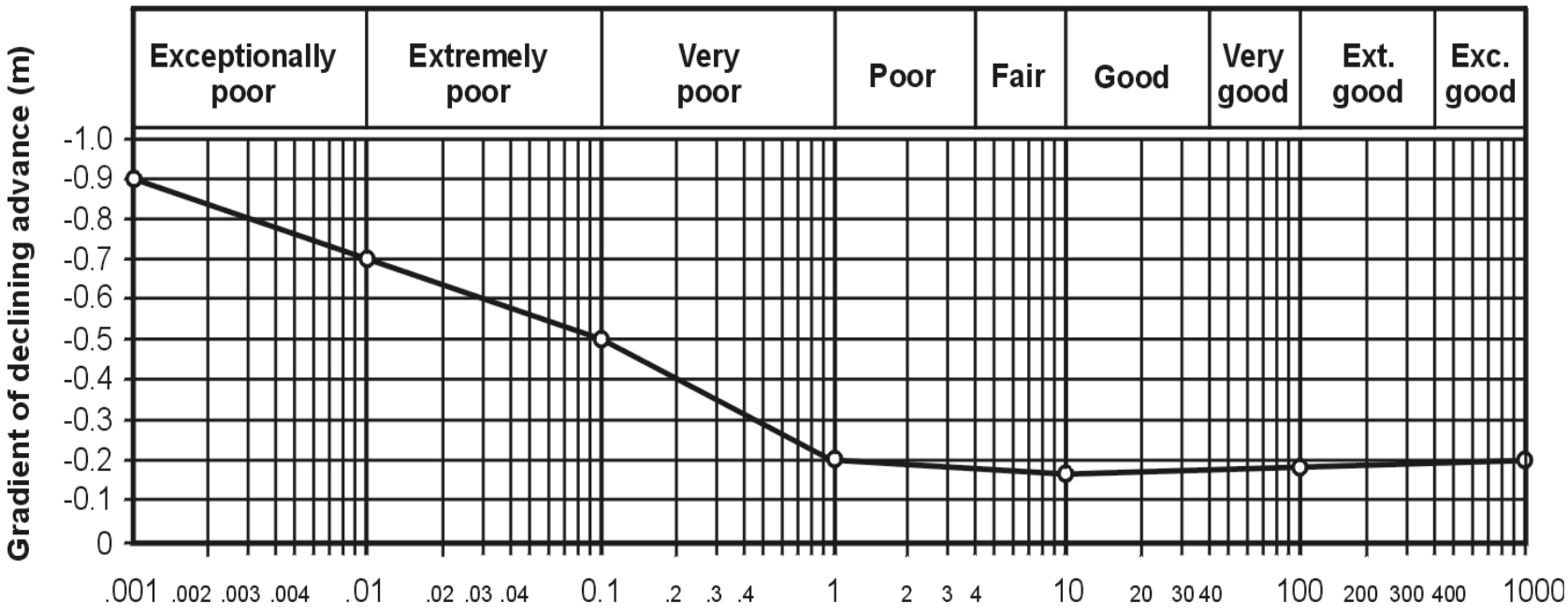
(Double-shield TBM efficiency gave….*m = -0.08 to -0.12)*



THE *'UNEXPECTED EVENTS'* (STANDSTILLS, BLOCKED CUTTER-HEAD, EXTRA DELAYS FOR HEAVY SUPPORT)

STRONGLY RELATED WITH *LOW Q-VALUES (more negative **m**)*

i.e. **mountain tunnel cases with blocked cutter-heads**



Rock mass quality $$Q = \left(\frac{RQD}{J_n}\right) x \left(\frac{J_r}{J_a}\right) x \left(\frac{J_w}{SRF}\right)$$

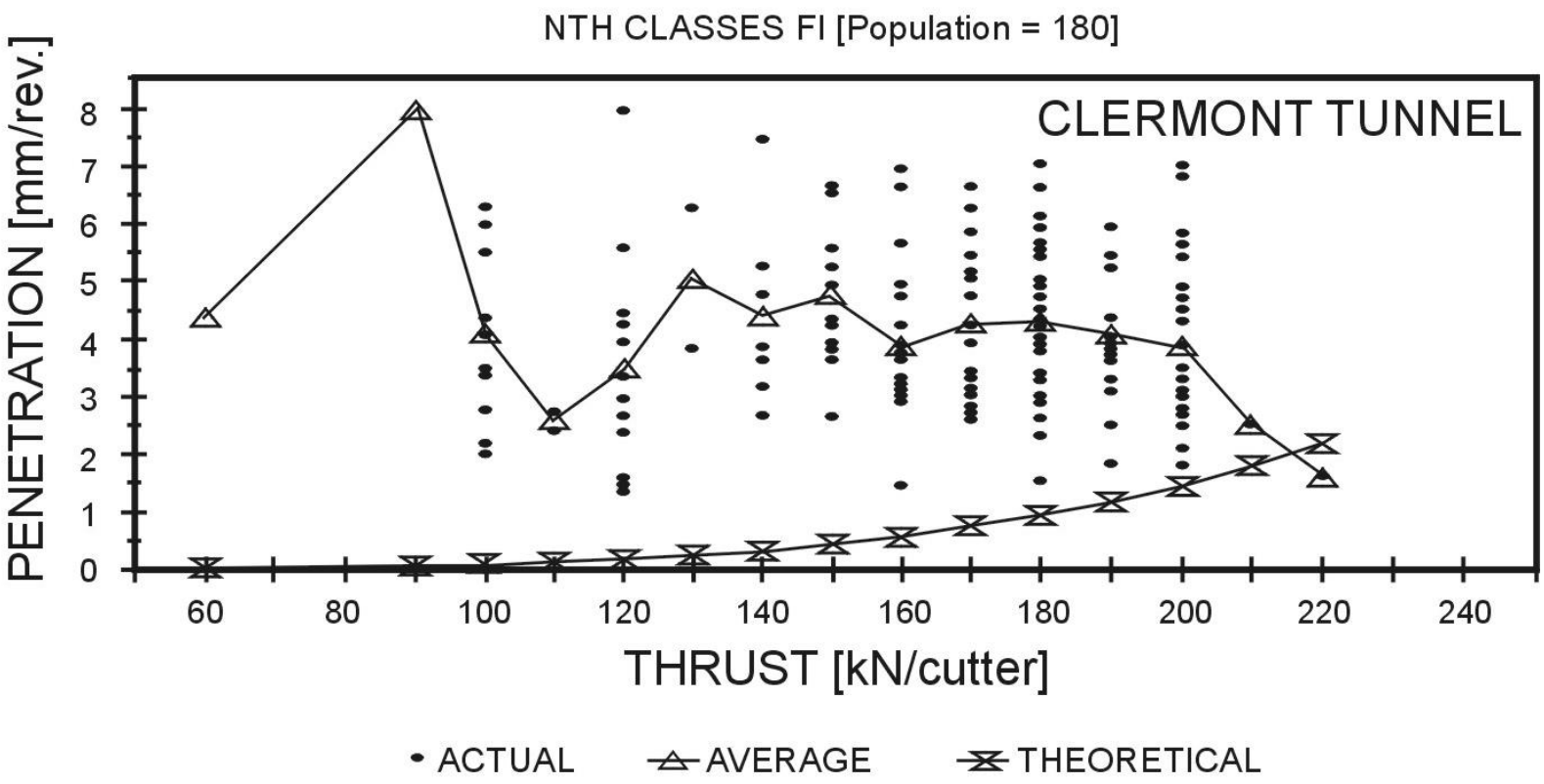
Gradient *(-)m* is ALL-IMPORTANT!

- AR = PR x ***U*** (where U= utilization for boring)
- **AR = PR x T^m (i.e. utilization is time-dependent)**

(T is actual hours)

(*large -**m*** in fault zones, *small -**m*** when no problems, maybe small -***m*** with double-shield, **but pre-treatment / pre-injection of major faults will be needed..... i.e. reduce -m)**

Typical prognosis model expects greater thrust to give greater PR……*occurs only if TBM sufficiently powerful!*



THE Q_{TBM} MODEL FOR TBM PROGNOSIS

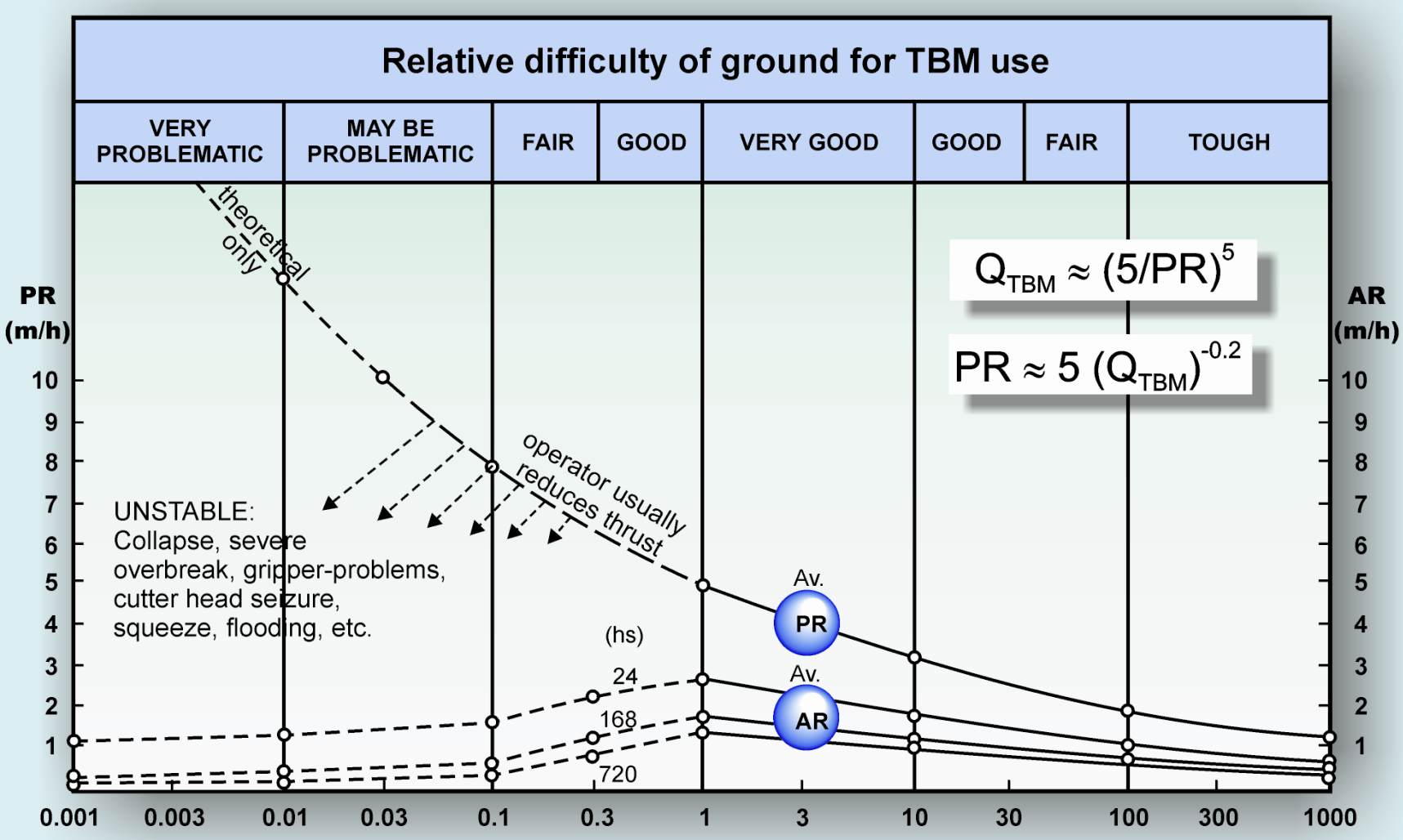
(involves Q and machine/rock interaction)

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

$$SIGMA \approx 5\gamma Q_c^{1/3}$$

$$PR \approx 5 Q_{TBM}^{-1/5}$$

Note *AR* estimation for 24 hrs, 1 week, 1 month

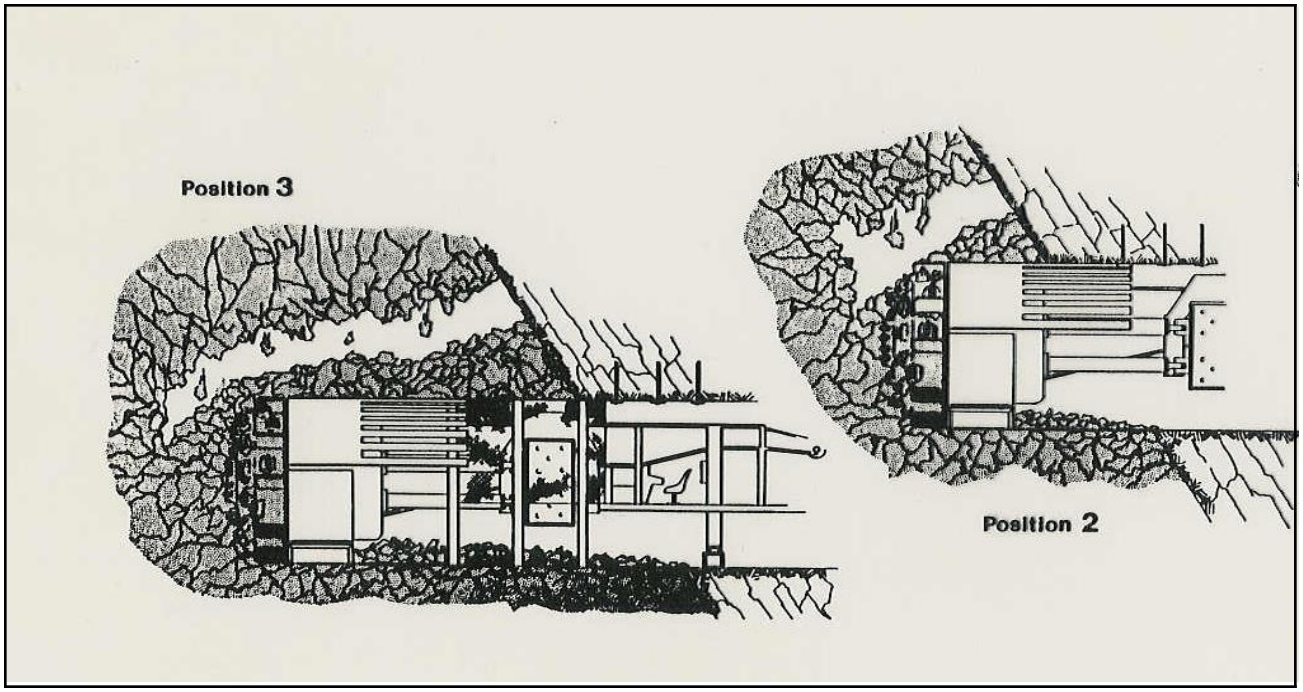


$$Q_{TBM} = \frac{RQD_o}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \times \frac{SIGMA}{F^{10}/20^9} \times \frac{20}{CLI} \times \frac{q}{20} \times \frac{\sigma_\theta}{5}$$

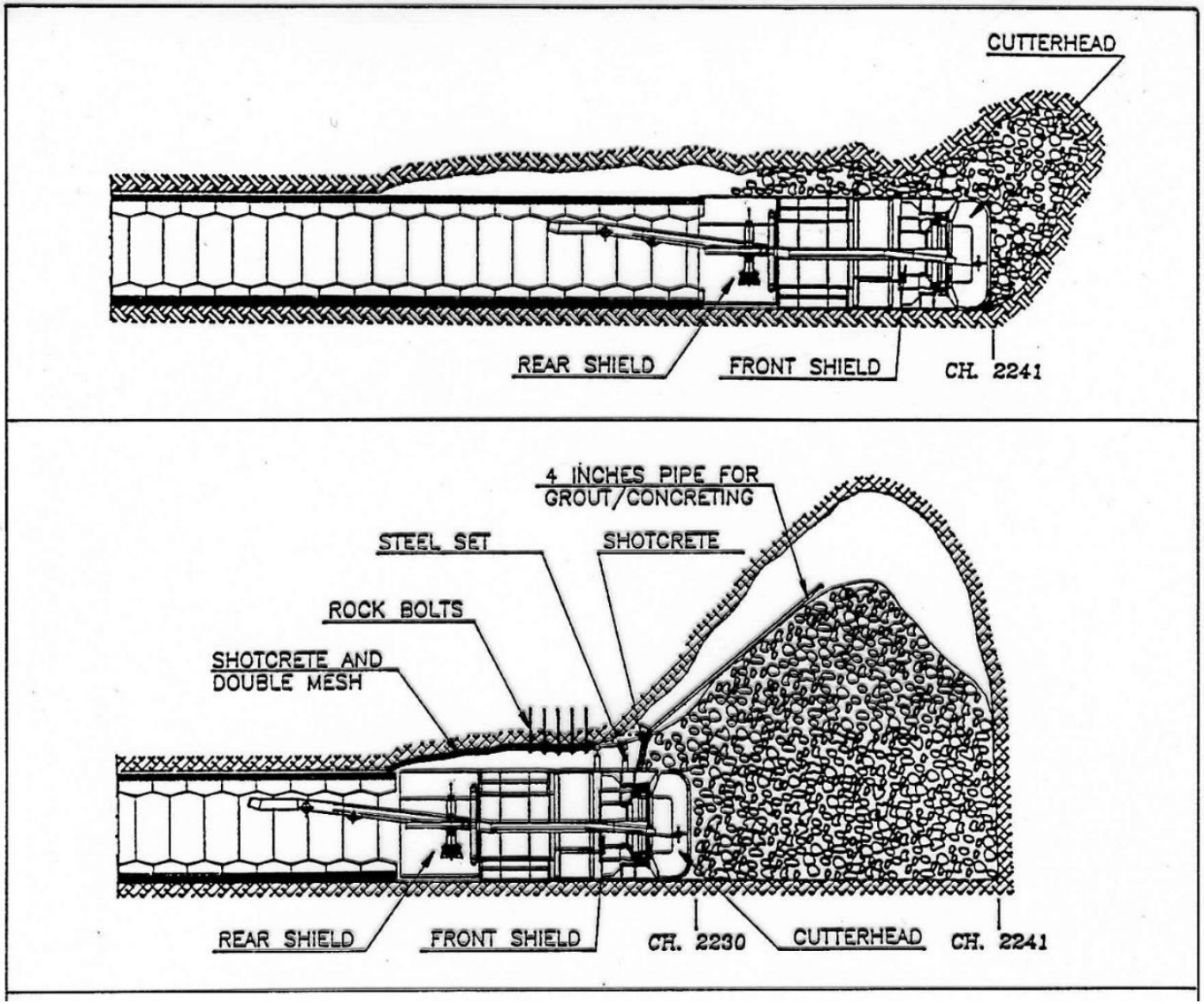
FAULT ZONES AND TBM

WHY DO FAULT ZONES TAKE SO LONG WITH TBM ????

PRACTICAL REASONS ARE ILLUSTRATED (Robbins et al., 1988)
FOLLOWED BY '*THEO-EMPIRICAL'* REASONS



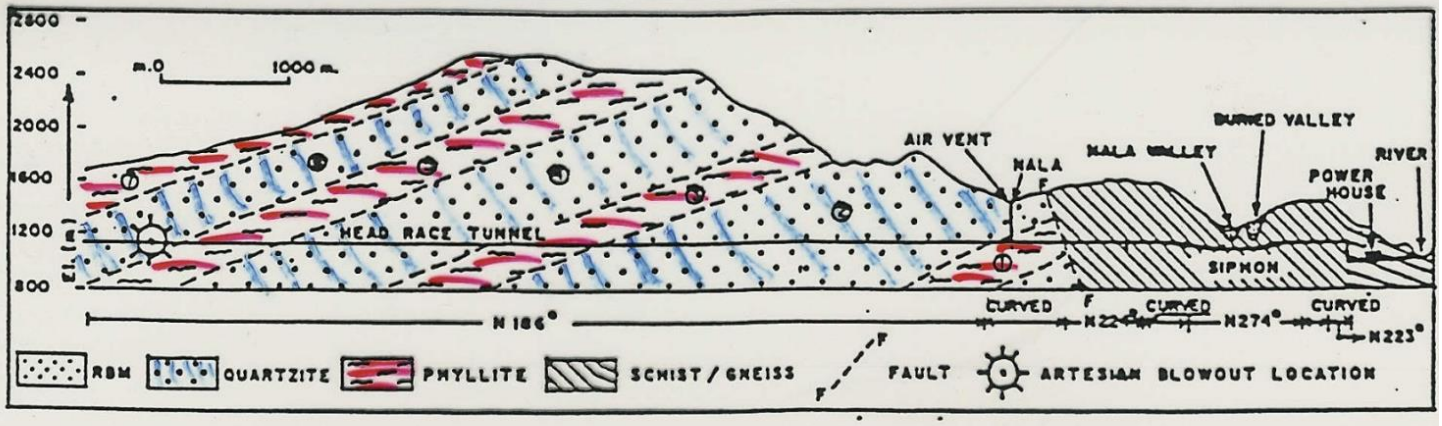
PROBE DRILLING…..and PRE-TREATMENT needed!

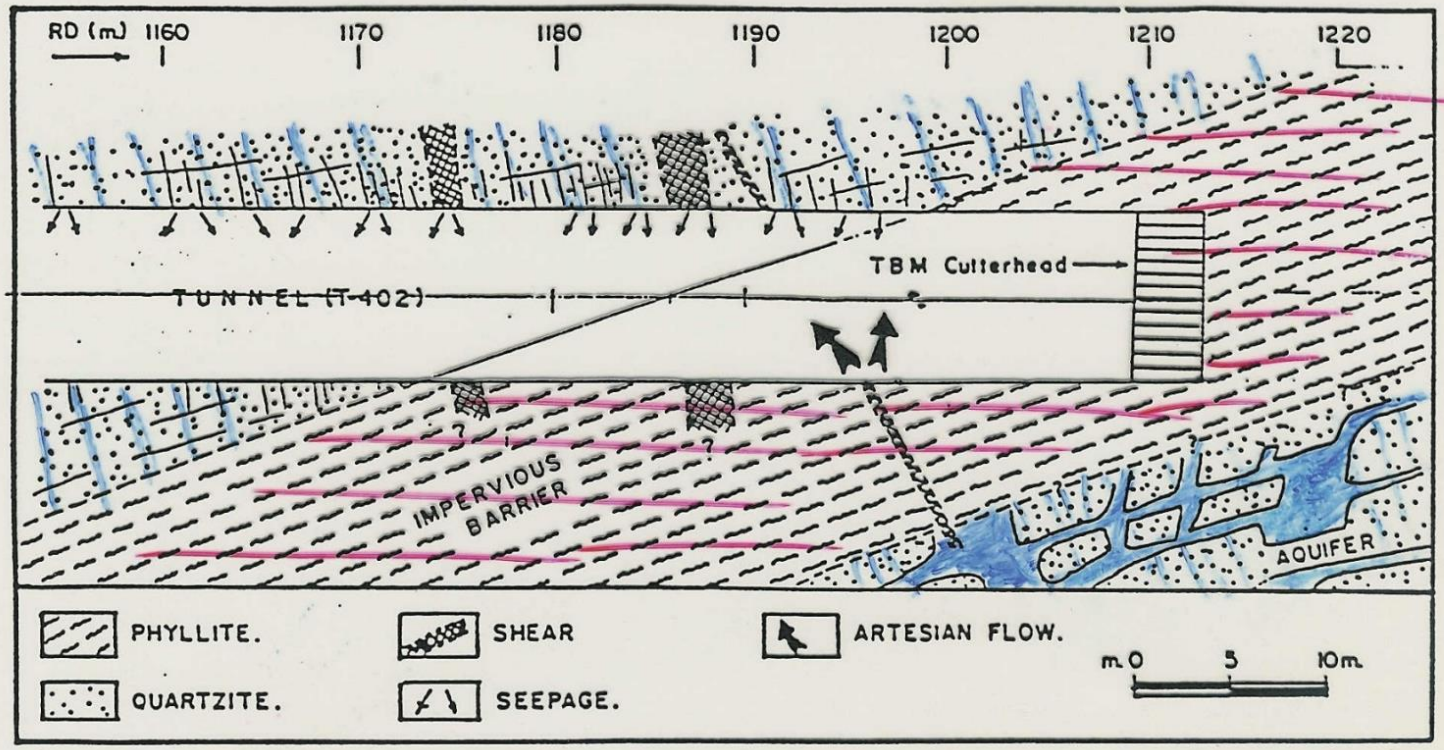


Fault zones also create great problems for *double-shield TBM* – if zone not pre-treated……

following likely *discovery by probe-drilling.*

(Evinos-Mornos, Grandori et al. 1996)

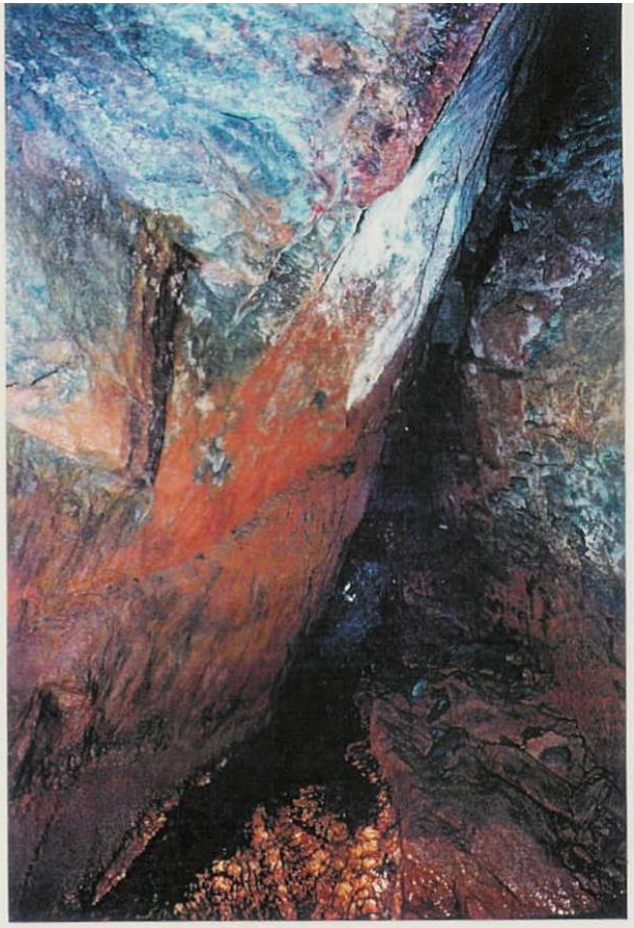


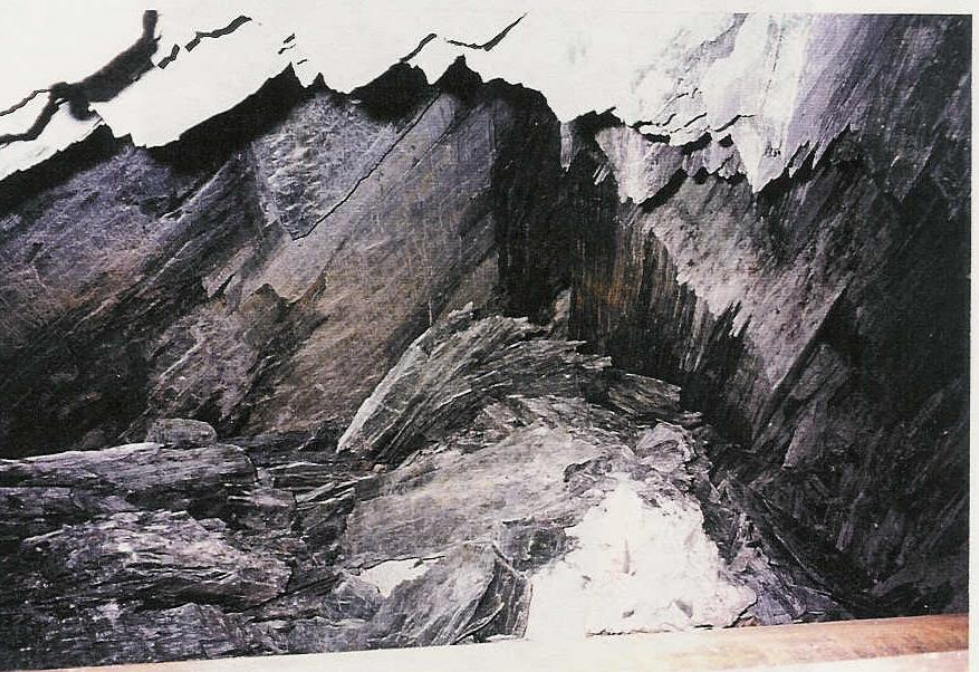


Dul Hasti headrace tunnel (Kashmir)

….*finally completed by D+B from power-house end of project*

This minor shear zone (water/gravel/sand) delayed TBM tunnelling 283 days! (*Dul Hasti, Kashmir*)





Later: in same tunnel:
sheared talcy/grafitic phyllites that had no stand-up time and "over-bored".

8 m diameter
⇨ 12 m

Pont Ventoux, Italy:

Note schist roof tiles in local villages. The planned 7km *hydropower tunnel* was parallel to this valley……..

……
and parallel to the foliation…… and to the (later discovered) fault zones

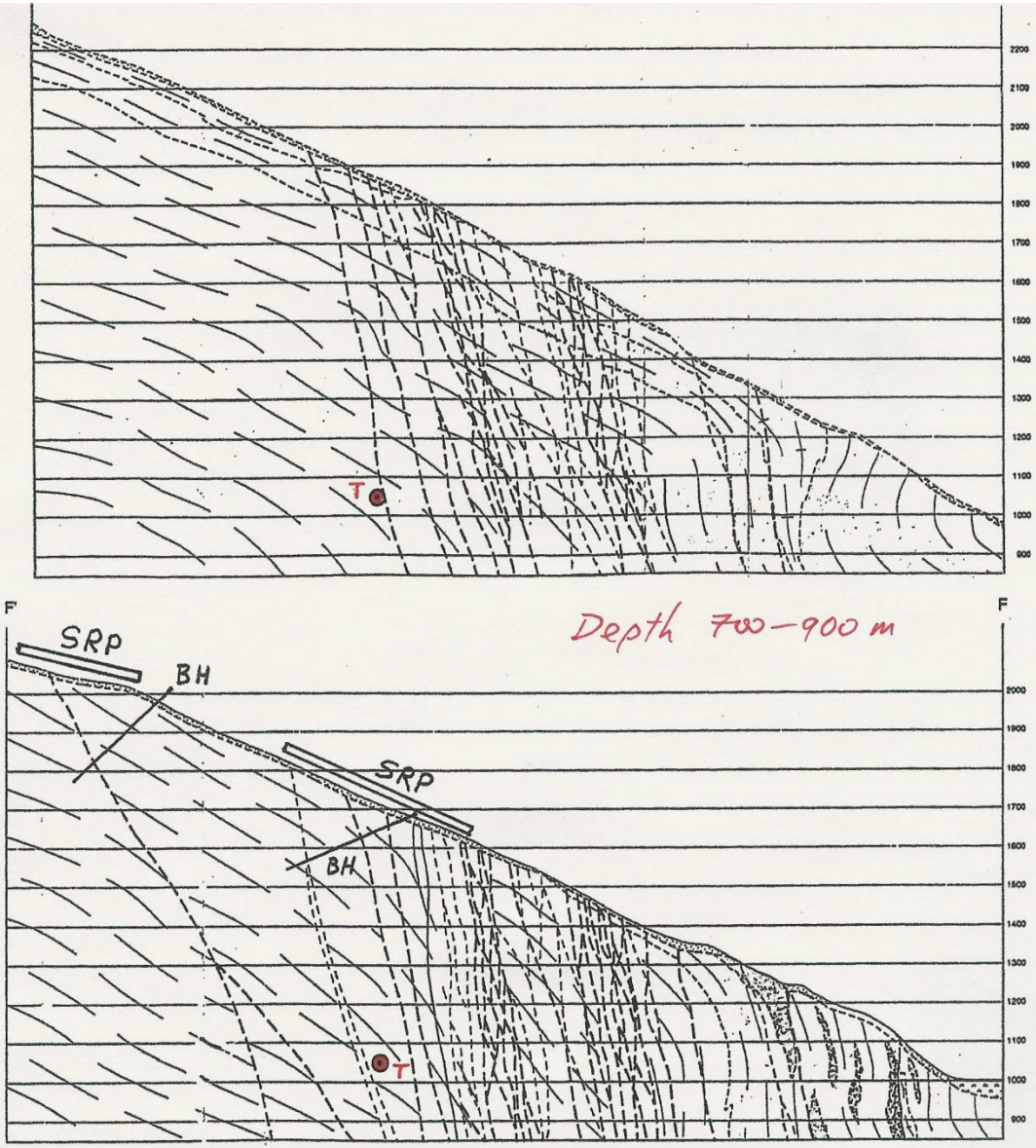


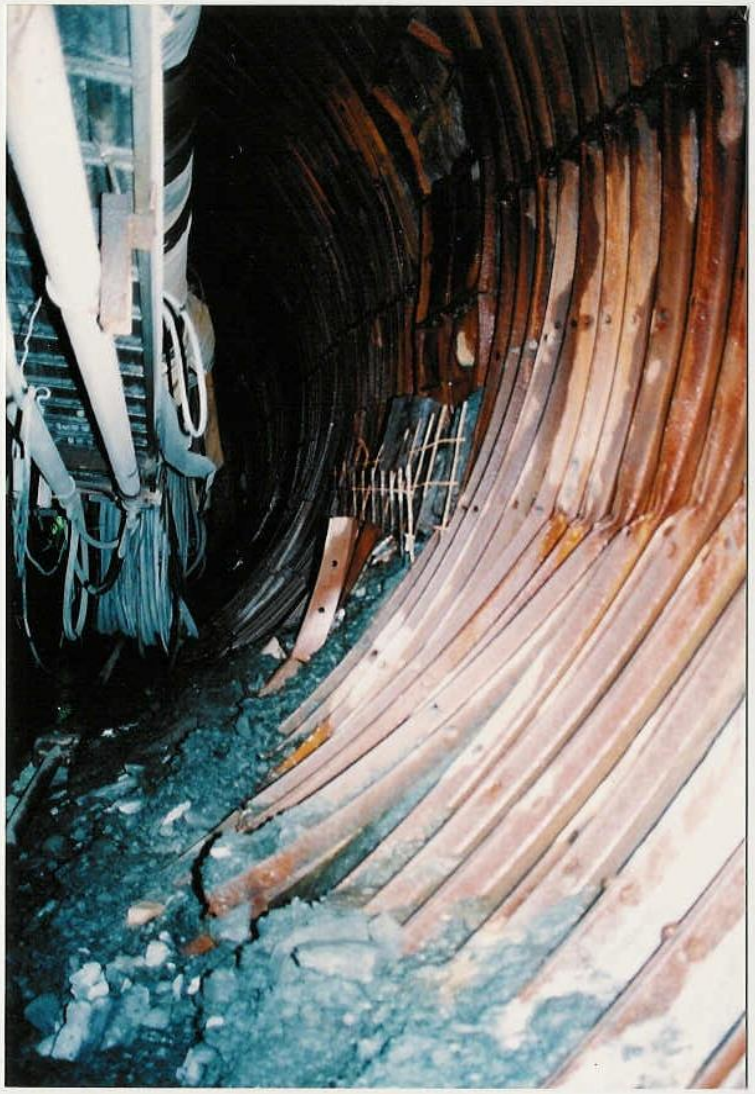
Figure 13. Perpendicular profiles showing assumed fault swarms. (From IC/02/02/GL/1/Z/00640, 2/7/98, 26/10/98. See text for "SRP", "BH" description.

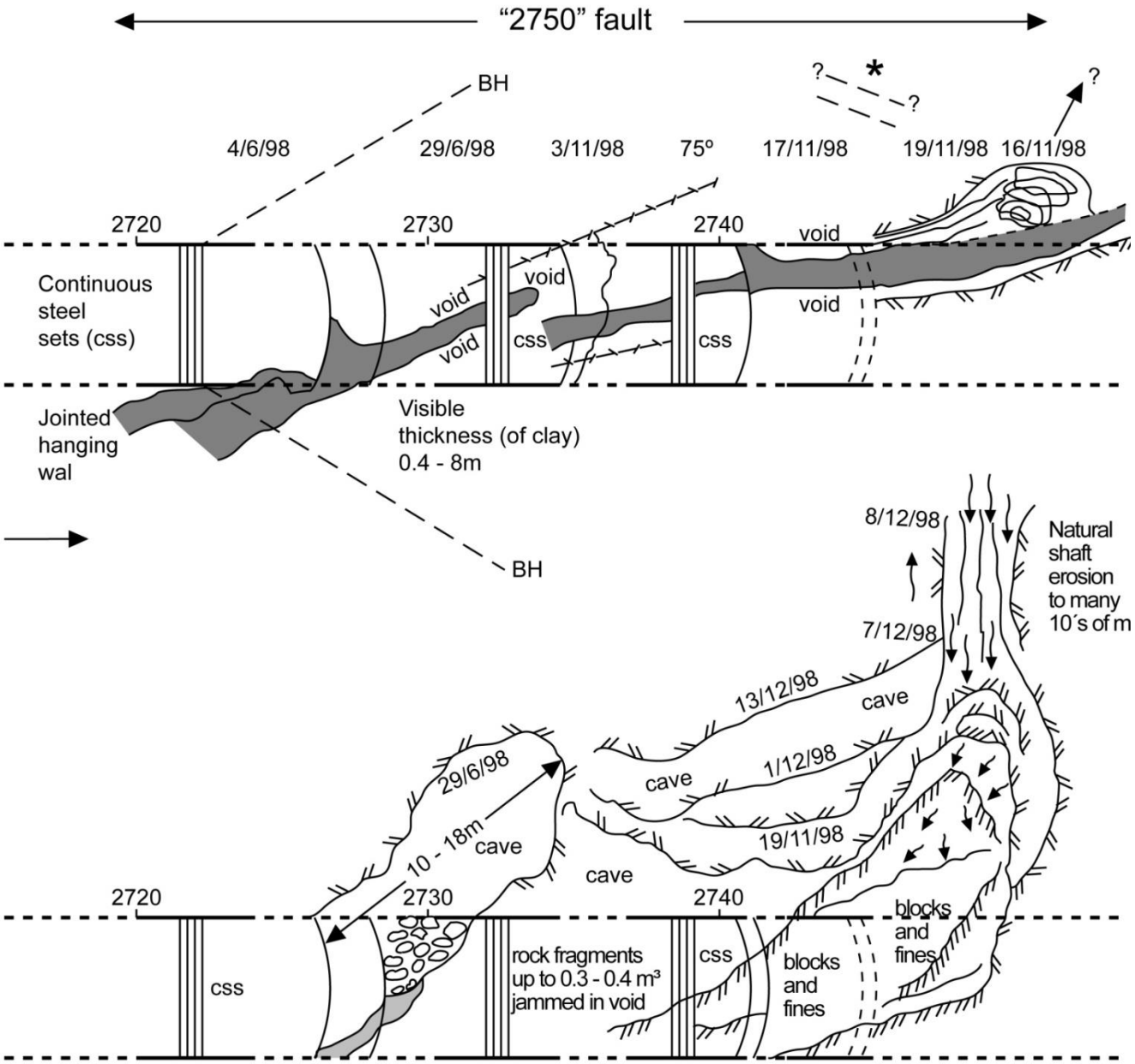
The structural geology and the chosen tunnel route…….

proved to be a guarantee for TBM disaster.

The tunnel was 'too deep' for satisfactory geological investigations ..???

Unsuitable TBM…..steel sets in fault crushed by own grippers





Note time scale

.....

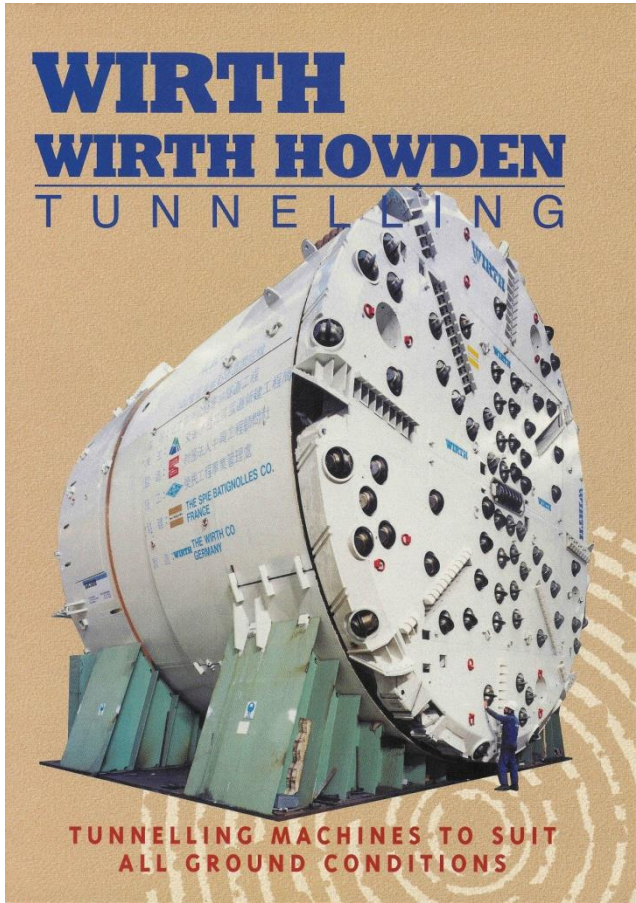
25 m in 5 months

Figure 4. Void at 2742, and silt-laden water due to erosion of fault(s) in chimney at 2750.

- ❑ Too much water for stability in the fault zone.
- ❑ Sand/gravel ‘delta’ behind back-up
- ❑ Derailment of the train was therefore frequent behind the back-up

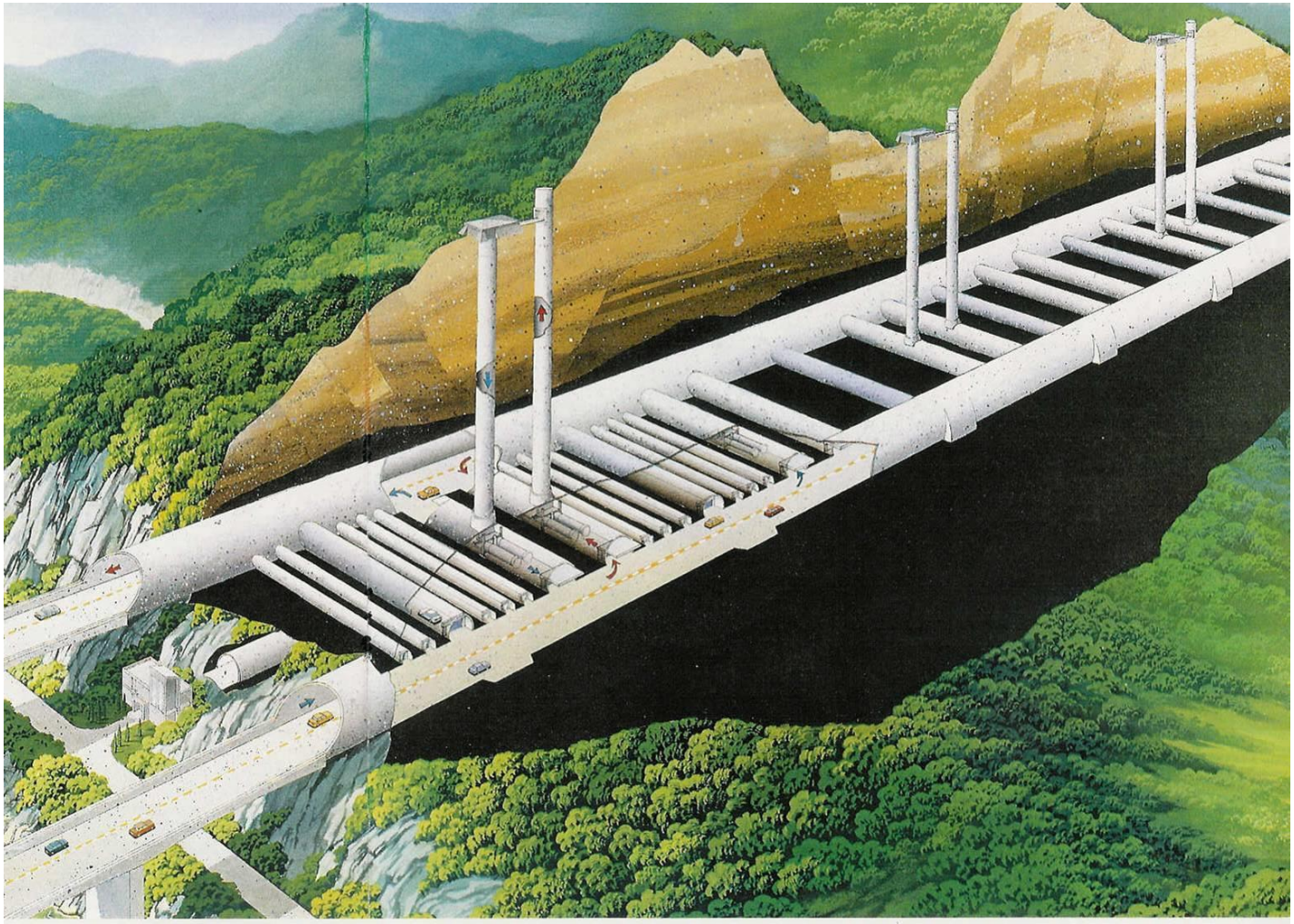
1. Pinglin
(2. XUESHAN)

(Taiwan)
1991-2004

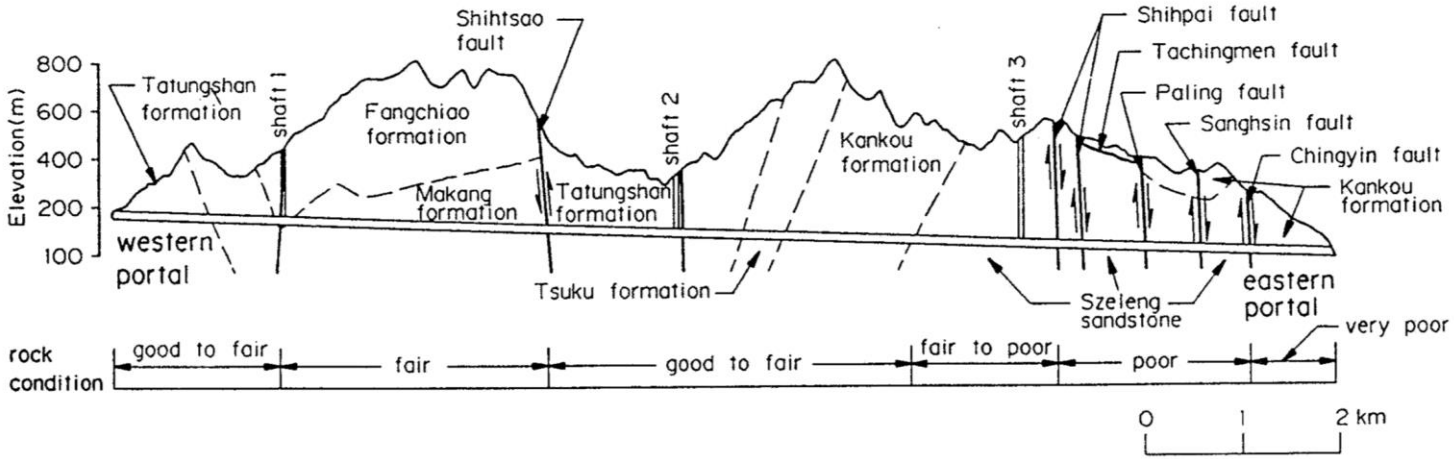


- 12.9 km (x 3)
- Cost US $ 560,000,000
- 25 lives lost during construction
- Tunnel renamed by President
- Unusual ‘TBM-hybrid’ project

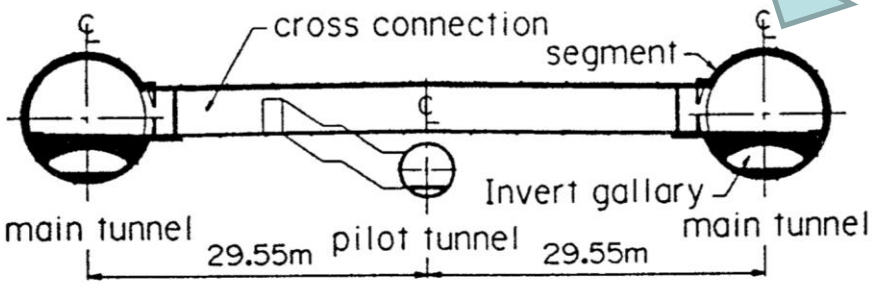
The intended scheme – note lower pilot TBM



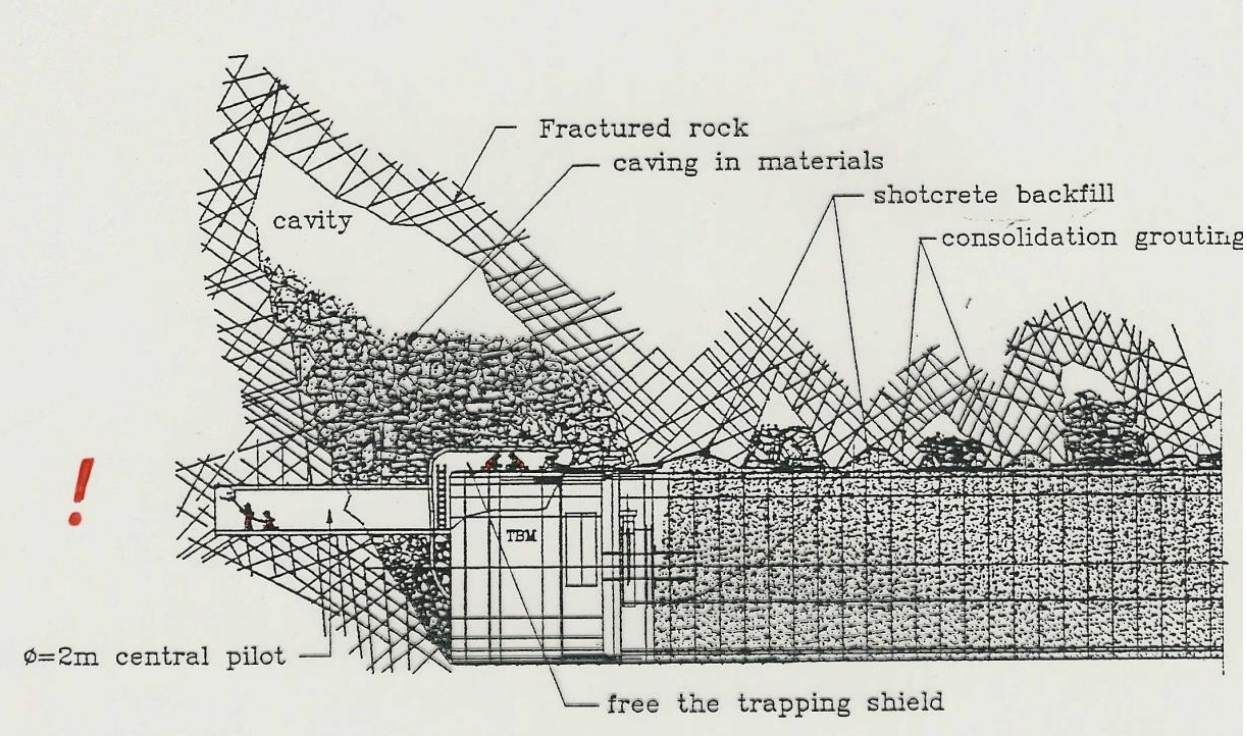
Start from Eastern portal (= destroyed in fault)



Geologic profile along the Pinglin Tunnel



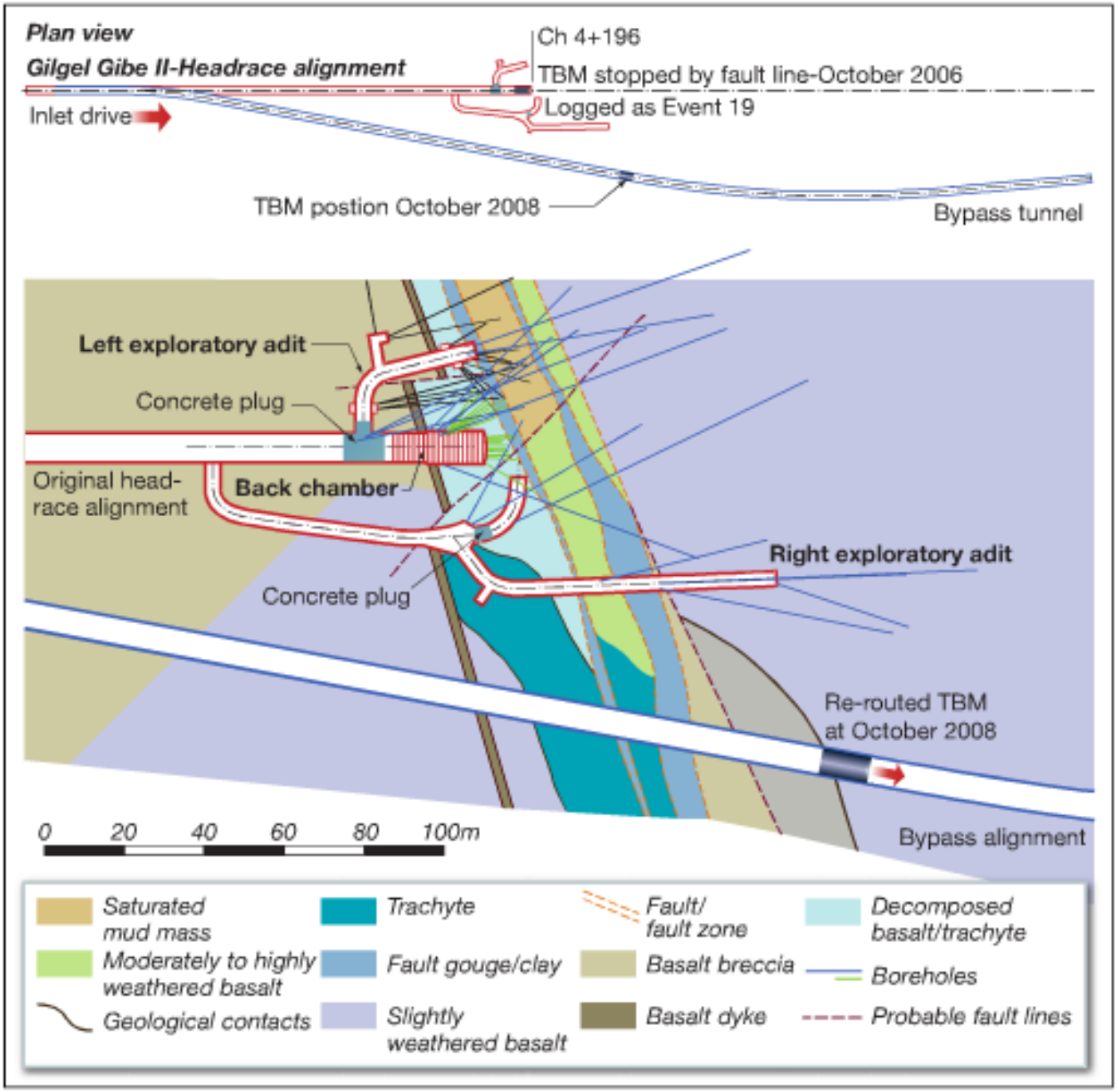
Cross-sectional layout of Pinglin tunnels



Numerous *by-passes* needed to free cutter-head(s)

- TBM used to mine bench for long stretches

At least 12 by-passes needed for the ‘pilot tunnel’



Gilgel-Gibe II headrace tunnel.

General 10-20 m per day progress.

(26 km, two TBM, double-shield, 7 m diameter)

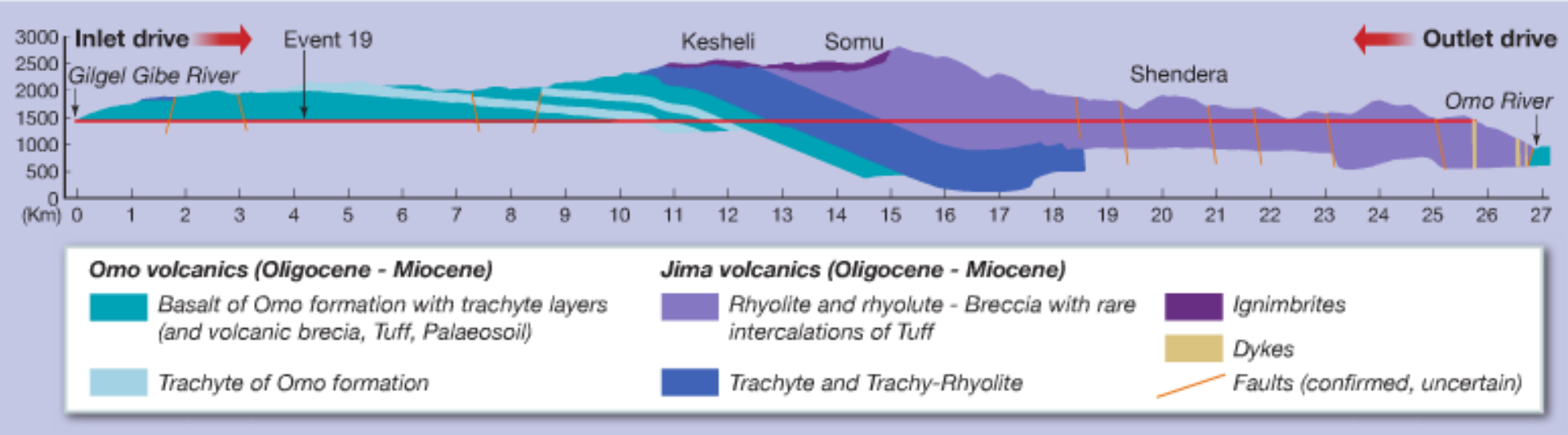
4 years for completion

Two years delay here!

Seli experiences with TBM at location “Event 19” – a 20 months “standstill” due to 4 MPa mud-pressure, in a 760 m deep section of a fault zone, following 4.2 km in 14 months steady progress.

Multiple attempts at by-pass, and multiple probe-drilling. The TBM deformed and displaced by squeezing mass, 600 mm backwards, and 400 mm laterally.

All local support destroyed. The re-routed TBM drive eventually traversed the fault in a different location, using resin pre-injection. *TTI December, 2009.*



THERE ARE VERY GOOD 'THEO – EMPIRICAL' REASONS WHY FAULT ZONES ARE SO DIFFICULT FOR TBM

We need three basic equations to start with

1. ***AR = PR x U*** (all TBM must follow this)

2. ***U = T^m*** (due to the decelerating advance rate with time)

3. ***T = L / AR*** (obviously time for length L must be proportional to 1/AR)

Therefore we have the following:

4. *T = L / (PR x T^m)* (from #1, #2 and #3)

5. ***T = (L / PR)*** $^{(1 / 1+m)}$

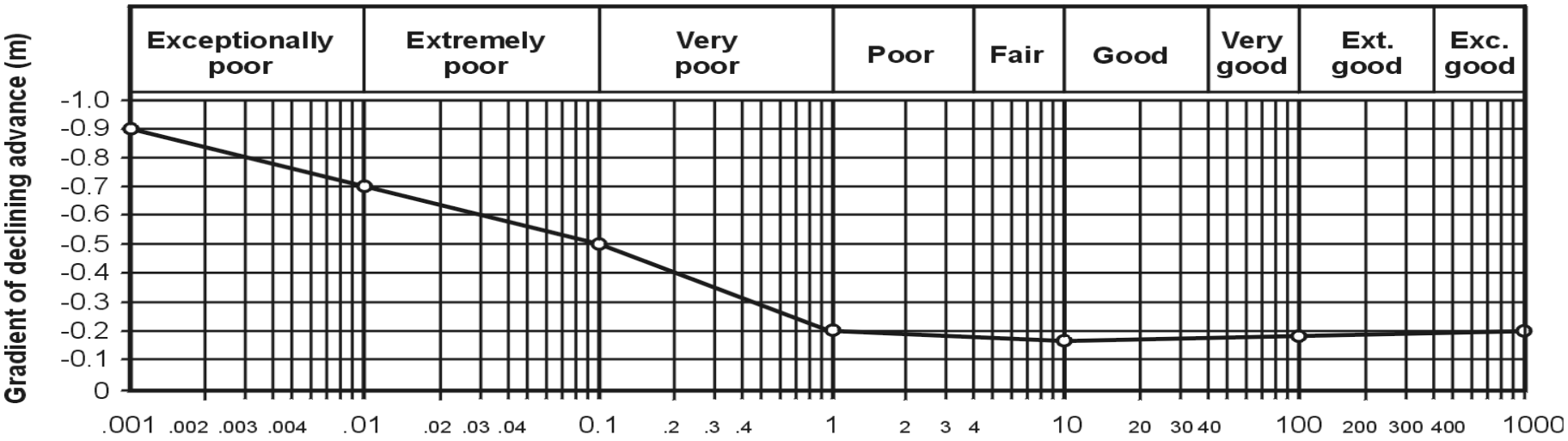
6. (this is VERY important for TBM……since m is strongly related to Q-values …..in FAULT ZONES, e.g. in mountain tunnels)

7. It is important because very ***negative (-)m*** values make ***(1/ (1+m)*** TOO BIG

8. If the fault zone is wide (large L) and PR is low (due to collapses etc.) then L/PR gets too big to tolerate a TOO BIG component (1/1+m).

9. It is easy (too easy) to calculate an almost ‘infinite’ time for a fault zone using this ‘theo-empirical’ equation. (Three permanently buried, or fault-destroyed TBM: Pont Ventoux, Dul Hasti, Pinglin…there are many more!)

BUT…Q CAN BE IMPROVED BY PRE-GROUTING !

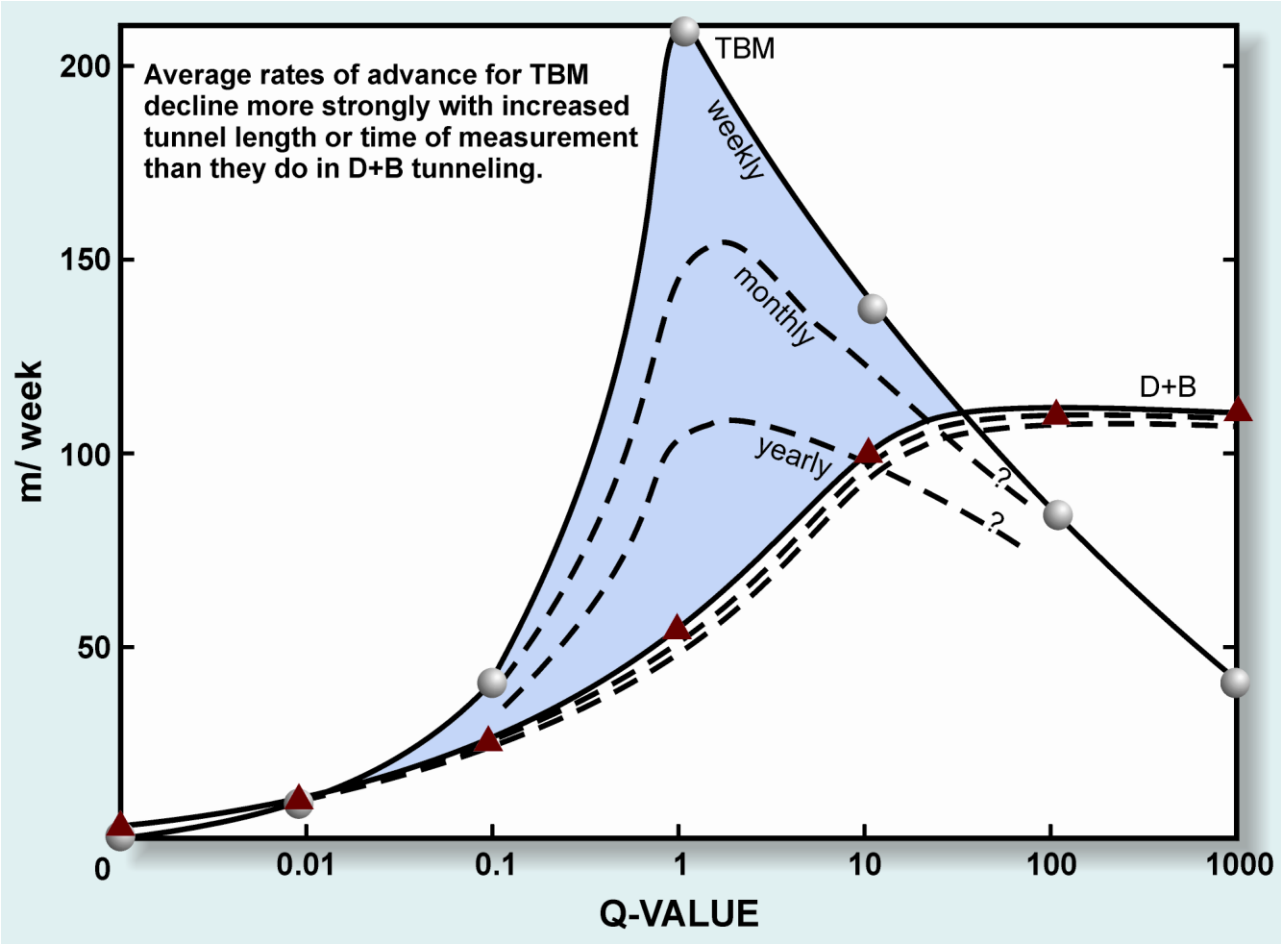


Rock mass quality $$Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$$

Comparing TBM with drill-and-blast

- Central qualities are required – if the TBM is to be much faster than D+B
- Are long tunnels faster with TBM?

THE TBM-SOLUTION IS BEST 'IN THE MIDDLE'
…but at a disadvantage at both ends

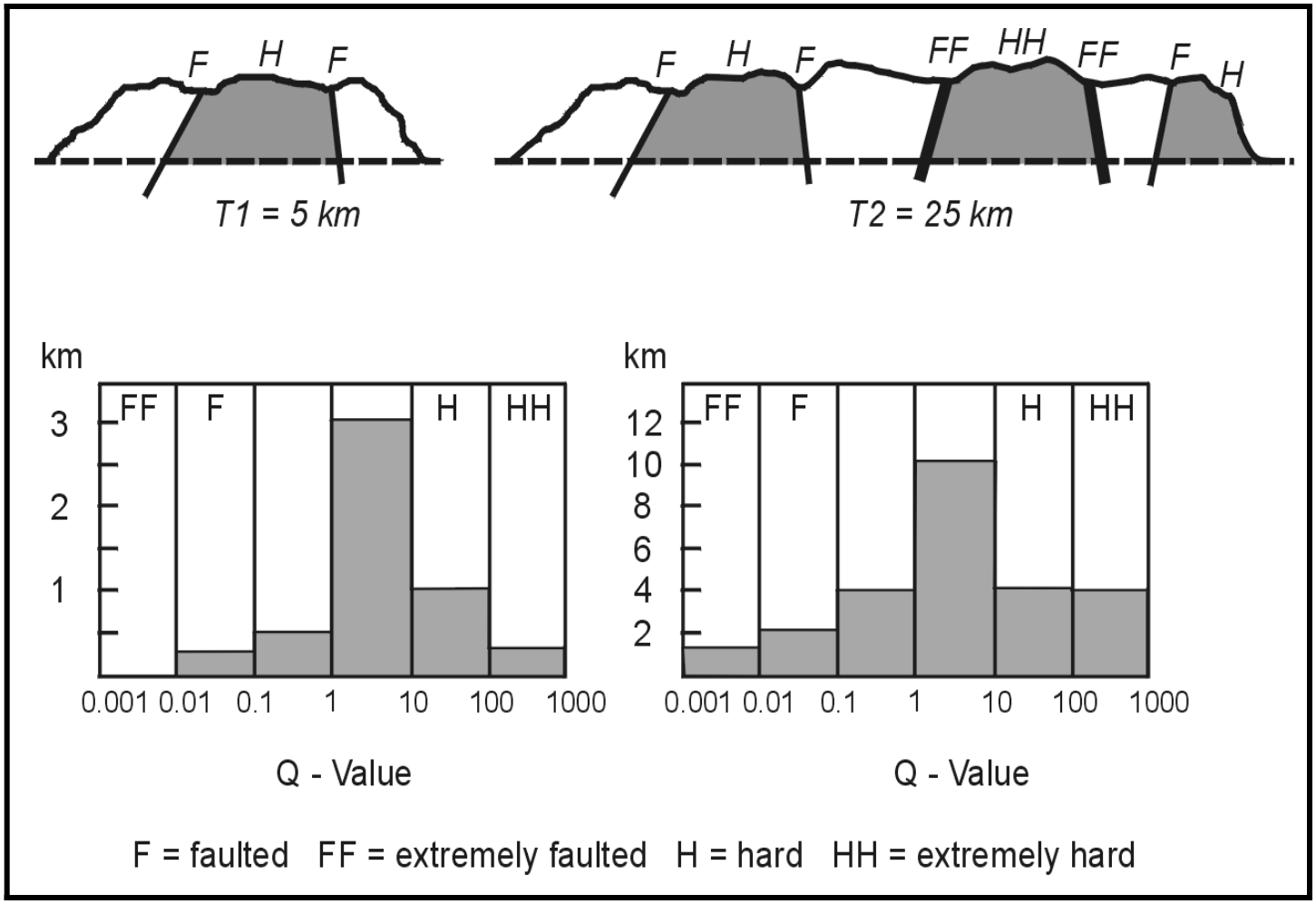


BUT DOUBLE-SHIELD TBM CAN CHANGE THIS….? (even in fault zones..?)

...seldom!

LONG TUNNELS WITH FAULTS…….BEWARE !

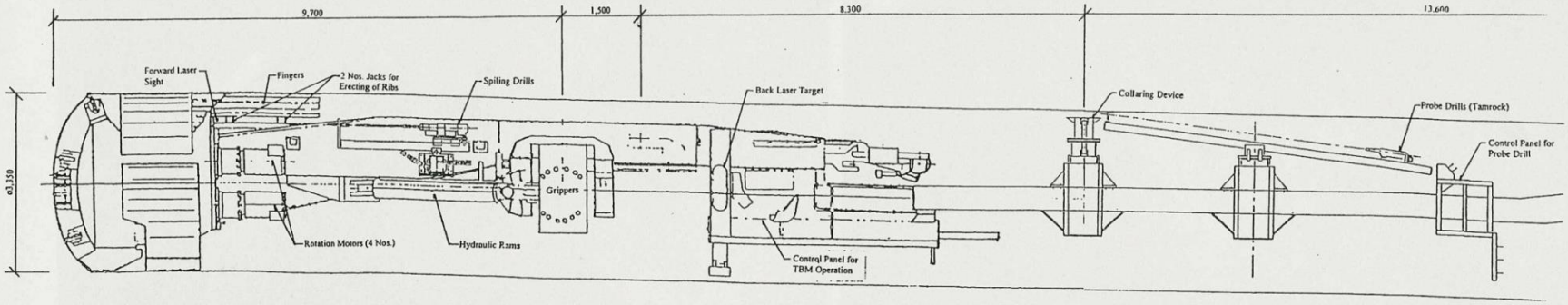
(assuming long tunnels are faster by TBM is guaranteed to increase risk!)

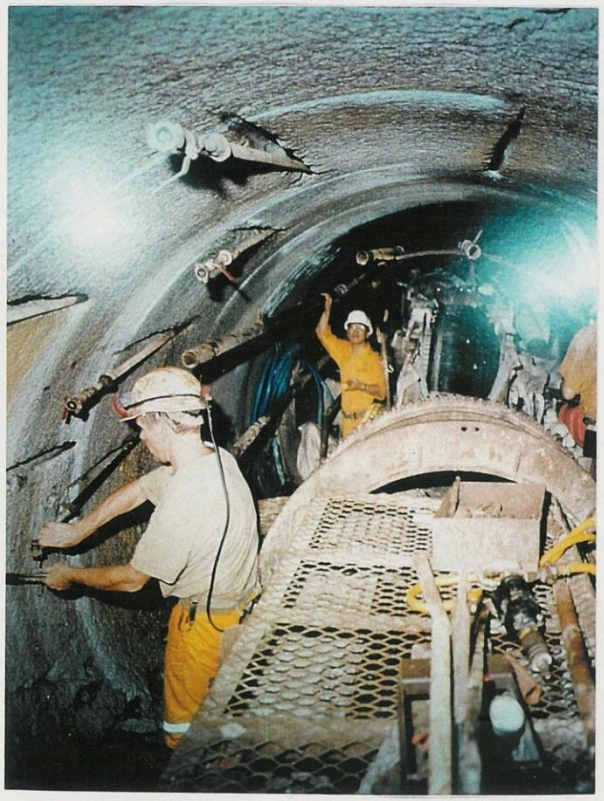


(due to a ‘large scale’ Weibull theory…..more ‘flaws’ the larger the ‘sample’)

Clearly not a mountain tunnel – *but a very important case record concerning mitigation measures.*

Pre-drilling equipment for TBM needs to be designed ***and mounted***, before starting the project!





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 746kW 13.2 rpm 55,010 kg-m 1	 At 4,330 psi (300 bar) At 4,500 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	 1,414 Tonne 2.8 : 1	 At 4,500 psi (262 bar)
System Electric Power:	30kW	

TOTAL LENGTH OF TBM + BACKUP = 117.1m

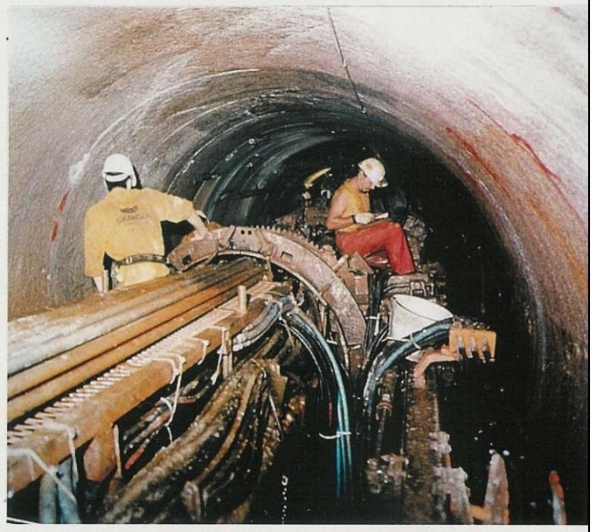


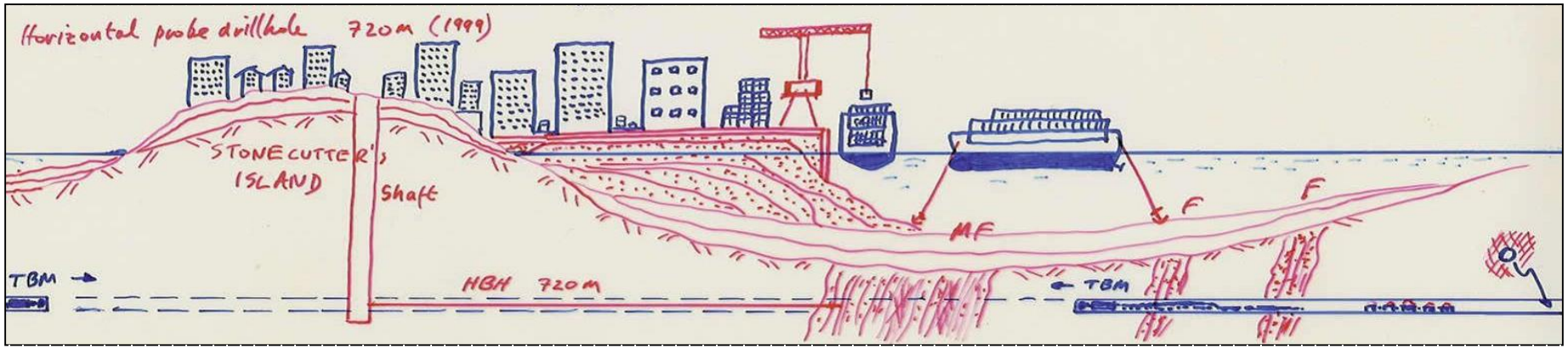
Fig. 36. The unfavourable position of the Tamrock drills, and measures used to collar closer to the face. (Skanska photos)

- 887m REMAINED WHEN NB WAS ASKED TO ADVISE SKANSKA IN 1999, 2000

- **THERE WAS A MAJOR REGIONAL (TOLO CHANNEL) FAULT ZONE AHEAD**

- THIS HAD NOT BEEN DRILLED, AND *SEISMIC INVESTIGATION HAD BEEN HINDERED* BY CONTAINER-PORT TRAFFIC

- A 'PILOT' HOLE WAS DRILLED (backwards from Stonecutter's Island. The hole went only 731m….. stopped by the Tolo Channel fault zone



Three attempts were made to (deviate) drill into the Tolo Channel Fault Zone.
These are the results…..from the end of the 720m long horizontal hole.

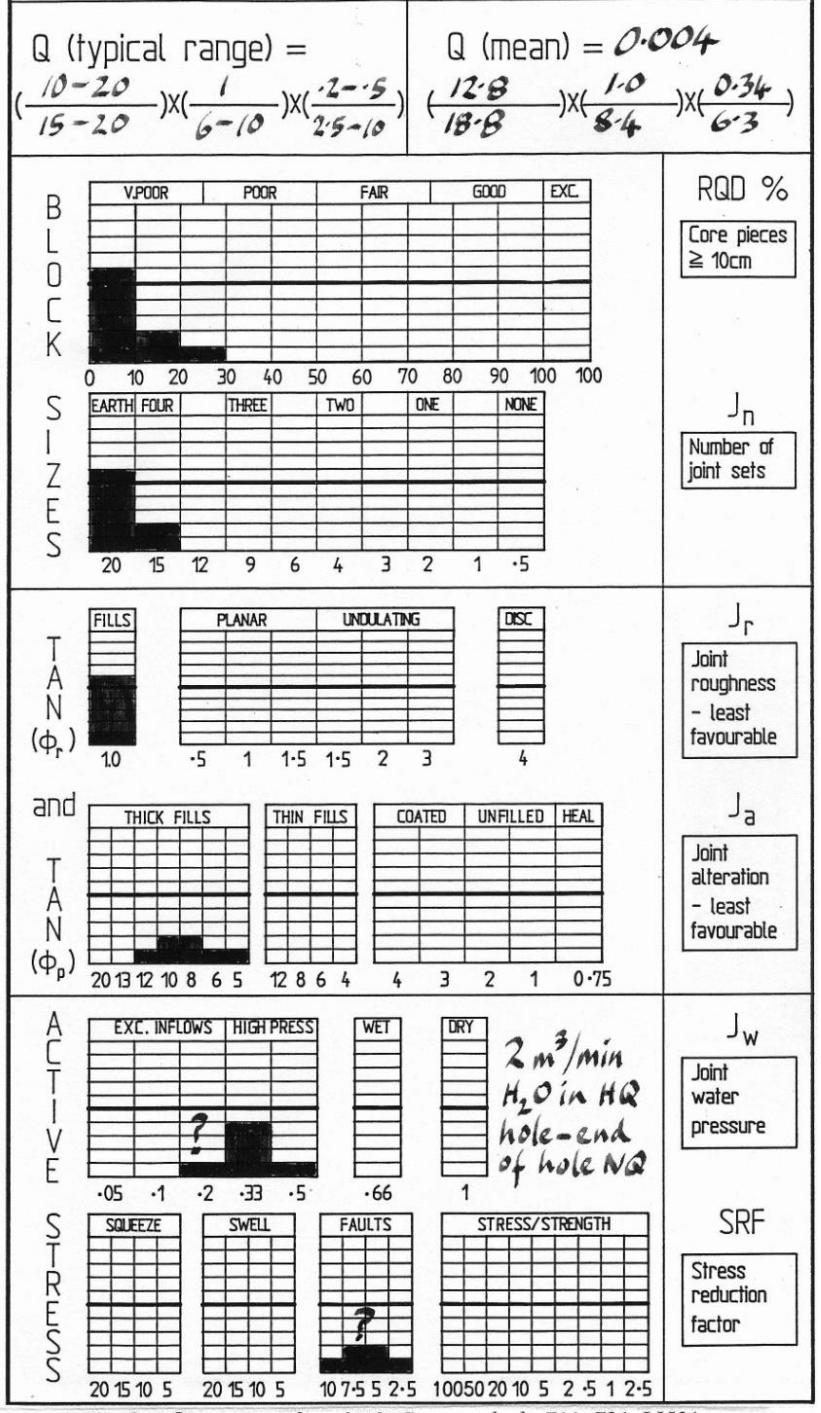


Fig. 8. Q-parameter log of TCFZ material, ch. 711–731, LH01.

These are the Q-parameter statistics for this (fault zone) end of the 720m long hole

Characteristics of the zone all plot 'to the left'.

Q_{mean} = 0.004 needs improvement.

SOME POSSIBLE ASSUMPTIONS OF THE EFFECT OF *PRE-GROUTING*

(as applied in this TBM tunnel)

- Several of the Q-parameters may be improved by pre-grouting due to sealing of successive joint sets.....

- It is the only technique (besides drainage) for assisting TBM through difficult (= impossible) fault zones.....

EXAMPLE OF POSSIBLE CHANGES DUE TO GROUTING

- RQD increases e.g. 30 to 50%
- J_n reduces e.g. 9 to 6
- J_r increases e.g. 1 to 2 (due to sealing of most of set #1)
- J_a reduces e.g. 2 to 1 (due to sealing of most of set #1)
- J_w increases e.g. 0.5 to 1
- SRF unchanged e.g.1.0 to 1.0

Before pre-grouting:

- $Q = 30/9 \times 1/2 \times 0.5/1 = 0.8$

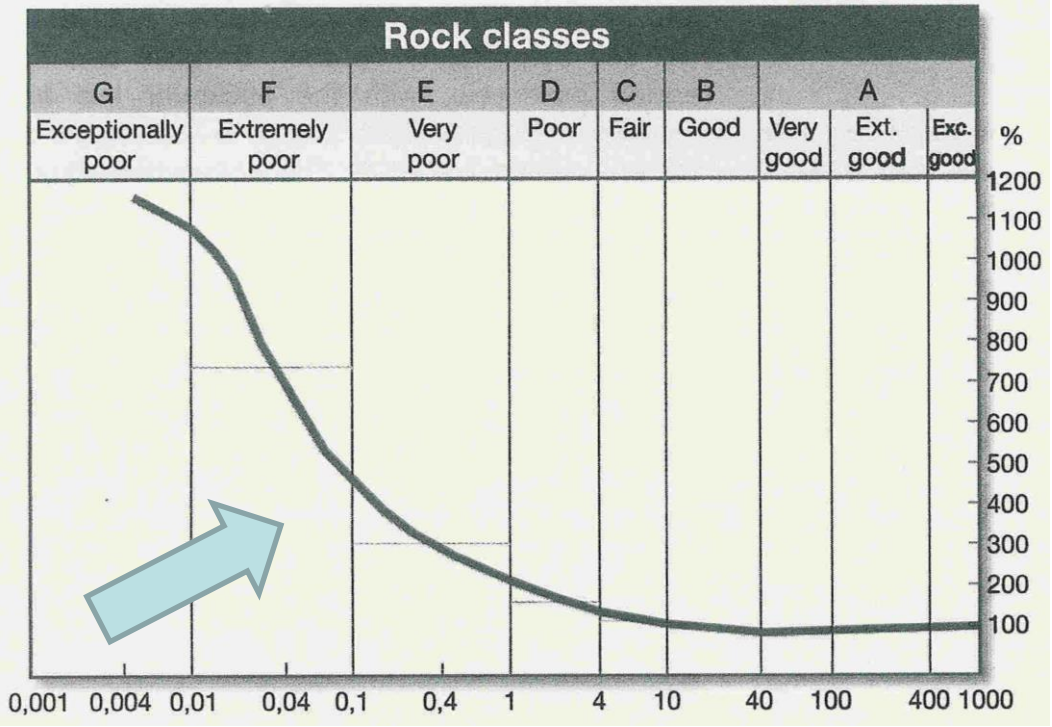
After pre-grouting:

- $Q = 50/6 \times 2/1 \times 1/1 = 17$

IMPROVING ROCK MASS PROPERTIES THROUGH PRE-GROUTING

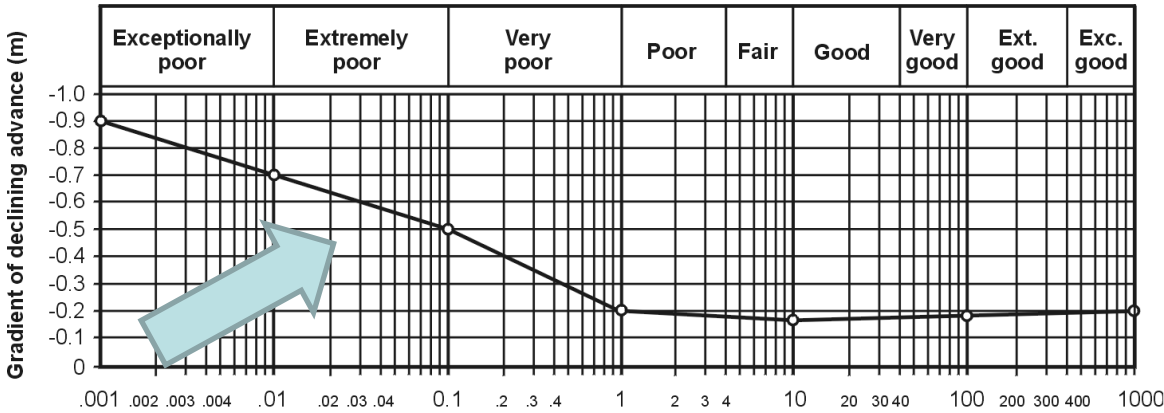
Example of rock mass and tunnelling improvements that might be achieved by pre-injection. In poorer quality rock masses there could be greater improvements

Before pre-grouting	After pre-grouting
Q = 0.8 (very poor) Q_c = 0.4 V_p = 3.1 km/s E_{mass} = 7 GPa	Q = 16.7 (good) Q_c = 8.3 V_p = 4.4 km/s E_{mass} = 20 GPa
B 1.6m c/c S(fr) 10 cm	B 2.4m c/c none



A (*drill-and-blast*) contractor's experience with influence of Q-value on relative time (and cost).

Benefit from pre-grouting is in same area as large (-)m <u>*deceleration*</u> in the case of TBM tunnels.



Rock mass quality $Q = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right) \times \left(\frac{J_w}{SRF}\right)$

1. No pre-grouting improvements….more than 1 year needed.

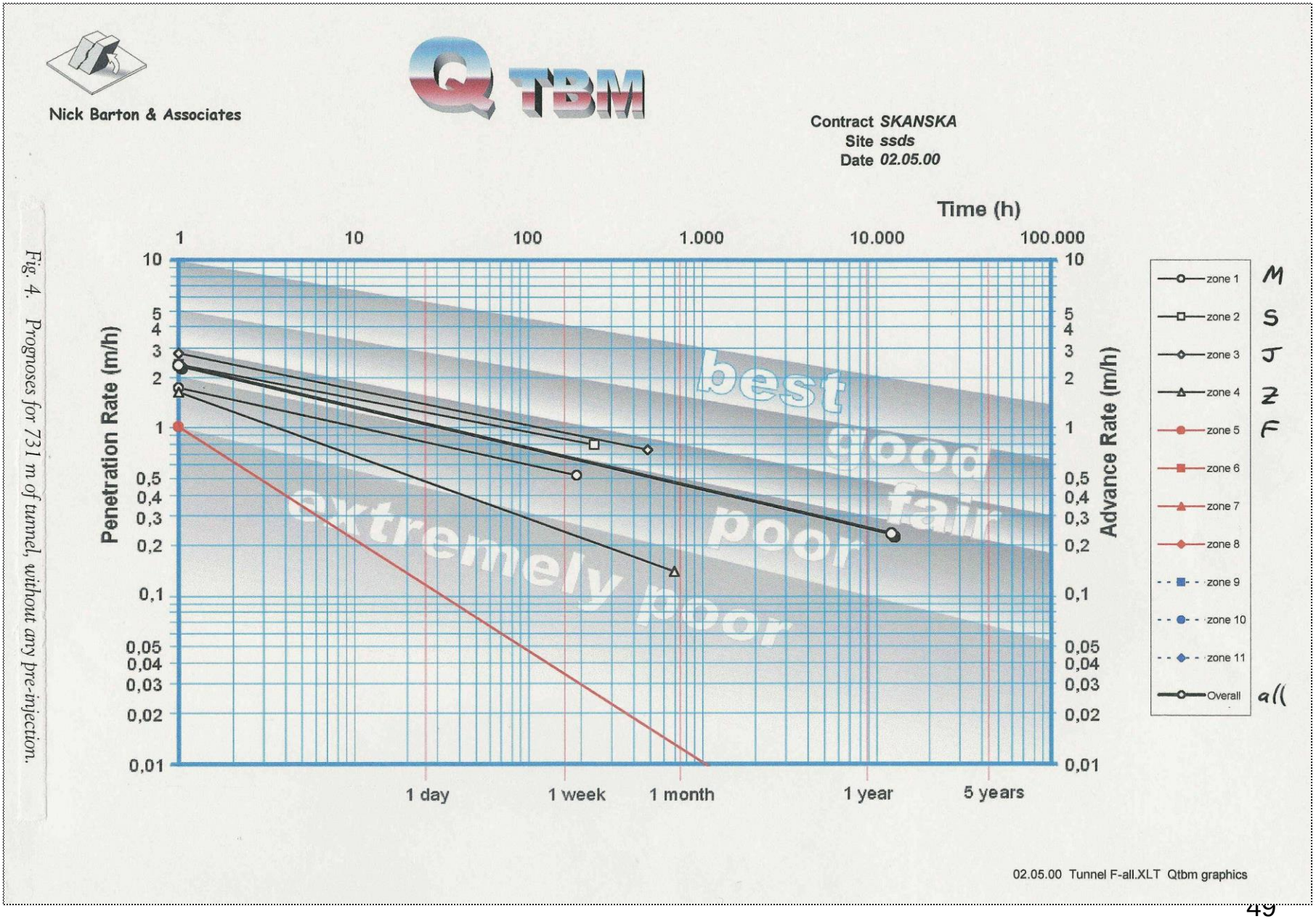


Fig. 4. Prognoses for 731 m of tunnel, without any pre-injection.

2. Total tunnelling time with pre-grout cycles (two estimates). ACTUAL TIME 2 months…FOR THE LAST 700m. TOTAL TIME FOR 3097m WAS 37 months.

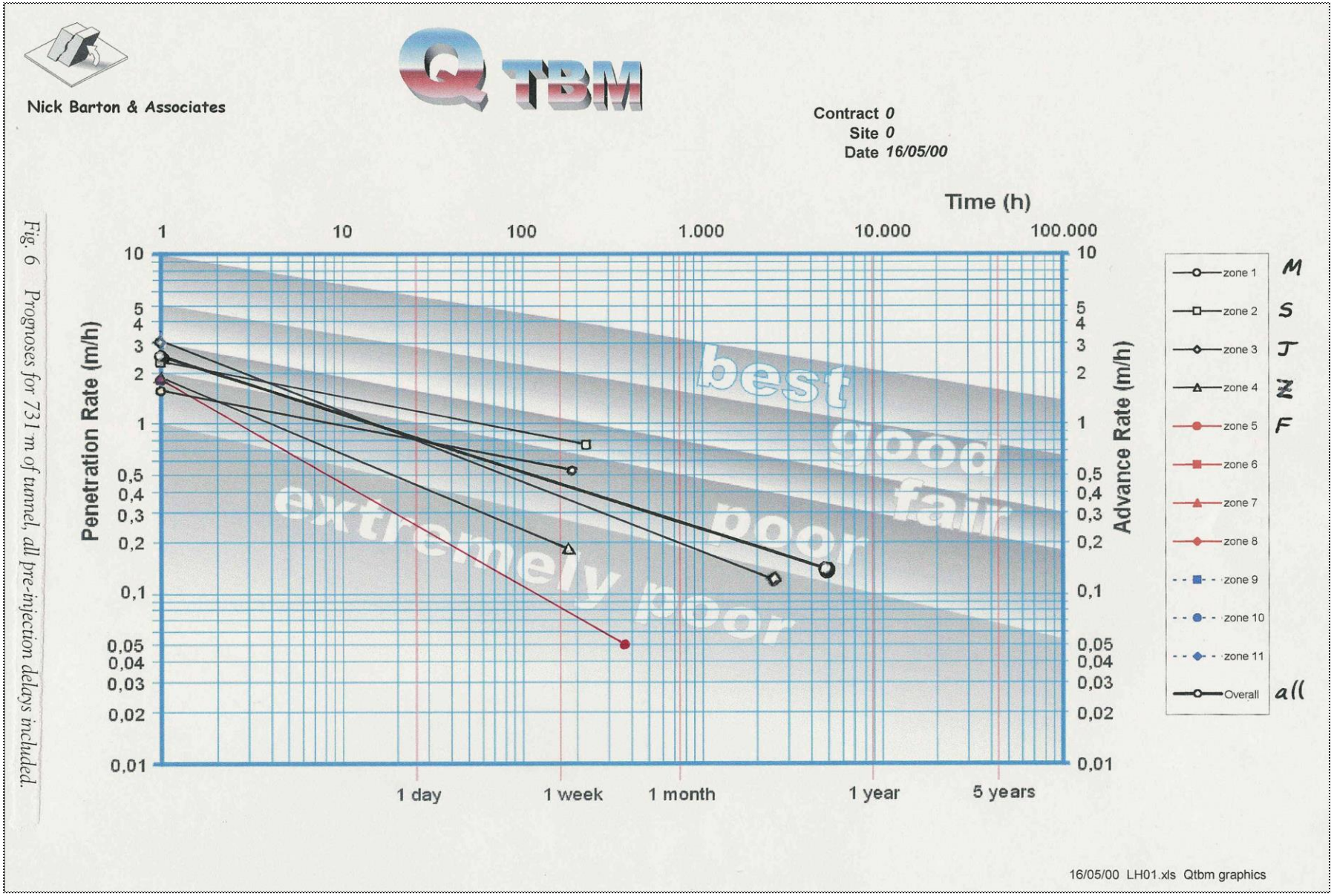
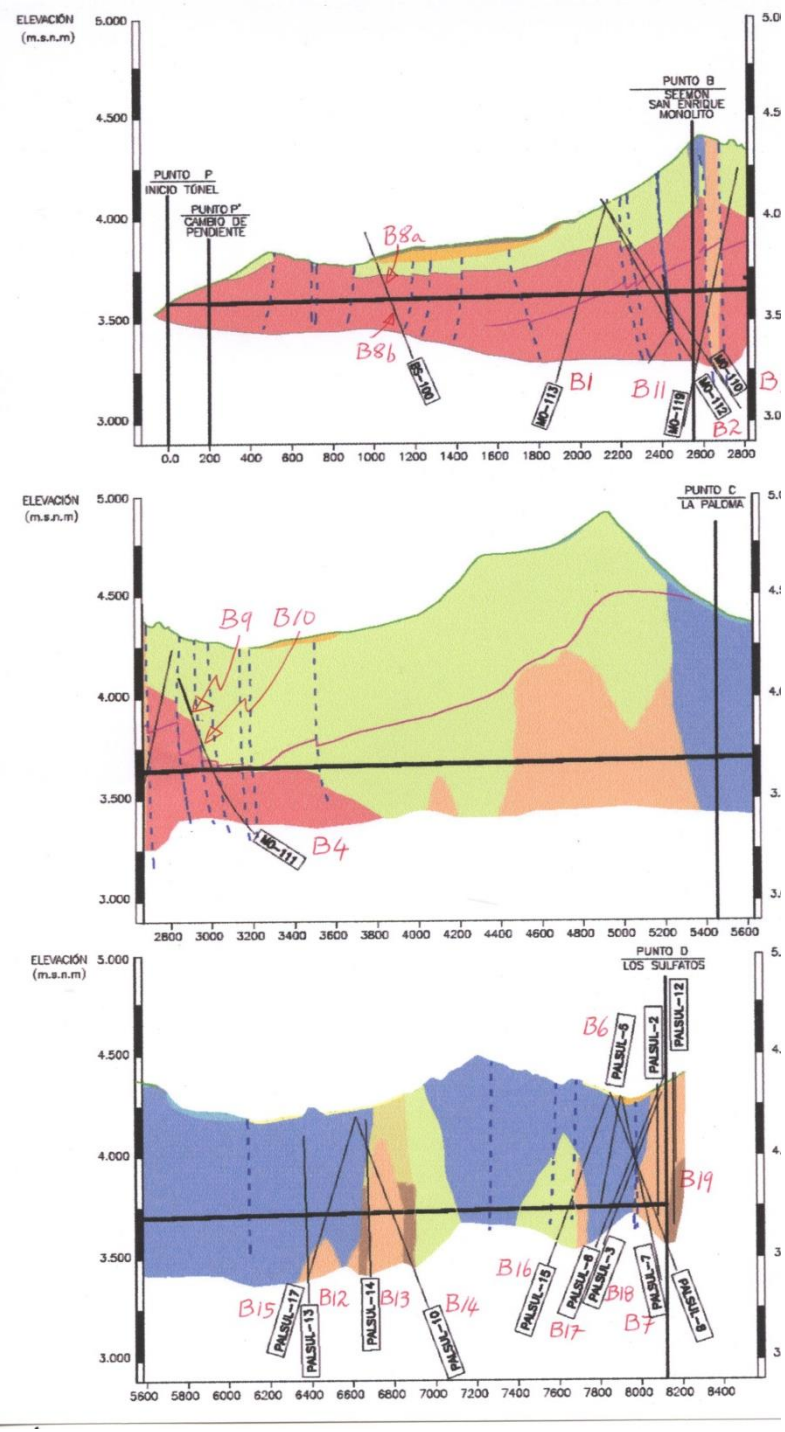


Fig. 6 Prognoses for 731 m of tunnel, all pre-injection delays included.



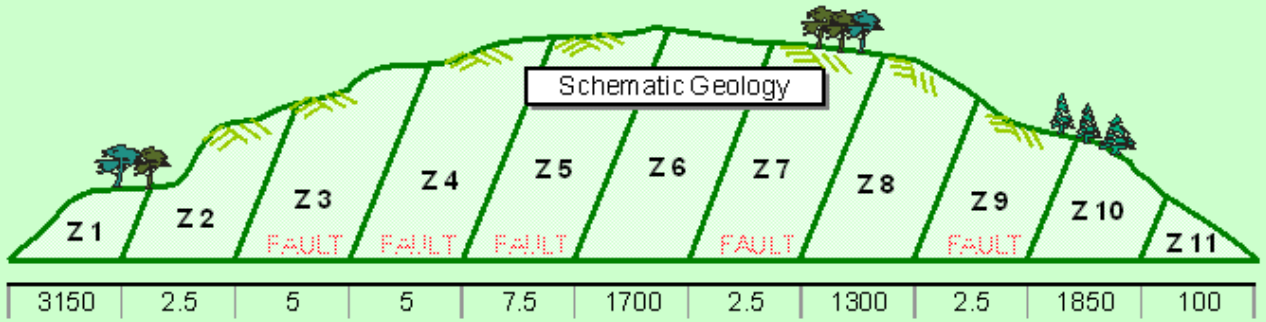
Deep mine-access tunnel in *Andes mountains*, with long boreholes for mineral assessment.

Unusually deep boreholes therefore available for Q-histogram logging.

Note five fault zones modelled

Nick Barton & Associates

Q TBM



ZONE	11	LITHOLOGY	BRECHA-CLORITA/-BIOTITA	ZONE LENGTH	100

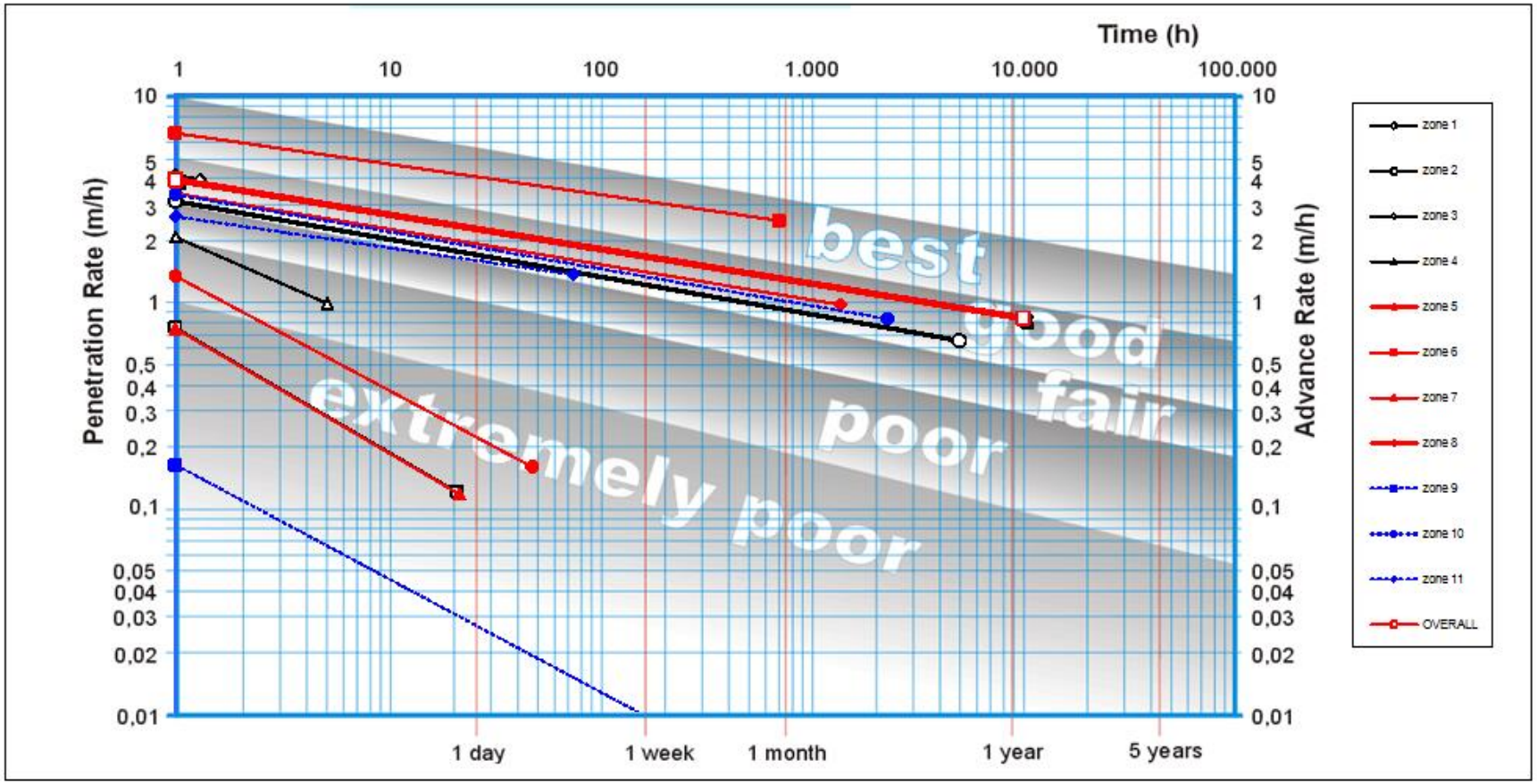
INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)	V_P (km/s)
100.0	4.0	1.5	3.0	1.00	1.0	-0.17	100.0	2.8	

β°	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
60.0	100.0	3.0	20.0	25.0	10.0	20.0	4.5	2.0

Date	20/Oct/2007

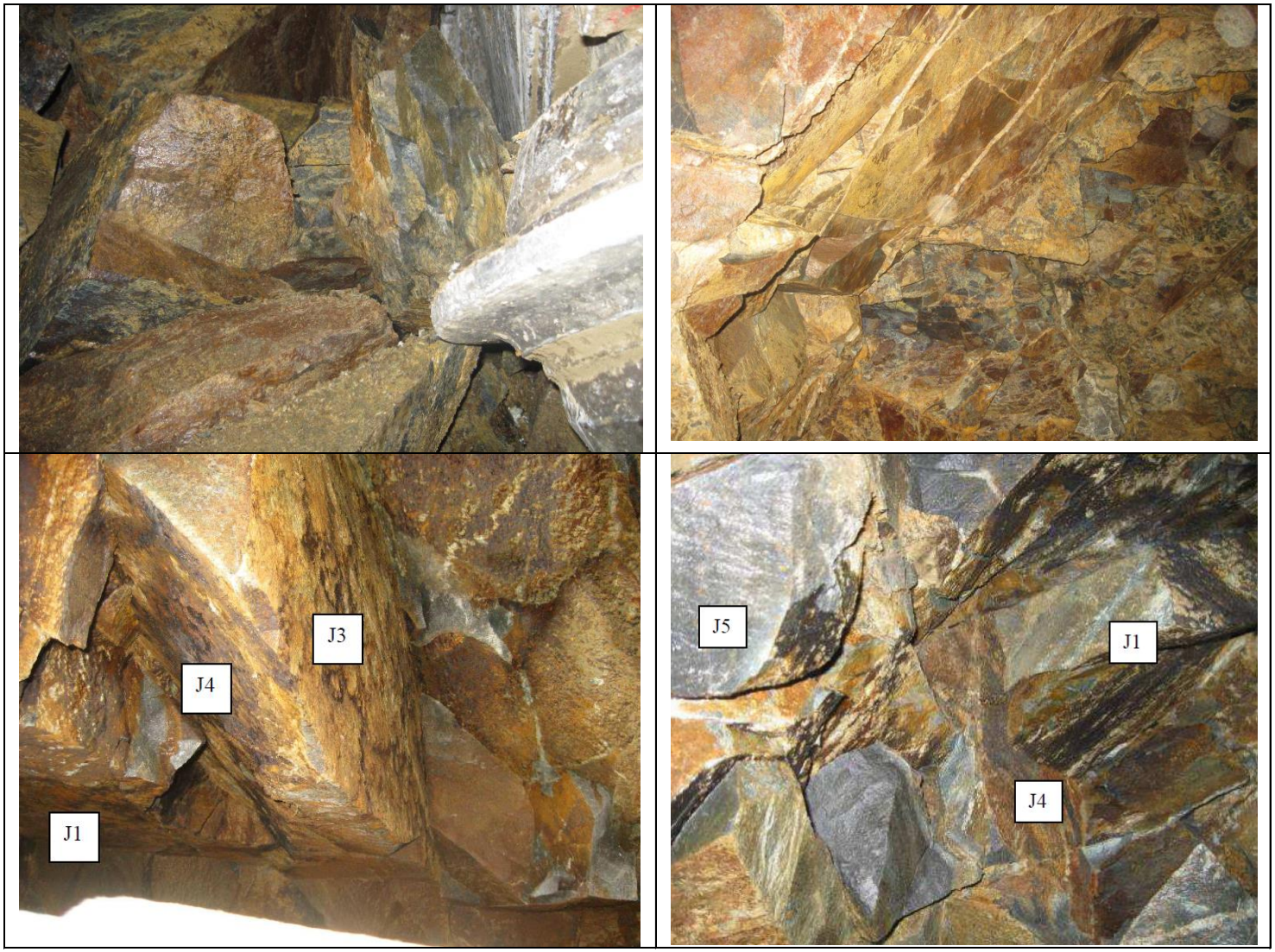
Part of the prognosis of the **TBM mine-access tunnel,** where a lot of deep coring was available from mineral exploration holes.



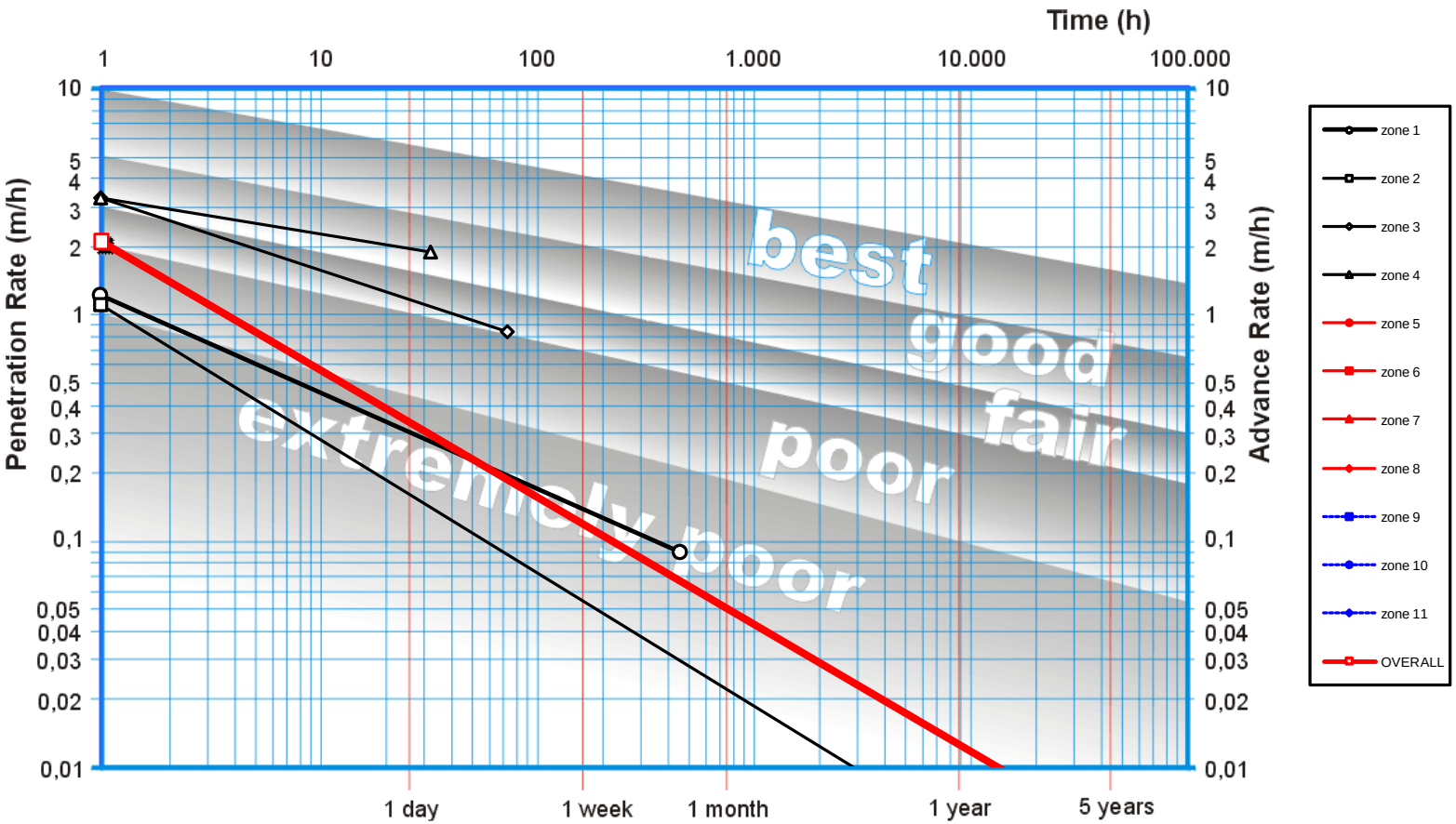
DEEP TBM TUNNEL FOR MINE ACCESS

Application of Q_{TBM}
where faulted zones
interrupt
fast progress

An early sheared zone in same tunnel – many delays as drilling equipment for probing/injection ***<u>not yet mounted</u>***

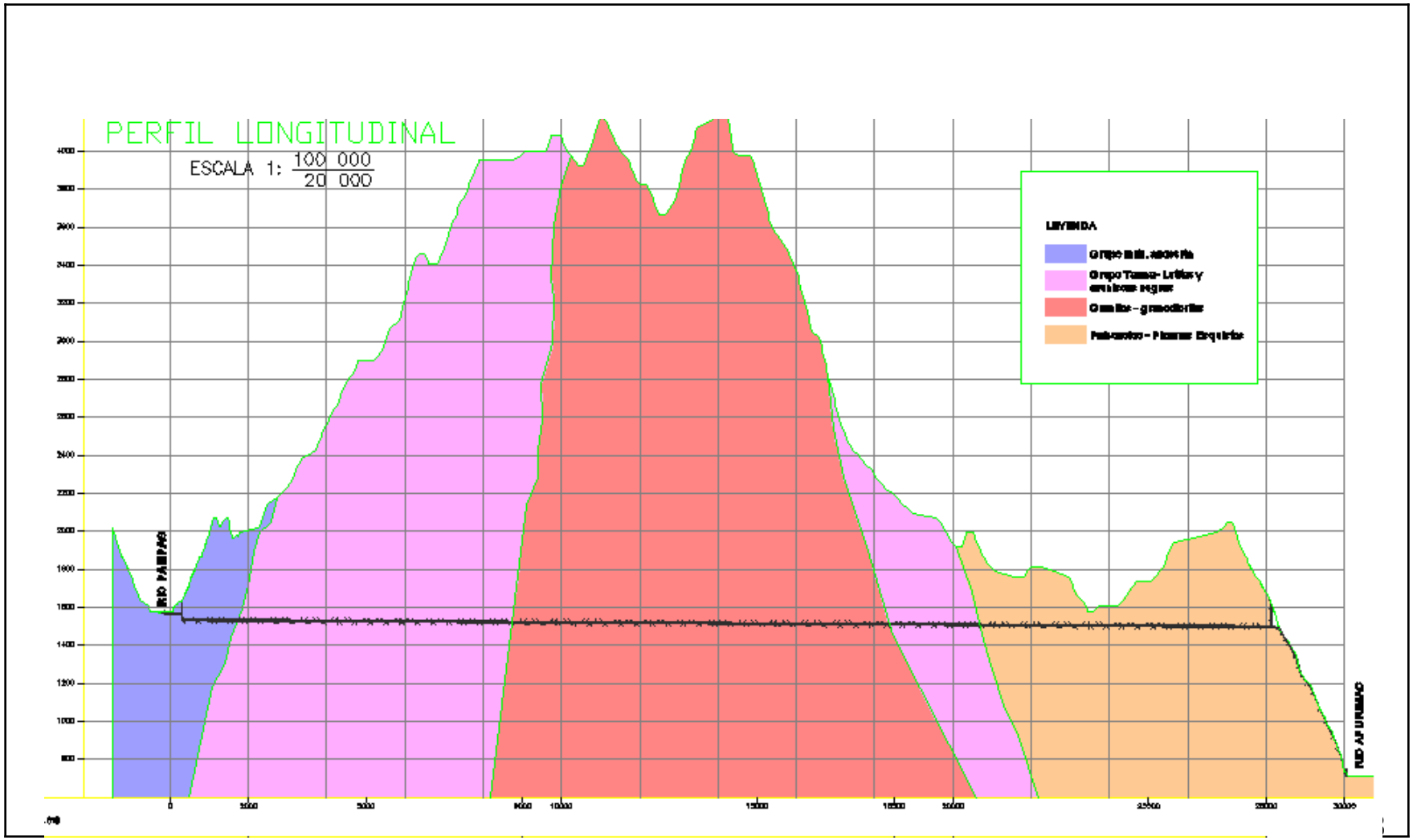


Unexplored, faulted conditions, can give prognoses like this….without pre-treatment.



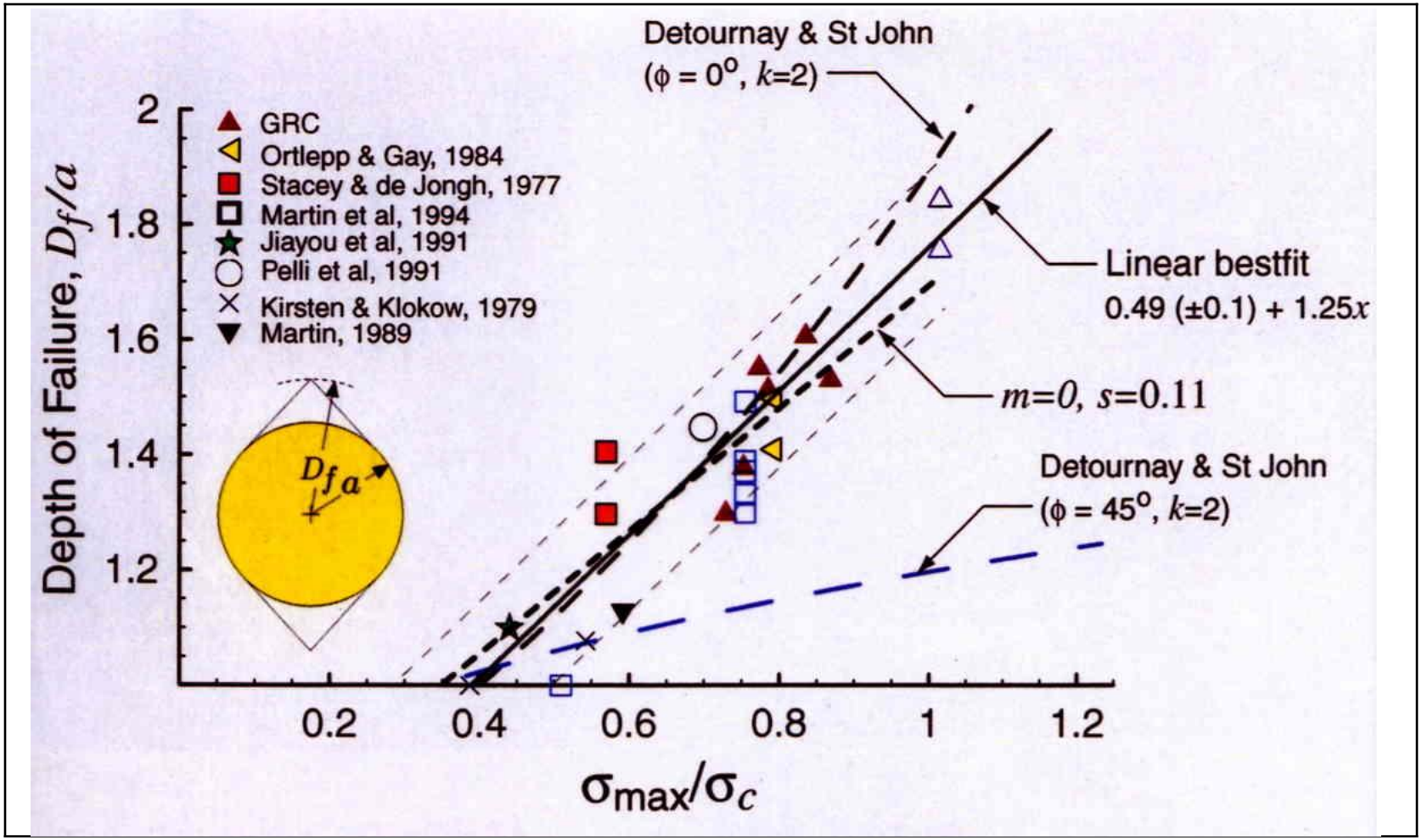
ULTRA DEEP TUNNELS
AND
ROCK BURST THREAT

VERY DEEP TBM TUNNEL (PLANNED) THROUGH ***ANDES MOUNTAINS*** IN PERU (max. 2.6 km cover …slightly more than JINPING II …..and 28 km long)



DO NOT *UNDER-ESTIMATE* $3 \times (\sigma_1 - \sigma_3) = \boldsymbol{\sigma}_{max}$

but also do not *OVER-ESTIMATE* $\boldsymbol{\sigma}_c$

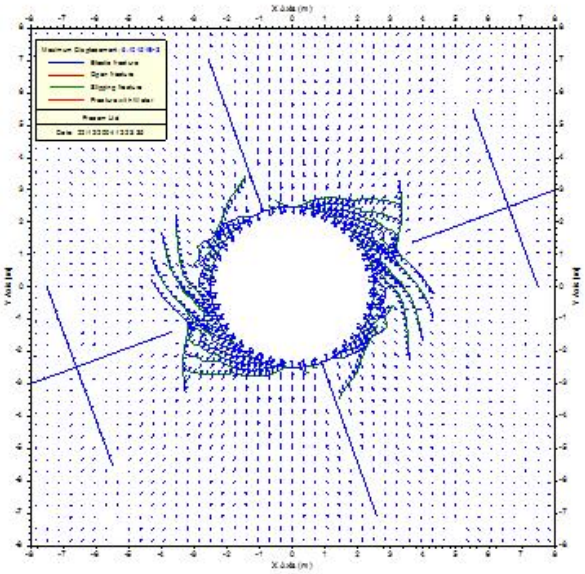


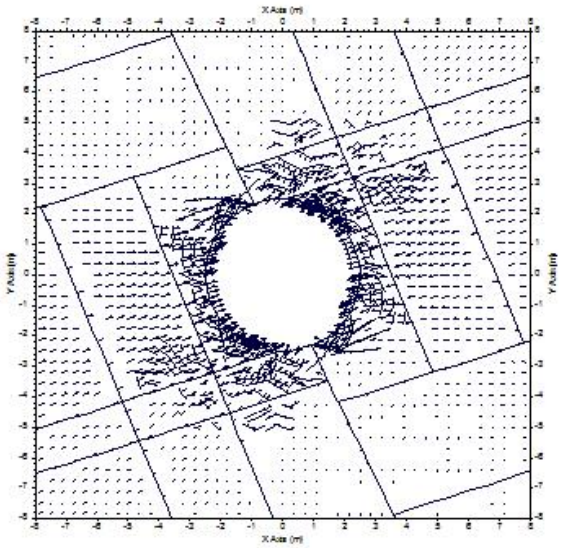
Also from Q-system…….beware σ_θ / σ_c !!

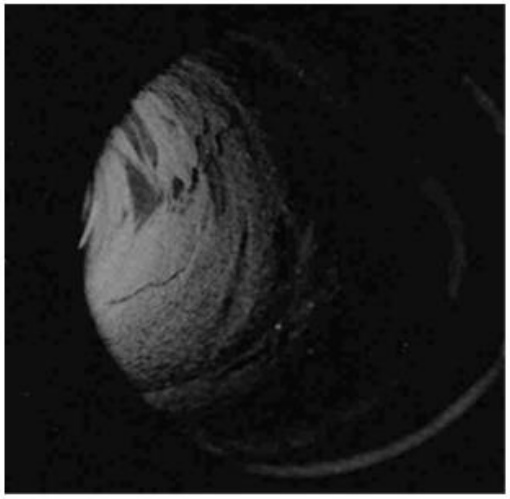
Table 13 . SRF for massive rock with high stress (Barton and Grimstad,1994).

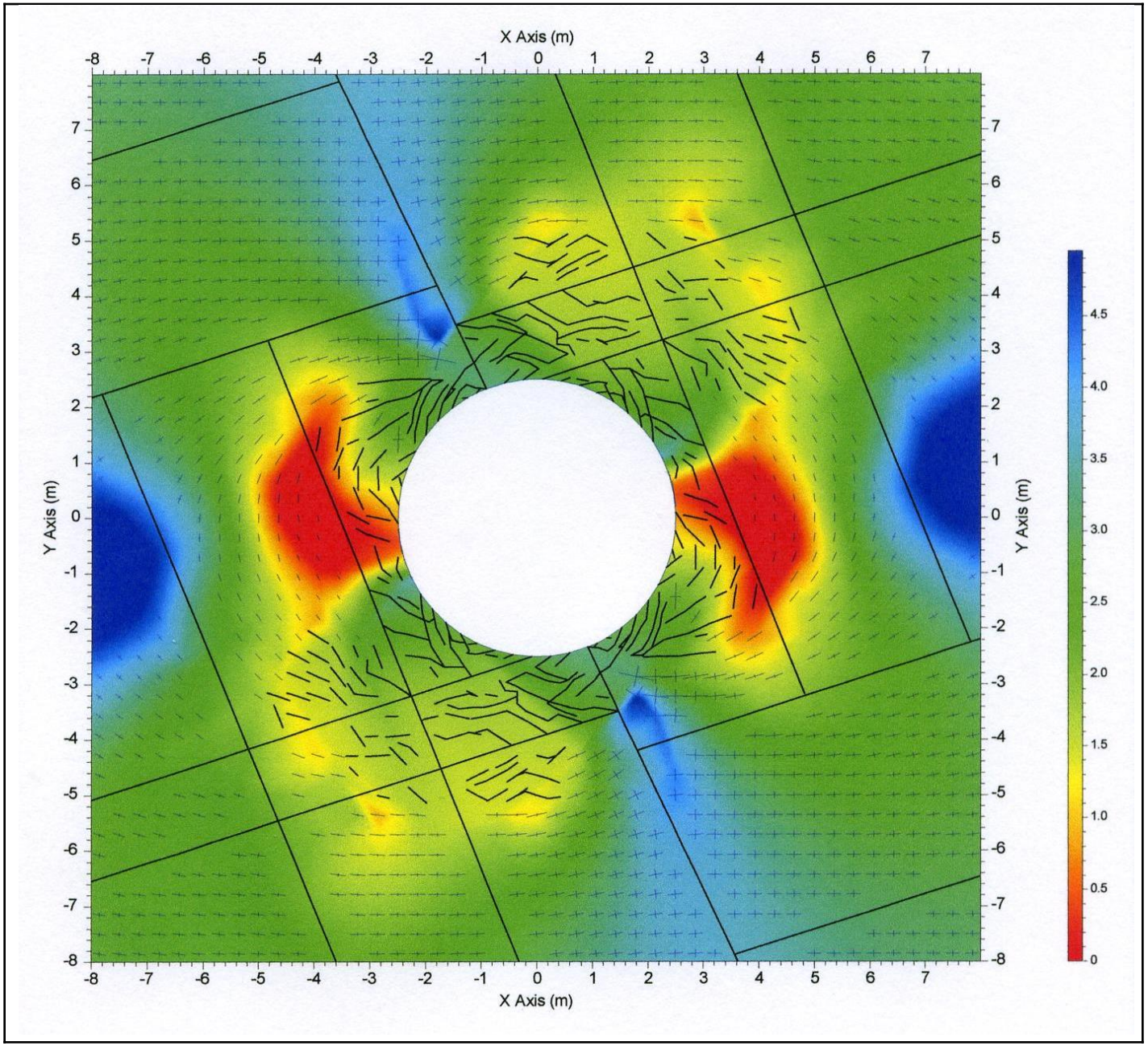
	6 b) Competent rock, rock stress problems	σ_c / σ_1	$\sigma_\varphi / \sigma_c$	**SRF**
H	Low stress, near surface, open joints.	> 200	< 0.01	2.5
J	Medium stress, favourable stress condition.	200-10	0.01-0.3	1
K	High stress, very tight structure. Usually favourable to stability, may be unfavourable for wall stability.	10-5	0.3-0.4	0.5-2
L	Moderate slabbing after > 1 hour in **massive** rock.	5-3	0.5-0.65	5-50
M	Slabbing and rock burst after a few minutes in **massive** rock.	3-2	0.65-1	50-200
N	Heavy rock burst (strain-burst) and immediate dynamic deformations in **massive** rock.	< 2	> 1	200-400

“FRACOD” and physical models of boring in over-stress

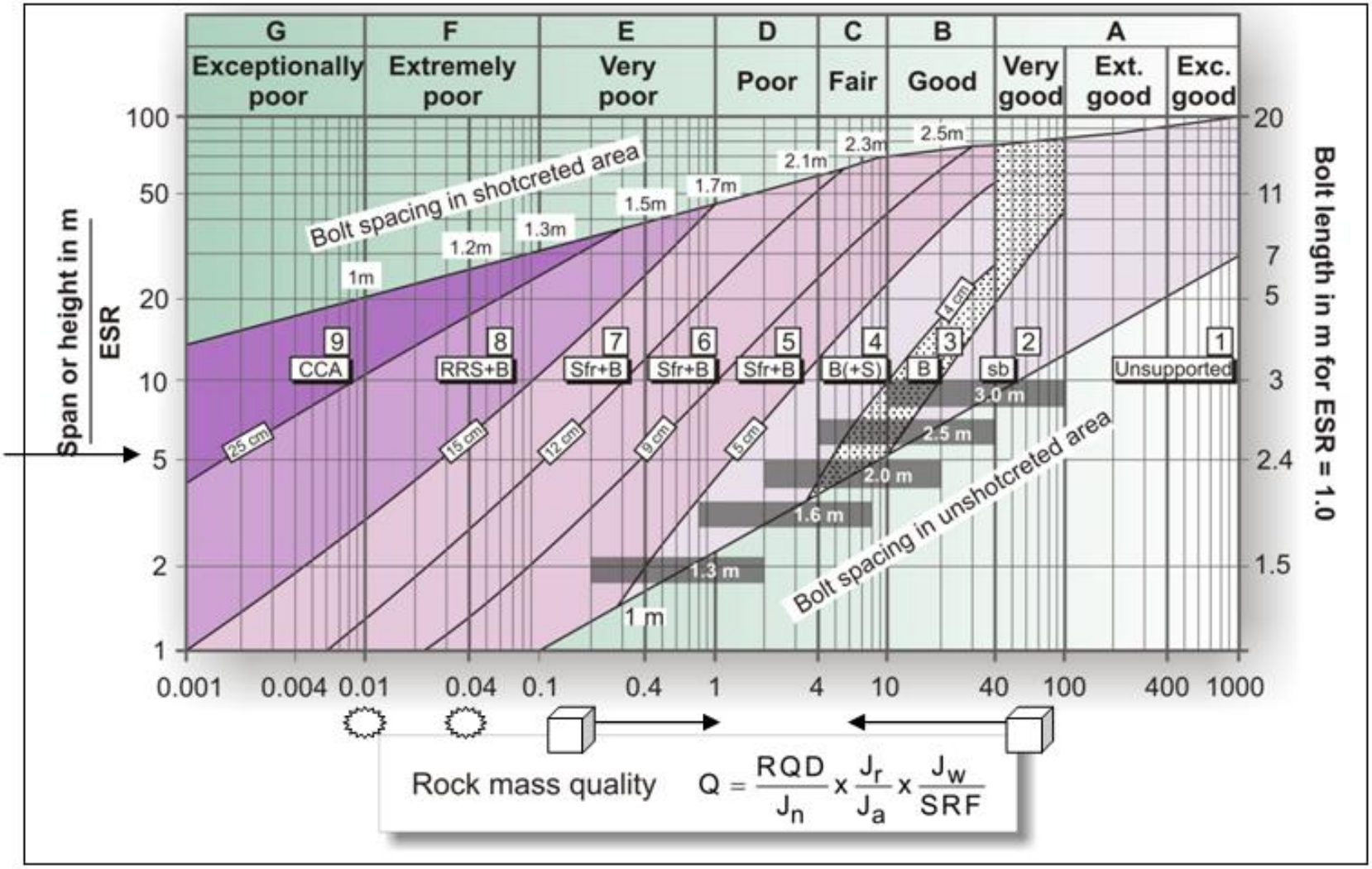


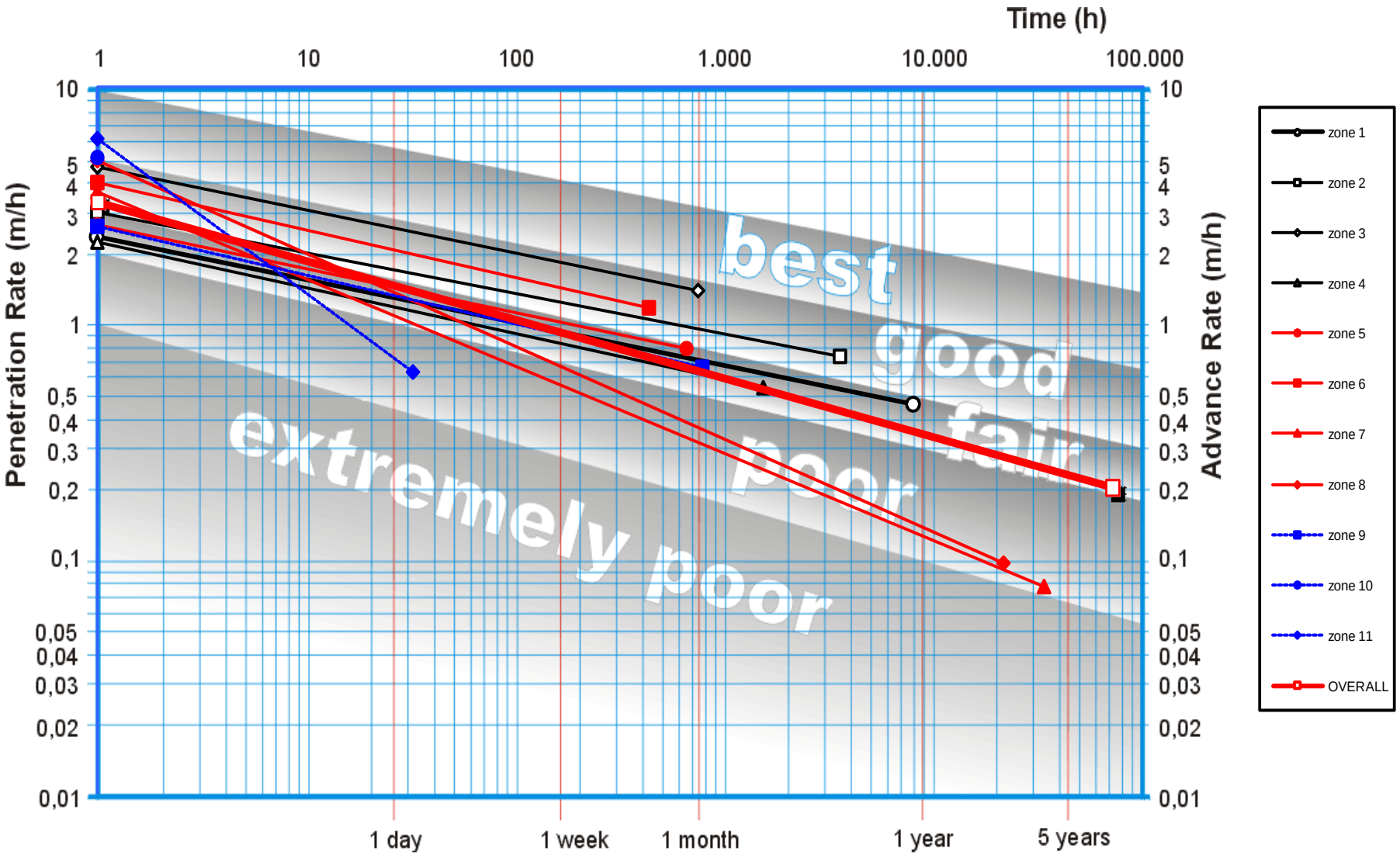





X Axis (m)
Y Axis (m)
-8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0

Rock-burst problems…..high SRF….low Q




Time (h)
1
10
100
1.000
10.000
100.000
Penetration Rate (m/h)
Advance Rate (m/h)
10
5
4
3
2
1
0,5
0,4
0,3
0,2
0,1
0,05
0,04
0,03
0,02
0,01
best
good
fair
poor
extremely poor
1 day
1 week
1 month
1 year
5 years
zone 1
zone 2
zone 3
zone 4
zone 5
zone 6
zone 7
zone 8
zone 9
zone 10
zone 11
OVERALL

Vertical stress too high in relation to **UCS or σ_c**

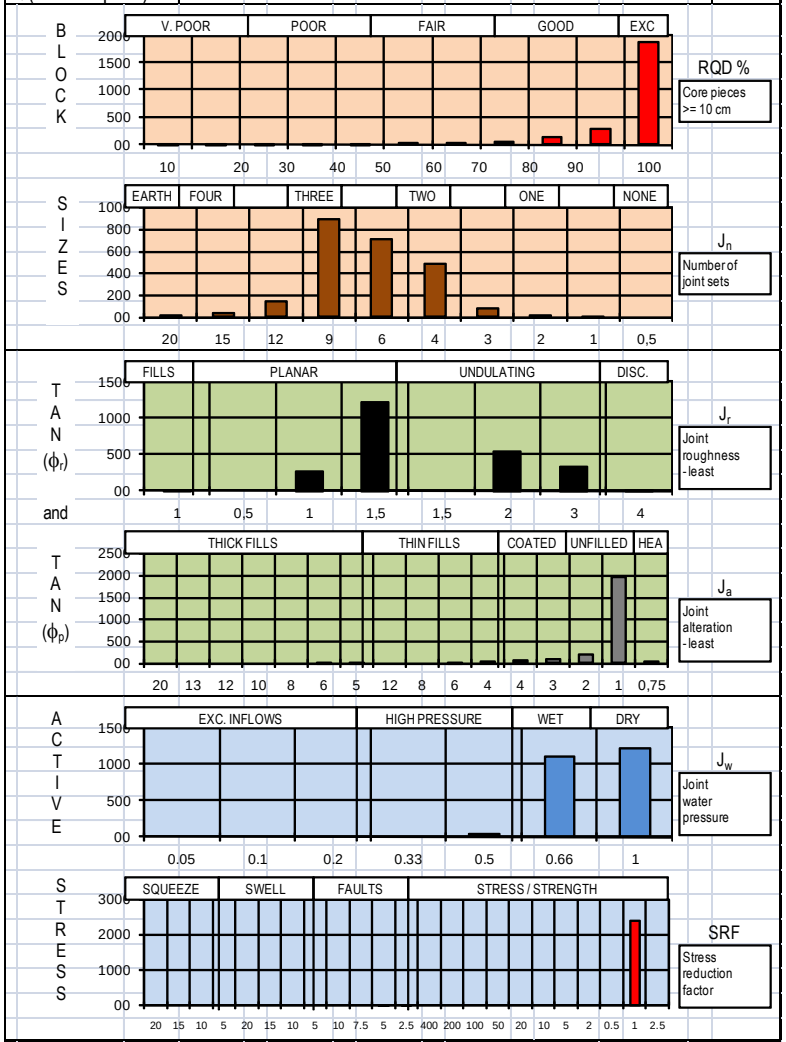
FINALLY A BRIEF COMPARISON

OF *OPEN-GRIPPER AND*

DOUBLE-SHIELD TBM

(in two tunnels for high-speed railway)

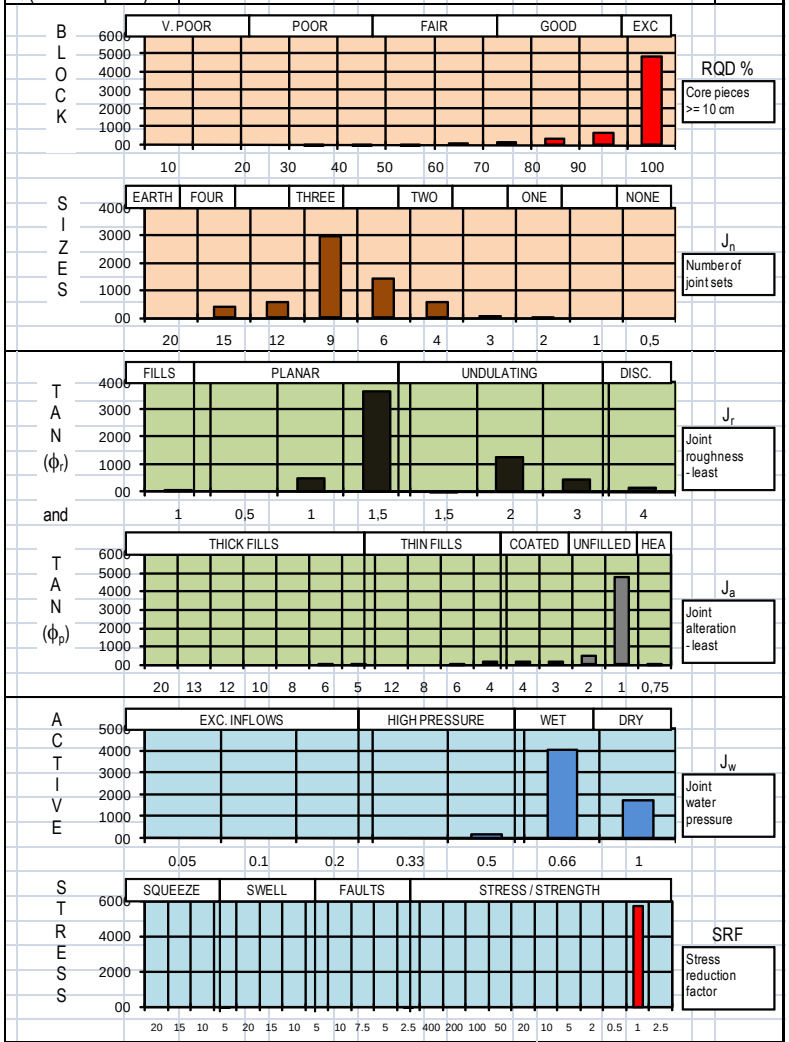
Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	4.0	*	0.50	/	1.0	=	**0.625**
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	1.0	=	**100.0**
Q (mean value)=	96	/	7.1	*	1.8	/	1.3	*	0.83	/	1.0	=	**15.36**
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	1.00	/	1.0	=	**16.67**



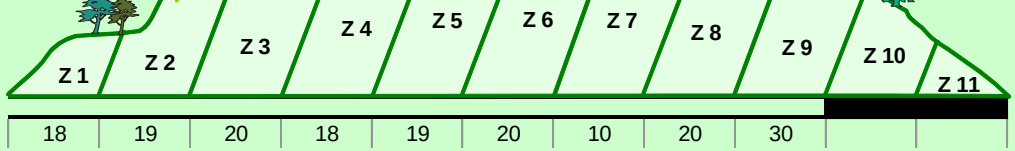
JBV OSLO-SKI	Rev.	Report No. NB&A #1	Figure No. 9
Q-histogram based on compilation of all rock-exposure	Borehole No. : rock exposures	Drawn by NB&A	Date 30.8.09
logging for TUNNEL-NORTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	

SOUTH NORTH COMPARED

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.0	/	5.0	*	0.50	/	1.0	=	**0.500**
Q (typical max)=	100	/	4.0	*	4.0	/	1.0	*	1.00	/	1.0	=	**100.0**
Q (mean value)=	98	/	8.4	*	1.7	/	1.3	*	0.75	/	1.0	=	**11.07**
Q (most frequent)=	100	/	9.0	*	1.5	/	1.0	*	0.66	/	1.0	=	**11.00**



JBV OSLO-SKI	Rev.	Report No. NB&A #1	Figure No. 10
Q-histogram based on compilation of all rock-exposure	Borehole No. : Rock slopes	Drawn by NB&A	Date 31.8.09
logging for TUNNEL-SOUTH, therefore excluding core	Depth zone (m) near-surface	Checked nrb	
and weakness zones.		Approved	



ZONE	9	LITHOLOGY	*Type 3 weakness zone*	ZONE LENGTH	*30*

INPUT DATA

RQD	J_n	J_r	J_a	J_w	SRF	$-m_1$	RQD_0	γ (g/cm³)	V_P (km/s)
						-0.25		2.7	3.4

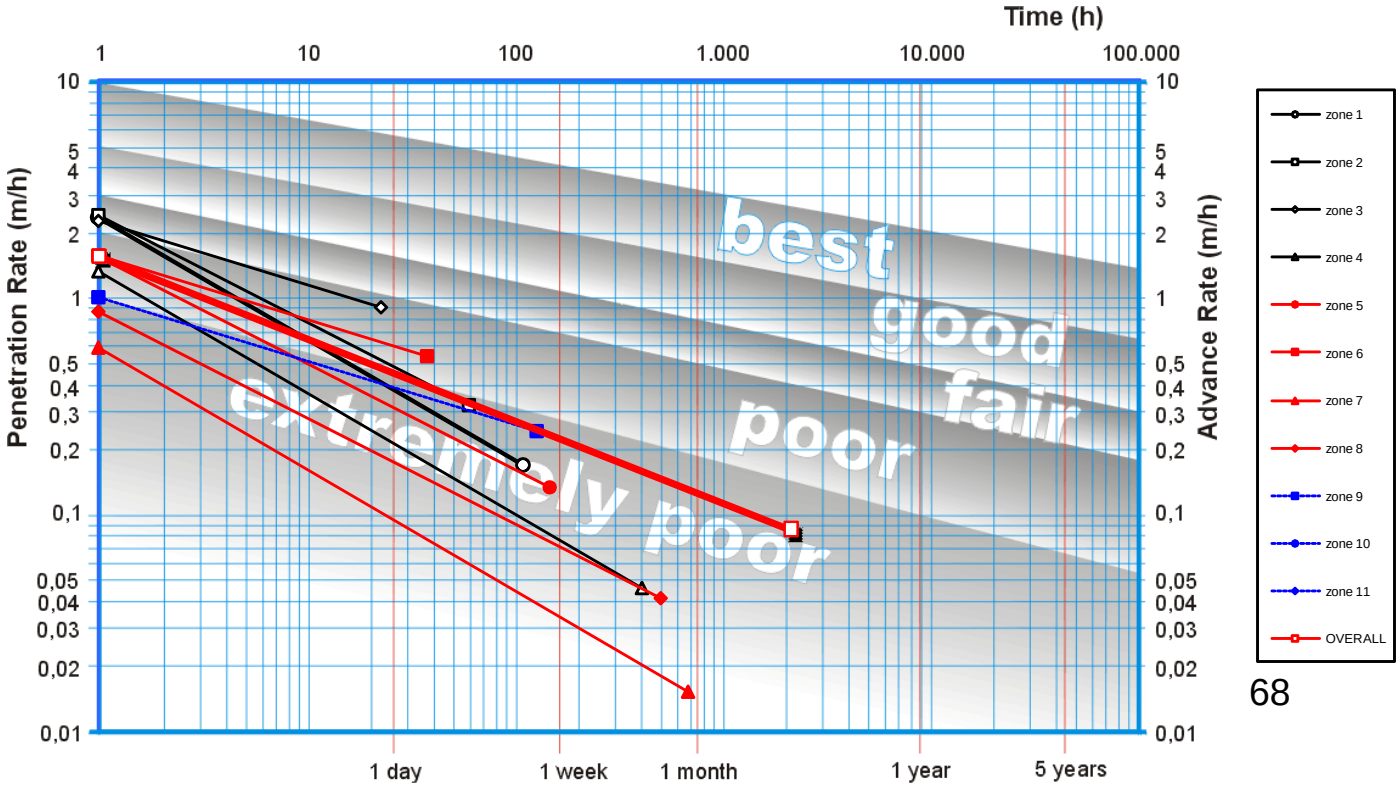
β°	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	150.0		8.0	20.0	25.0	5.0	10.0	2.0

Cumulated time for nine simulated weakness zones is nearly three months (2.9 months).

TIME FOR TUNNEL COMPLETION (months)

2.9

Site *Weakness zones, types 1, 2 an*
Date *08/09/2009*

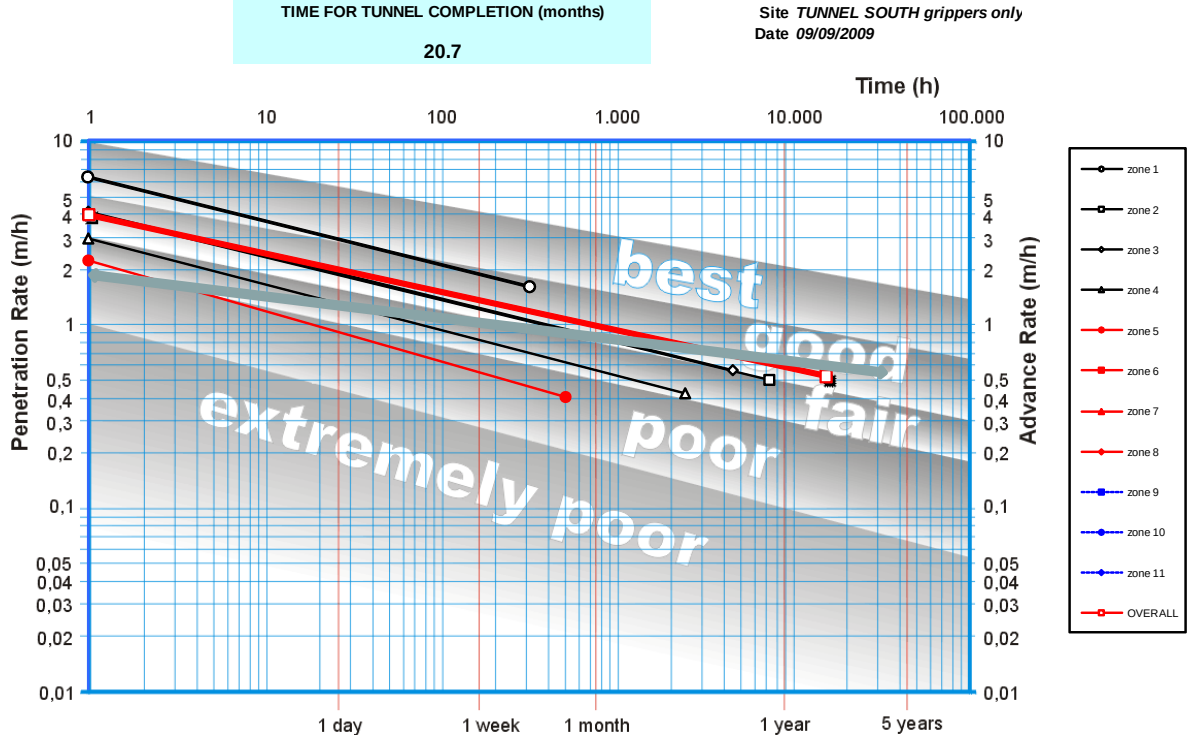


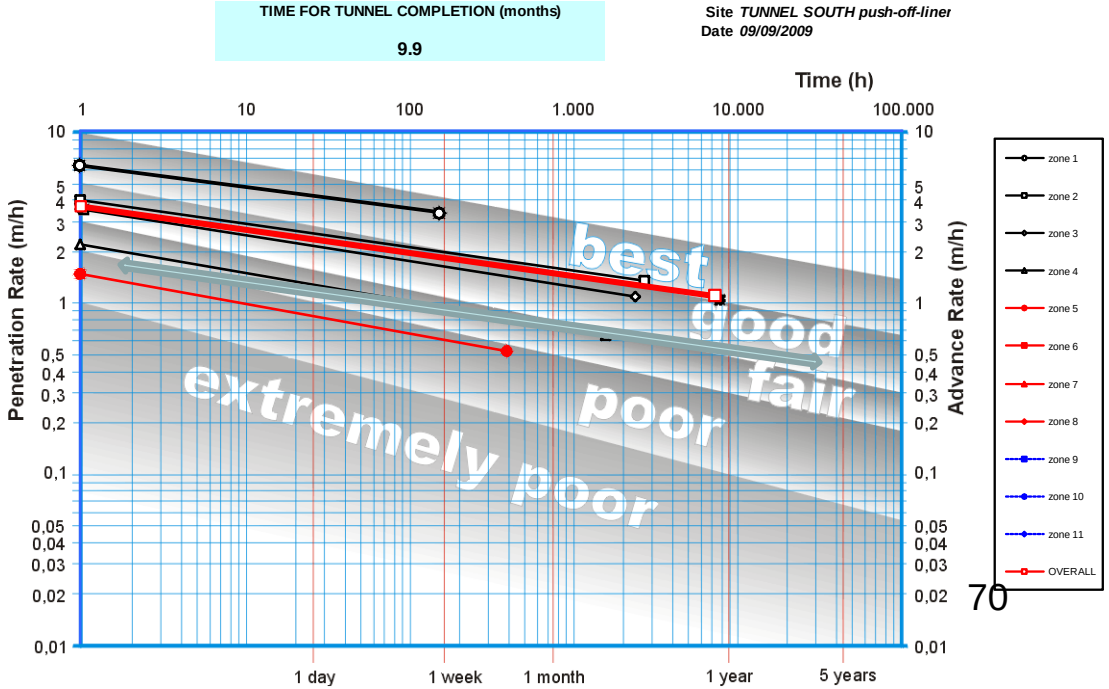
A NARROW WEAKNESS ZONE

SOUTH TUNNELS

Comparing *open gripper TBM and double-shield TBM*

(21 months or 10 months, but *minus weakness zones prognosis*)





CONCLUSIONS

1. Whether single-shield or double-shield, must probe-drill and pre-treat major fault zones.

2. Do not assume engineering geologists are superfluous if double-shield.

3. Pre-injection helps to improve most of the six Q-parameters…….(-m) less negative.

4. Do not underestimate the tangential stress concentration in relation to (0.4 x) UCS