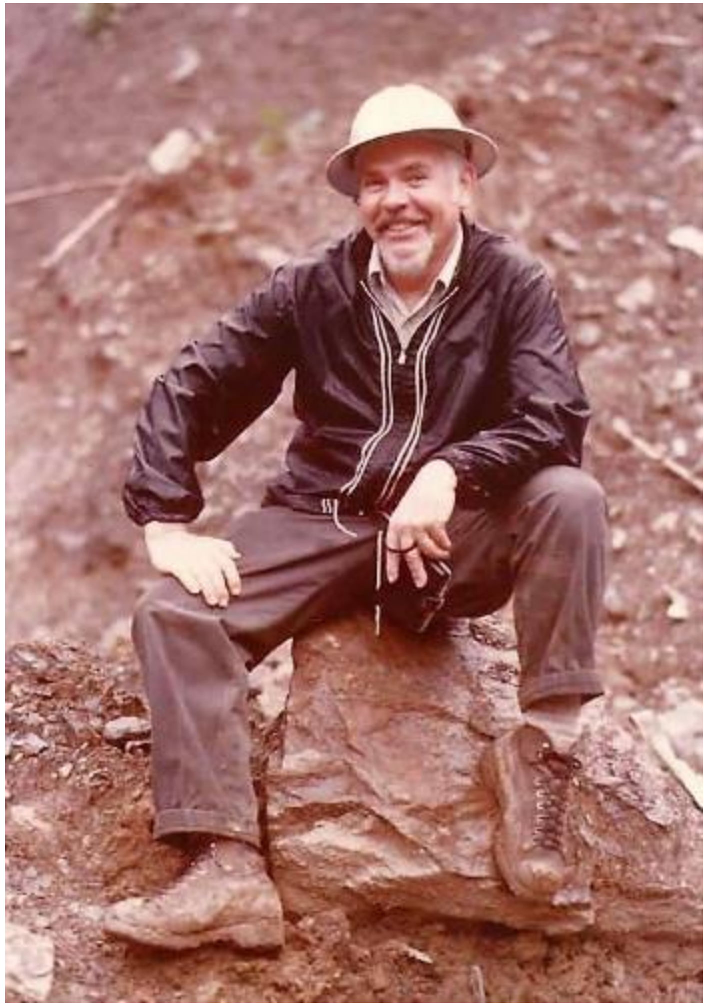


THE NEXT HALF-CENTURY OF RQD FROM A DRILL-QUALITY AND *Q-SYSTEMS* PERSPECTIVE

Nick Barton, NB&A, Oslo

CONTENT

- Some words about Bieniawski
- RMR and Q have their differences, but NB-ZTB, 2008
- Some words about Deere
- In defence of RQD (contra Jv of Palmstrøm)
- Cecil (1970), RQD, number of joint sets in Q development
- Q-histograms and ‘central place’ of RQD
- Q_{TBM}........ Qslope........Q_{H2O} in brief (all contain RQD)
- RQD and Vp (Sjøgren et al. 1979)
- Competition for GSI ? (includes RQD)

ROCK MASS CLASSIFICATION

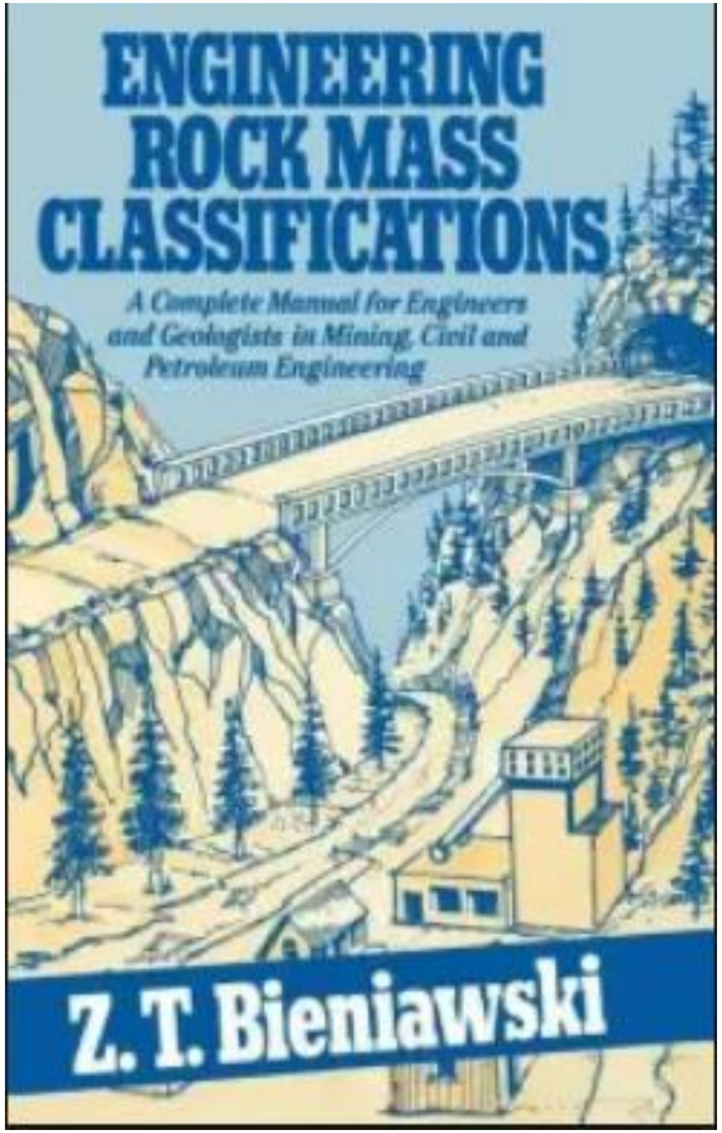
RMR and Q - Setting records straight

The RMR and Q rock mass classifications were independent developments in 1973 and 1974, whose common purpose was to quantify rock mass characteristics previously based on qualitative geological descriptions. They were originally developed for assisting with the rock engineering design of tunnels.

The value of thorough geological exploration was never disputed, indeed it was always emphasised. In addition, it was

After 35 years of use throughout the tunnelling world, the RMR and Q classifications have proved themselves on numerous projects. They still face misconceptions however, as reflected in recent articles in T&T International. Here, Nick Barton, of Nick Barton & Associates, Norway, and ZT Bieniawski, of Bieniawski Design Enterprises, USA, clear common misunderstandings and provide the "ten commandments" for proper use of these rock mass classification systems

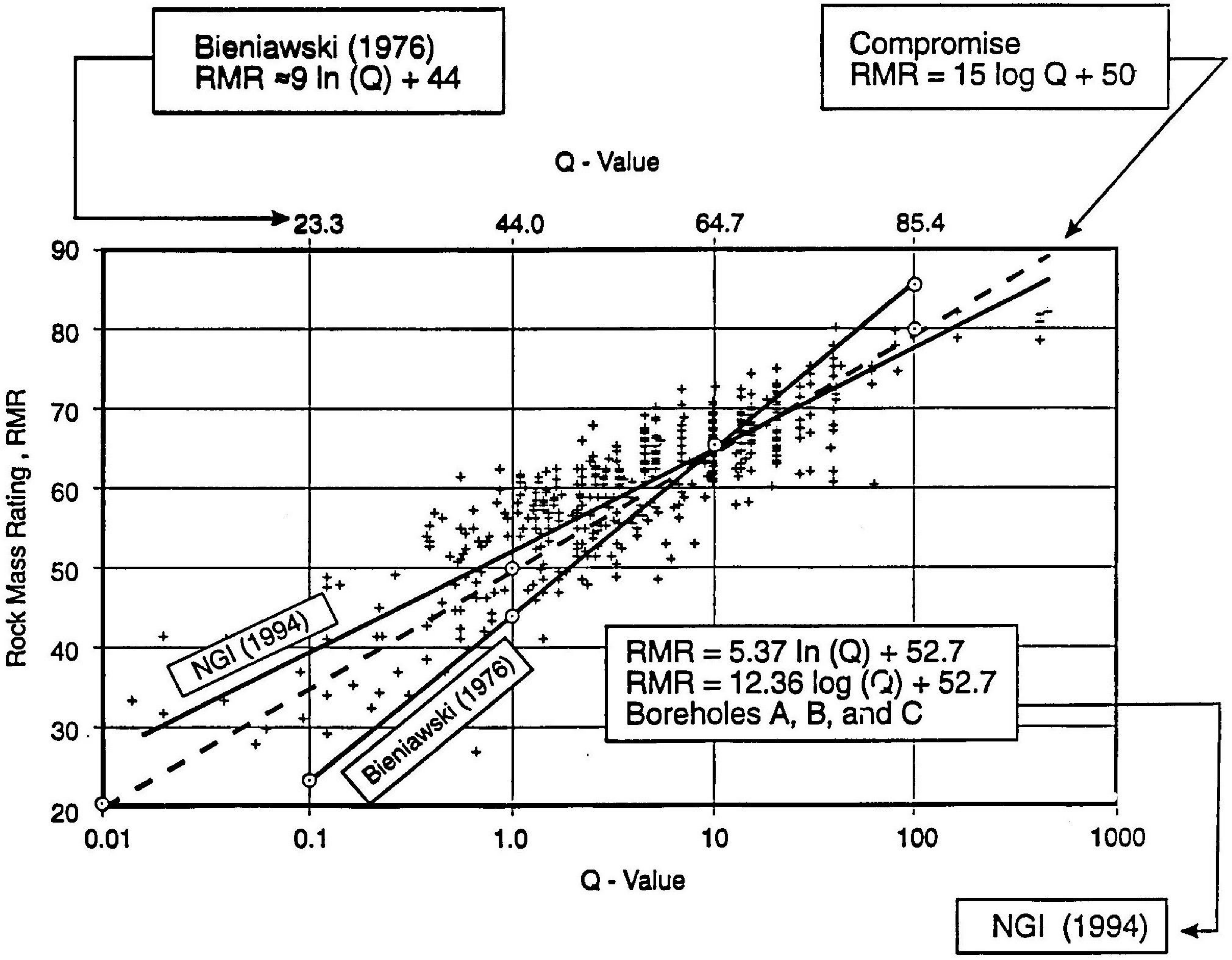
- A 2008 cooperation with Dick Bieniawski – finally! Mainly to address misplaced critical discussion from 'beam-theorist' Pells in Australia, and from Schubert/Reidmuller of Austria (as told in Goodman TTI article) about rock mass classification for tunnels.
- **A 2016 article in a Canadian journal by the same Pells of Australia has proposed 'putting RQD to rest'.**
- In fact these authors, which strangely had Bieniawski as a co-author, **recommended using GSI to estimate RQD.** This really does not sound like Bieniawski!



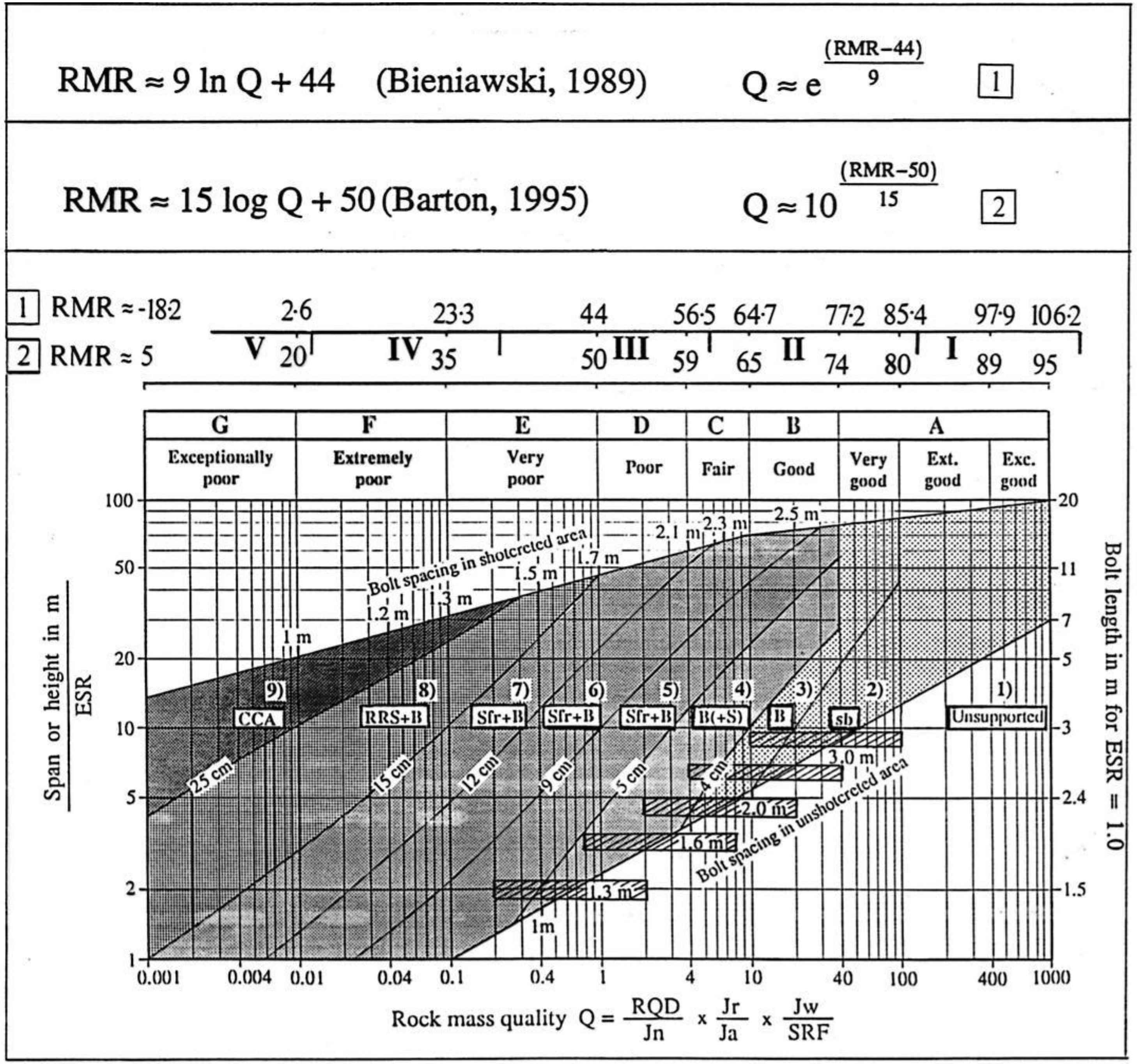
'For Q-system see Bieniawski, 1989'….! (Hudson and Harrison)

ALSO - A FOND MEMORY OF DICK – FROM ISTANBUL……………….. 'close encounter of the third kind' with a belly-dancer!

And from TEHRAN (ARMS)…'this is the last lecture of my career' (2008)……..thanks to the Brazilians and ITA it was not!



‘Proof’ that RMR and Q are different, though may ‘correlate’ in central areas of quality.



These two equations (there are dozens) are in ‘good agreement’ when RMR89 = 65, and Q = 10.

Maybe avoidance of zero and negative RMR is a good reason for choosing the $\log_{10}$ version?

D. U. Deere[1] *and D. W. Deere*[2]

The Rock Quality Designation (RQD) Index in Practice

REFERENCE: Deere, D. U. and Deere, D. W., **"The Rock Quality Designation (RQD) Index in Practice,"** *Rock Classification Systems for Engineering Purposes, ASTM STP 984*, Louis Kirkaldie, Ed., American Society for Testing and Materials, Philadelphia, 1988, pp. 91–101.

ABSTRACT: The Rock Quality Designation (RQD) index was introduced 20 years ago at a time when rock quality information was usually available only from geologists' descriptions and the percent of core recovery. The RQD is a modified core recovery percentage in which unrecovered core, fragments and small pieces of rock, and altered rock are not counted so as to downgrade the quality designation of rock containing these features. Although originally developed for predicting tunneling conditions and support requirements, its application was extended to correlation with *in situ* rock mechanical properties and, in the 1970s, to forming a basic element of several classification systems. Its greatest value, however, remains as an exploratory tool where it serves as a red flag to identify low-RQD zones which deserve greater scrutiny and which may require additional borings or other exploratory work. Case history experience shows that the RQD red flag and subsequent investigations often have resulted in the deepening of foundation levels and the reorientation or complete relocation of proposed engineering structures, including dam foundations, tunnel portals, underground caverns, and power facilities.

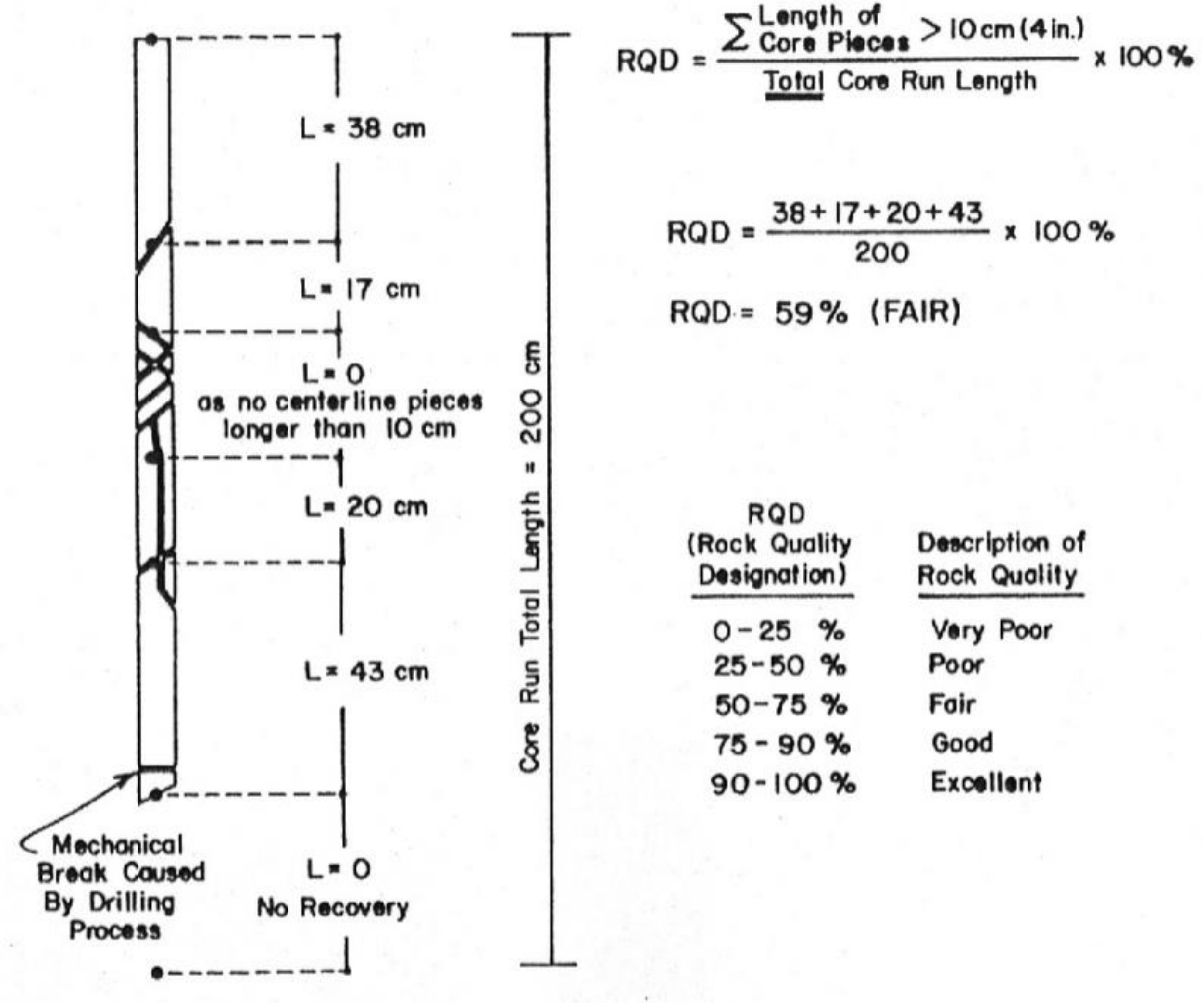
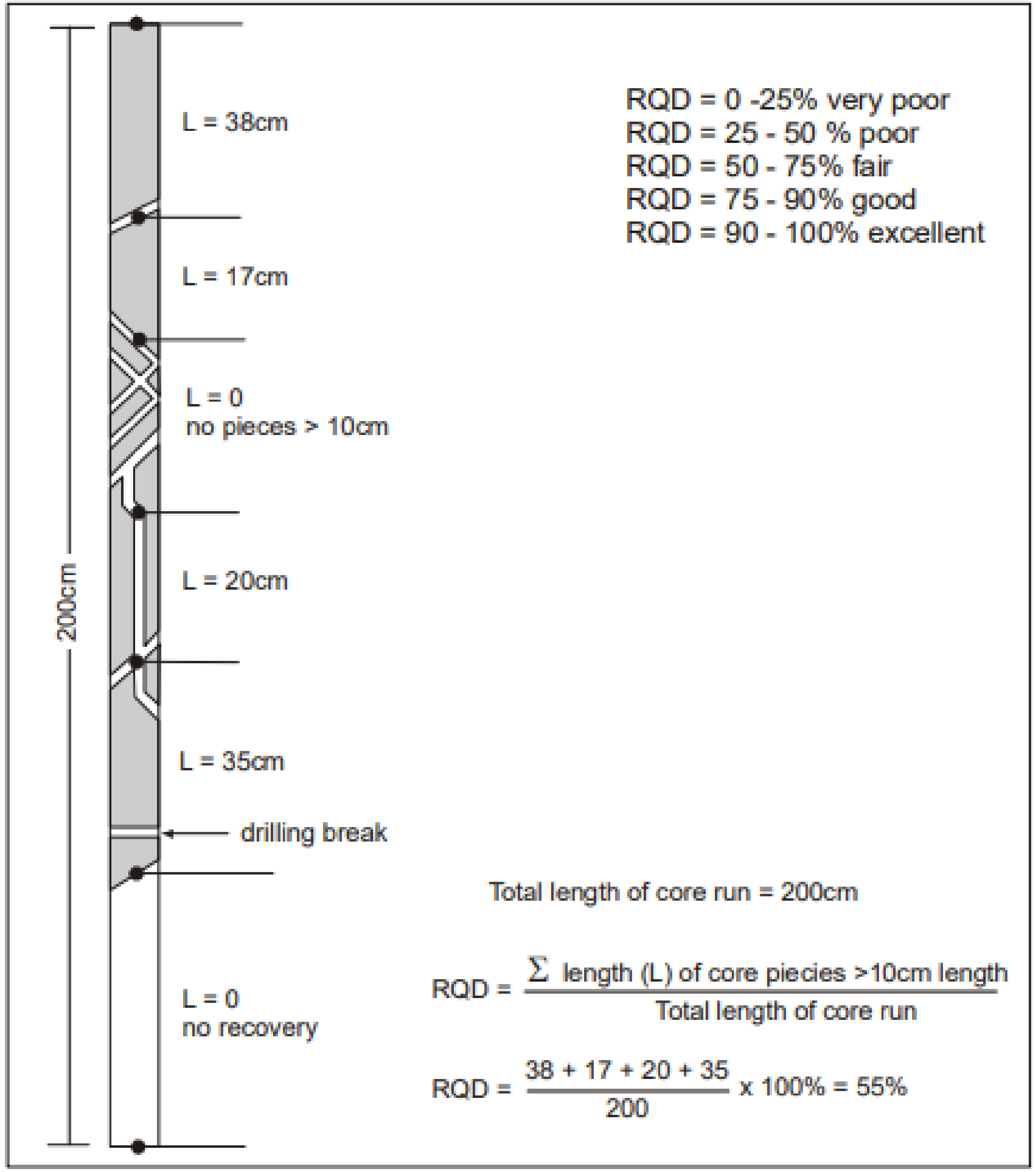


FIG. 1—*Procedure for measurement and calculation of RQD.*

From Deere and Deere, 1988



Redrawn in Palmstrøm, 2005

> for measuring RQD is illustrated in Fig. 1. The RQD index is an index of rock quality in that problematic rock that is highly weathered, soft, fractured, sheared, and jointed is counted against the rock mass. Thus it is simply a measurement of the percentage of ''good'' rock recovered from an interval of a borehole.

'counted against'.....i.e. *discounted*

'serves as a red flag to identify low RQD zones which deserve greater scrutiny'

Do not penalise a core because it has a parallel joint causing break-up

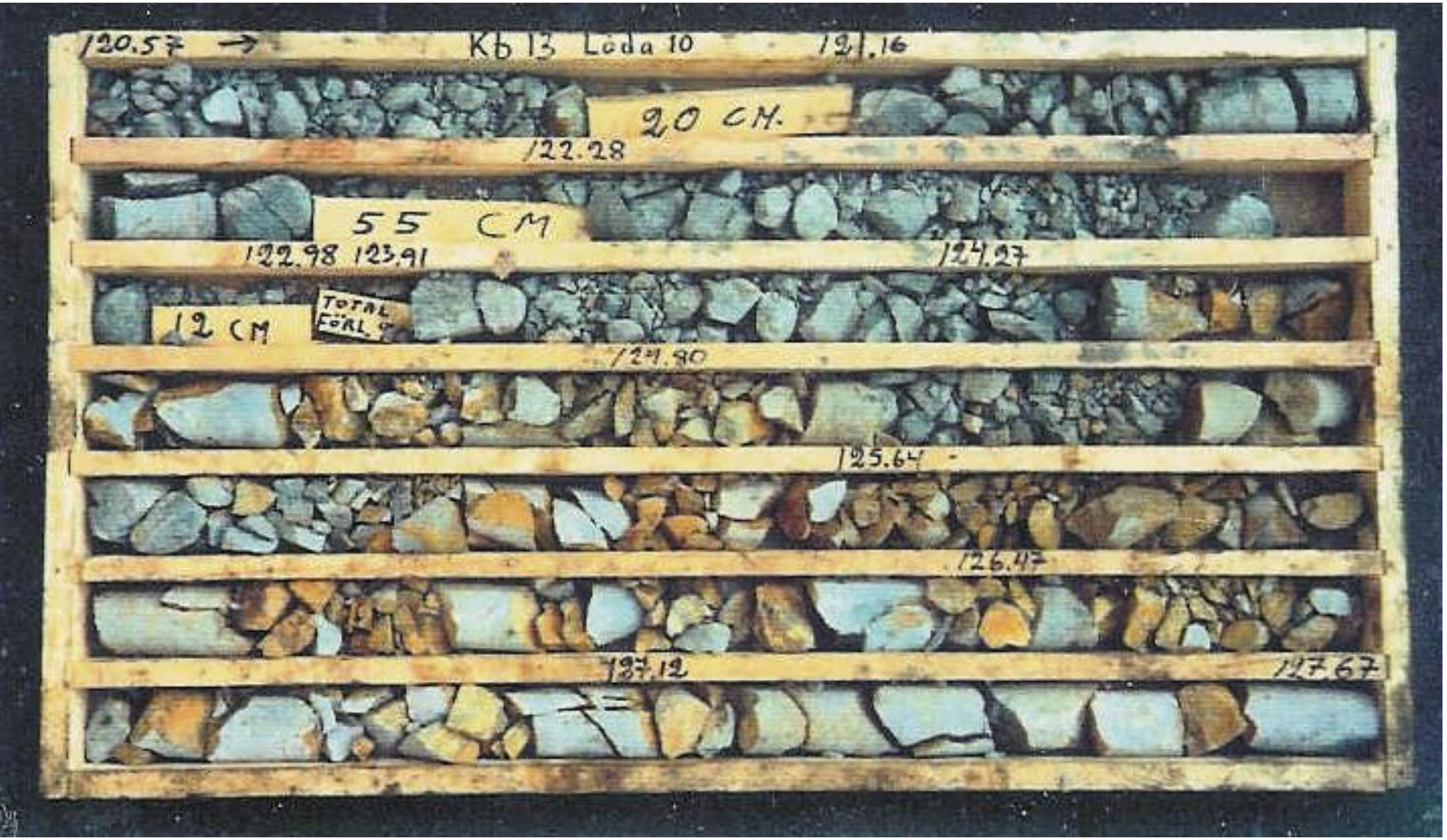
107m (with another core box) of definitively zero RQD.

Maybe:

Q = 10/20 x 1/4 x 0.5/5 ≈ 0.01

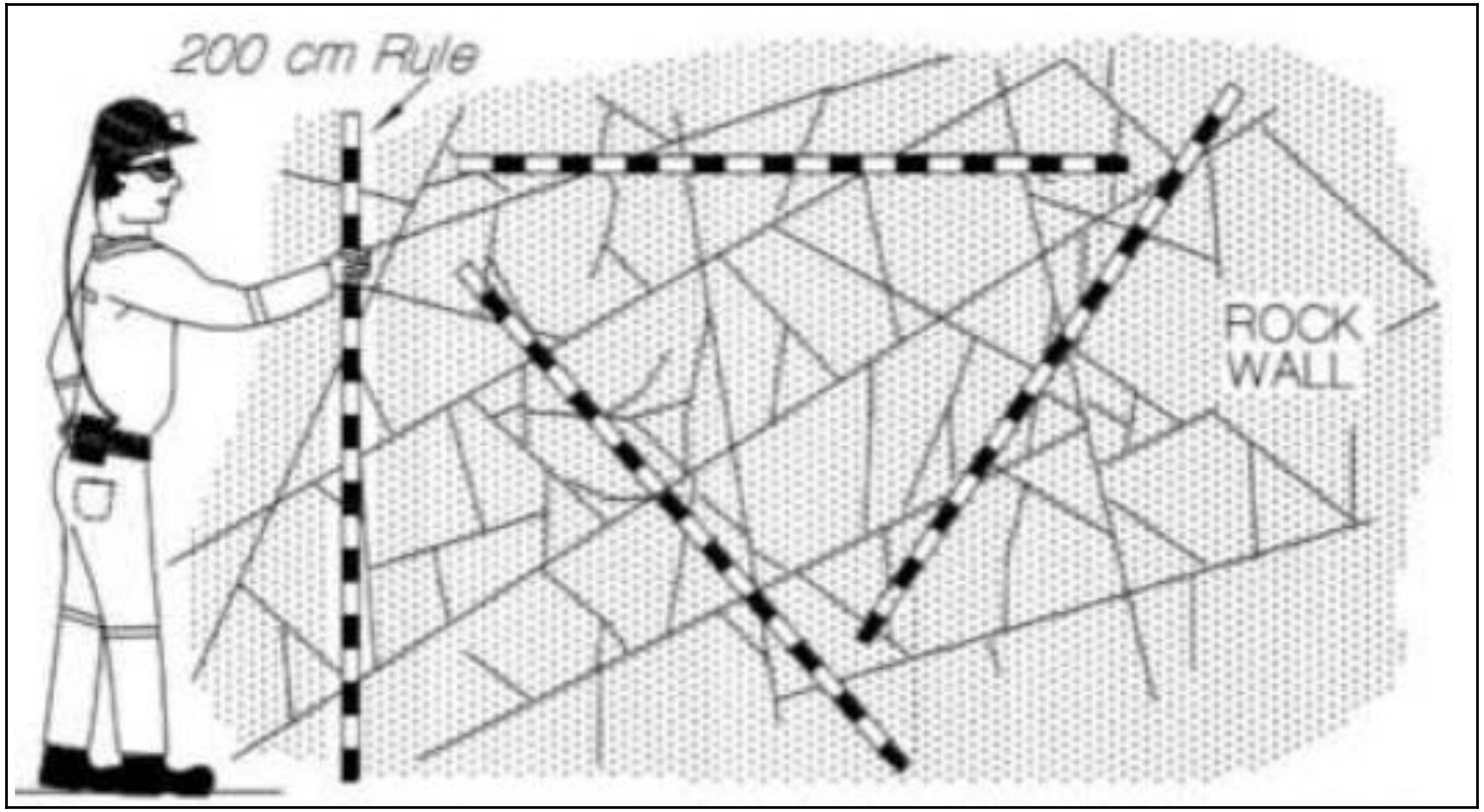

20.60
20.60
20.91
21.37
21.92


SM-ML4-17



RQD = 0 or 100%

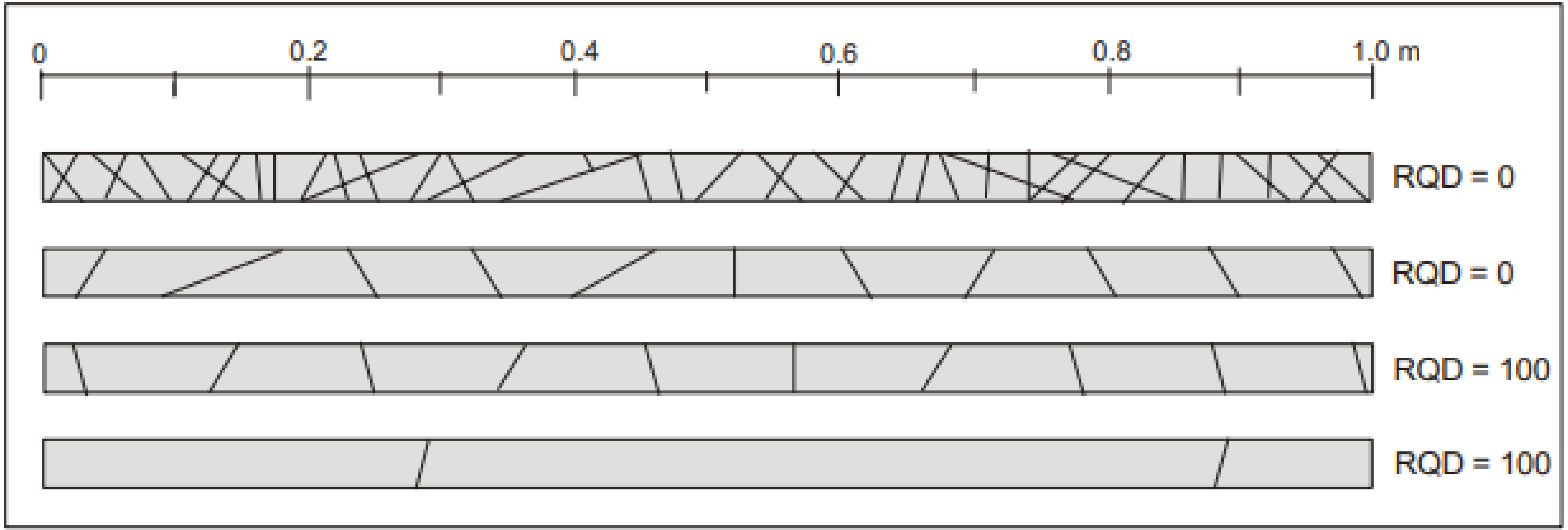
(the '100' value is a nice demonstration of the importance of hole orientation ….actually three joint sets in this Hong Kong granite)



YouTube figure

'Take RQD_W as the average of many measurements'

(OR WE CAN UTILIZE RQD AS AN ANISOTROPIC PARAMETER)



Palmstrøm, 2001....CRITIQUE OF RQD ....ALSO AS A WAY OF SUPPORTING HIS J_V

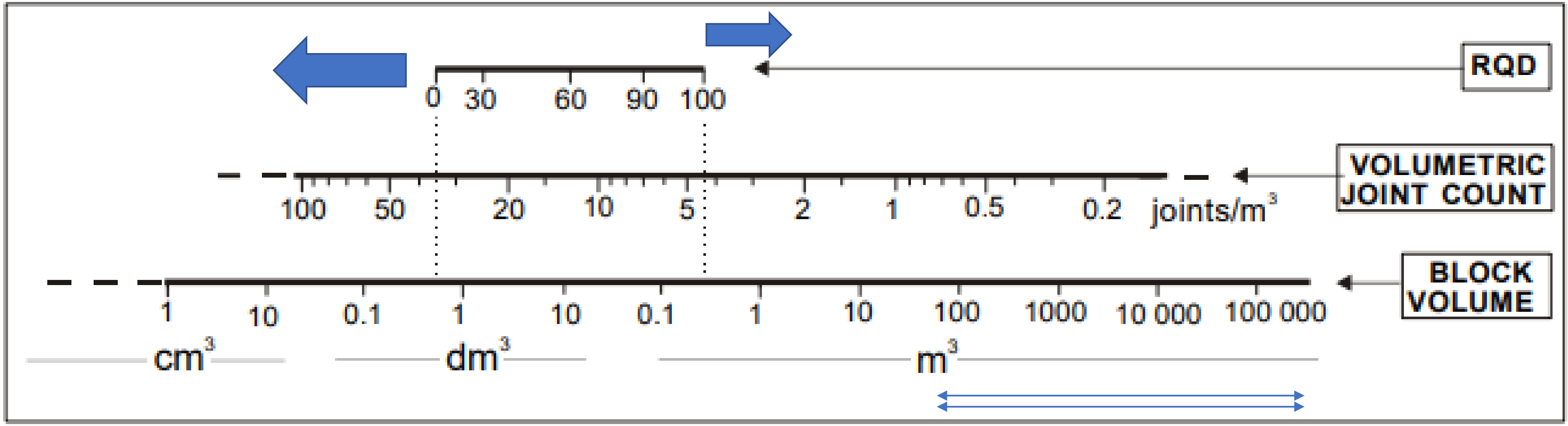
10/15 x 1/2 x 0.5/2.5 = 0.07

10/9 x 1.5/1 x 0.66/1 = 1.1

100/6 x 1.5/1 x 1/1 = 10

100/2 x 2/1 x 1/1 = 100

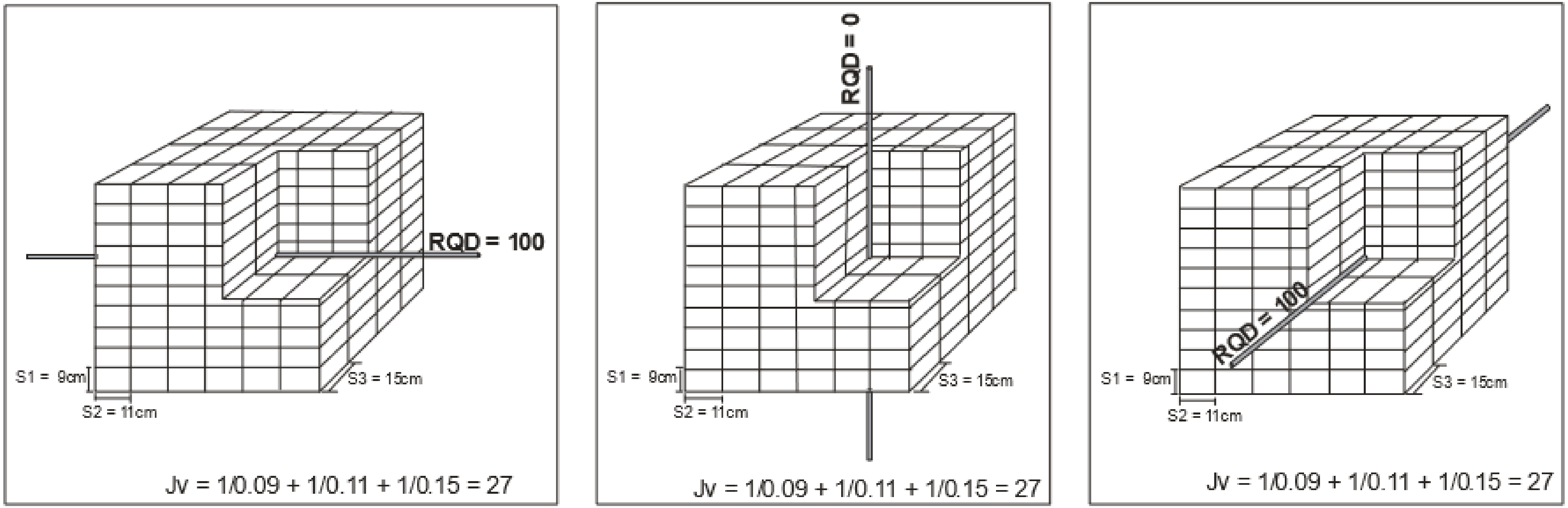
POSSIBLE Q-VALUE ESTIMATES



WHO IS INTERESTED IN ROCK THAT IS THIS MASSIVE?

Palmstrøm, 2001 critique of RQD. Due to his ignoring the number of joints in different orientations, his poor opinion of RQD is misplaced.

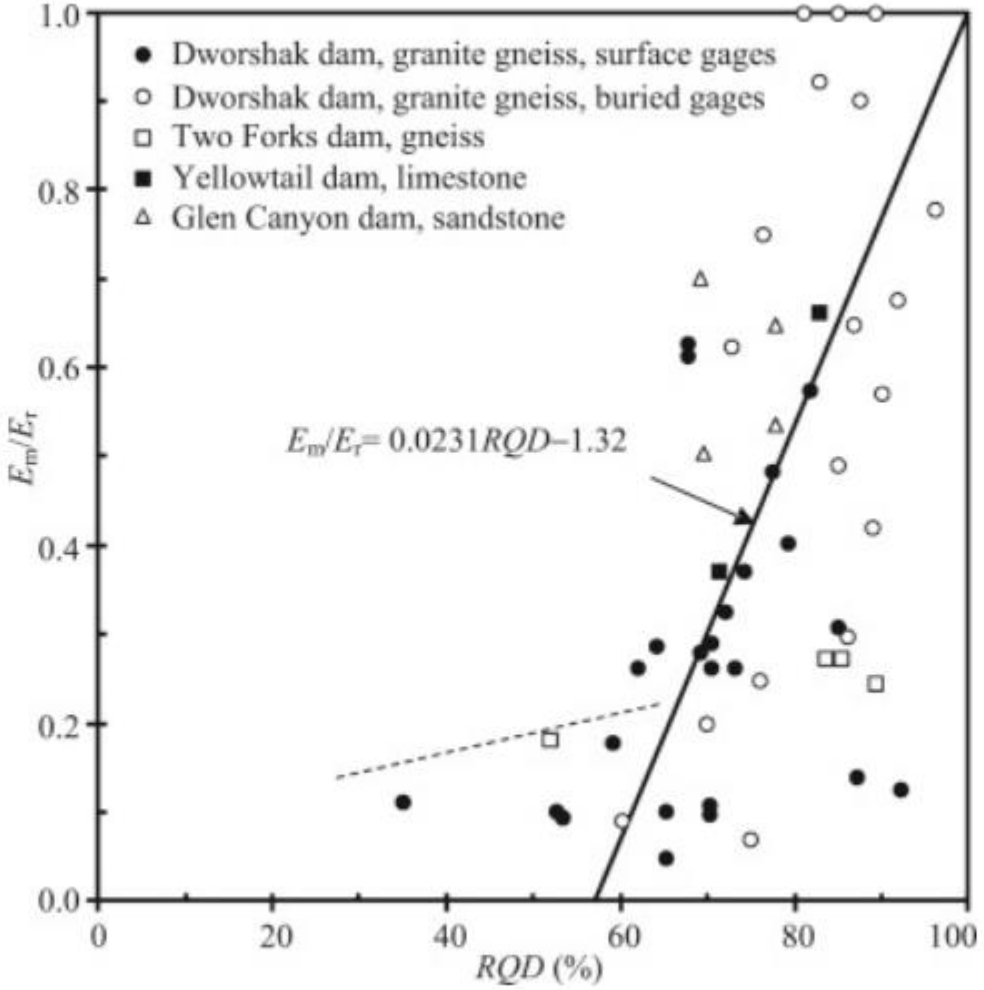
(Is his focus on dimension-stone quarries? where 10m joint spacing is so liked?)



- Another Palmstrøm, 2005 attempt to discredit RQD, and promote his volumetric joint count Jv – which was referenced/supported in Barton et al. 1974.

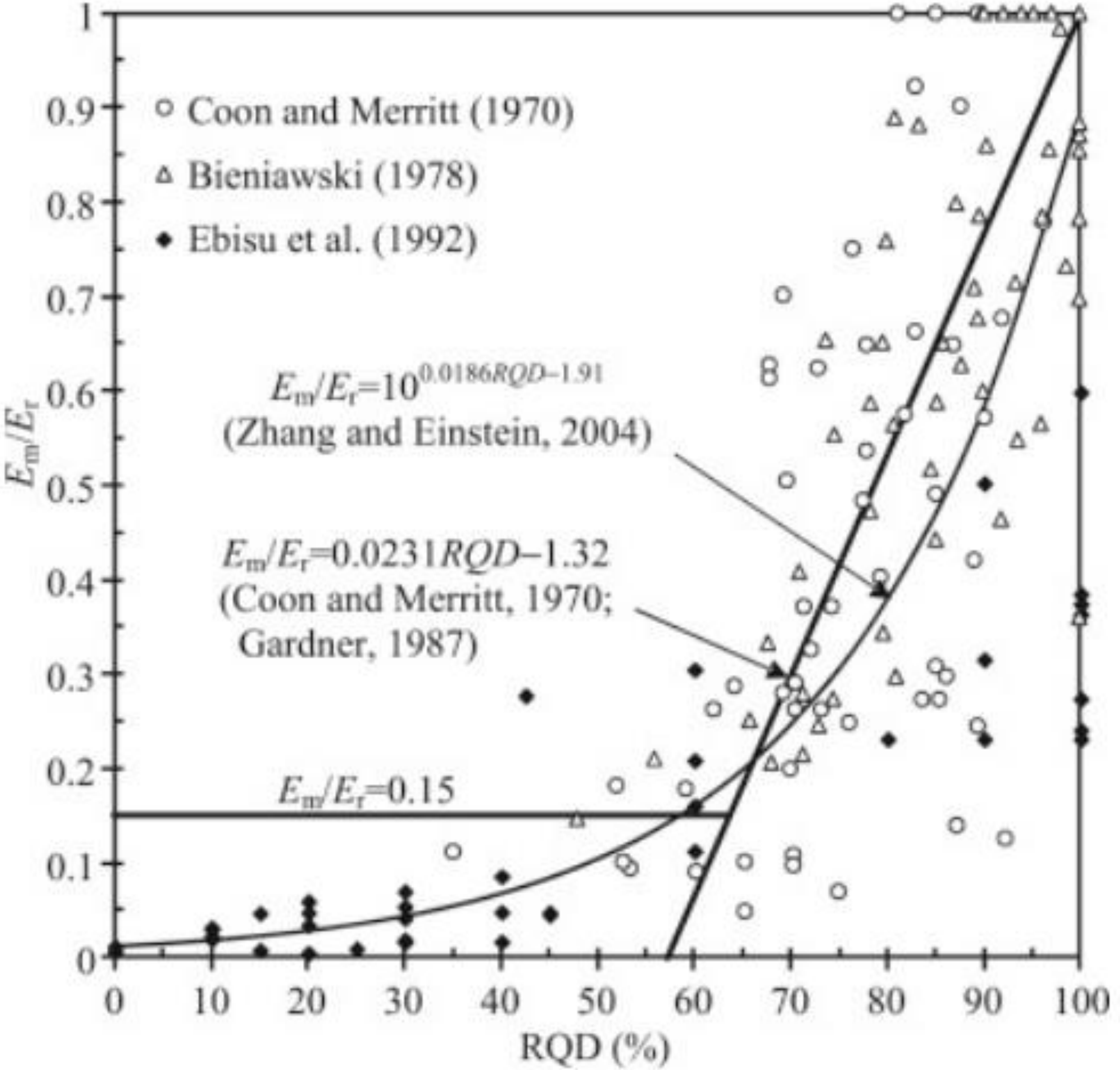
- Rock masses are seldom so uniform (unless sedimentary)…..but treating RQD as an anisotropic parameter has ADVANTAGES compared to Jv! *(For instance, use of tunnel-oriented* ***RQD₀*** *is recommended in* ***Q***$_{\mathbf{TBM}}$ *prognosis method – where it is essential).*

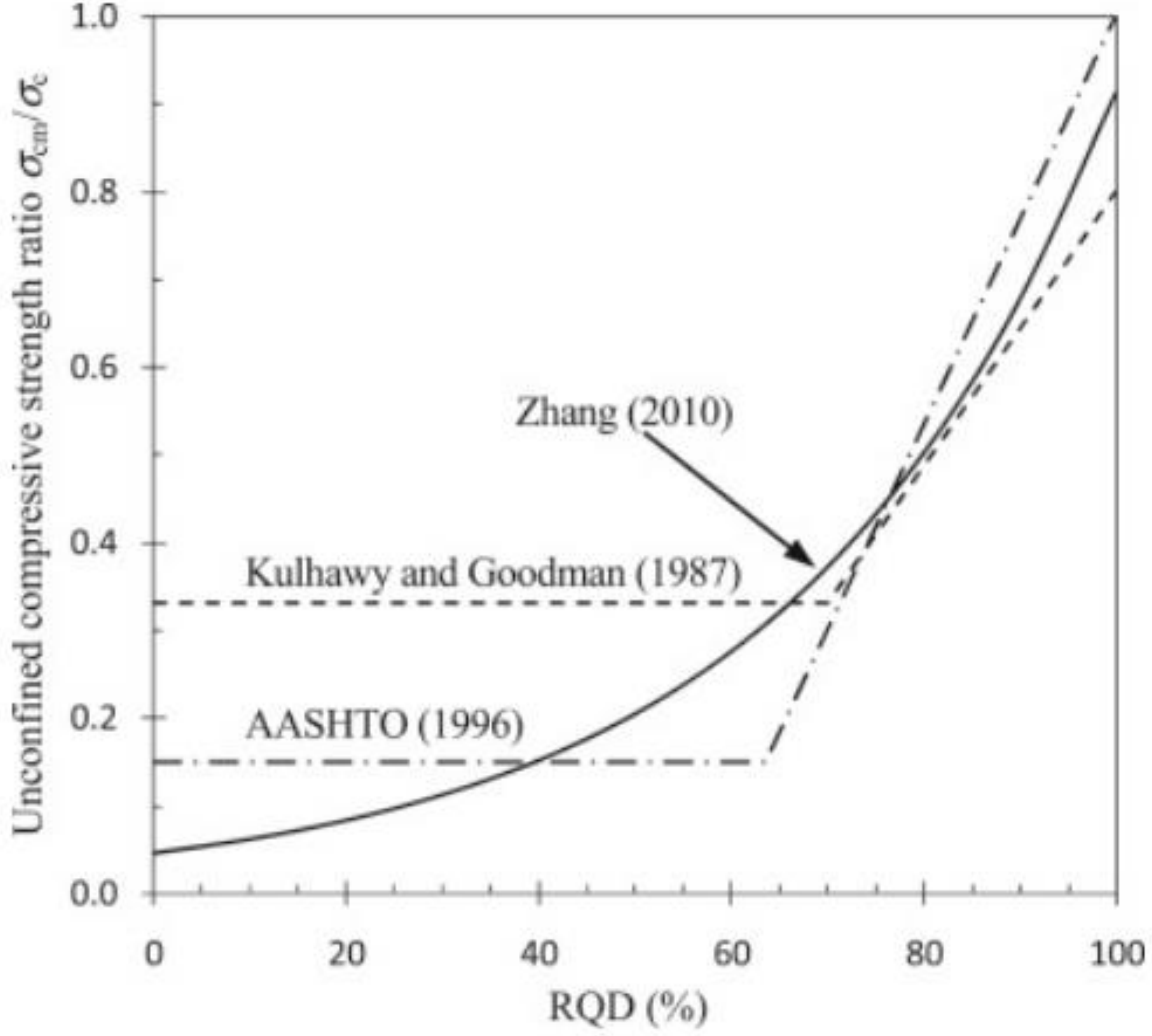
SOME SUGGESTED CORRELATIONS OF RQD with rock mass deformation modulus and strength



Coon and Merrit, 1970

Zhang and Einstein, 2004





Zhang, 2010

σ_{cm}/σ_c

DEVELOPMENT OF THE Q-SYSTEM IN 1973

NB was/is INDEBTED TO ONE OF DEERE'S PH.D. STUDENTS: CECIL, 1970 – for approx. 90 Norwegian and Swedish case records…………………………………………… AND CECIL'S EMPHASIS THAT *NUMBER OF JOINT SETS* WAS IMPORTANT…..not just his professor's RQD!

Cecil, 1970 case records

(this selection reproduced in Barton, Lien, Lunde, 1974)

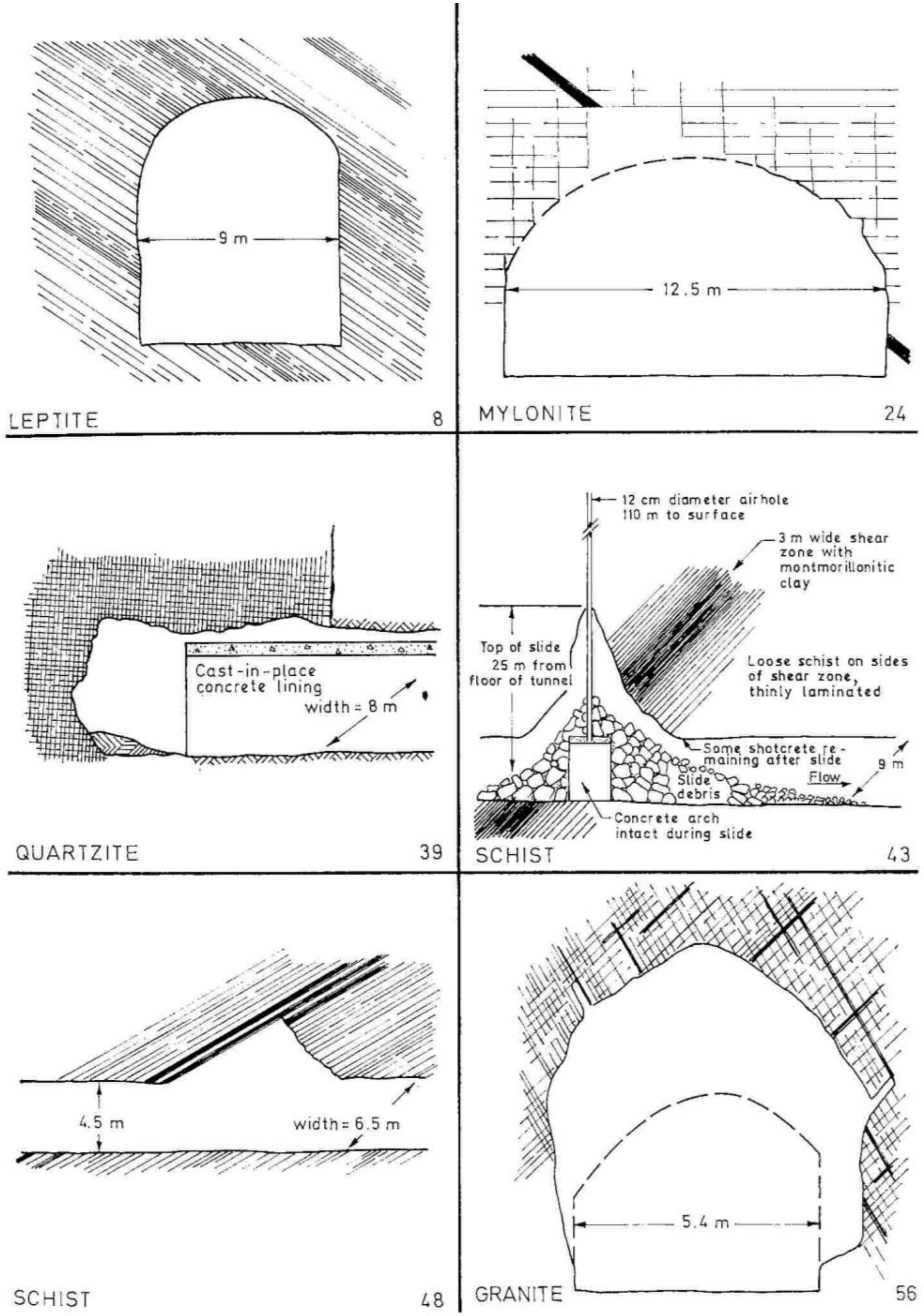


Fig. 7. Sketches of the six case records described in Table 8, after Cecil (1970)

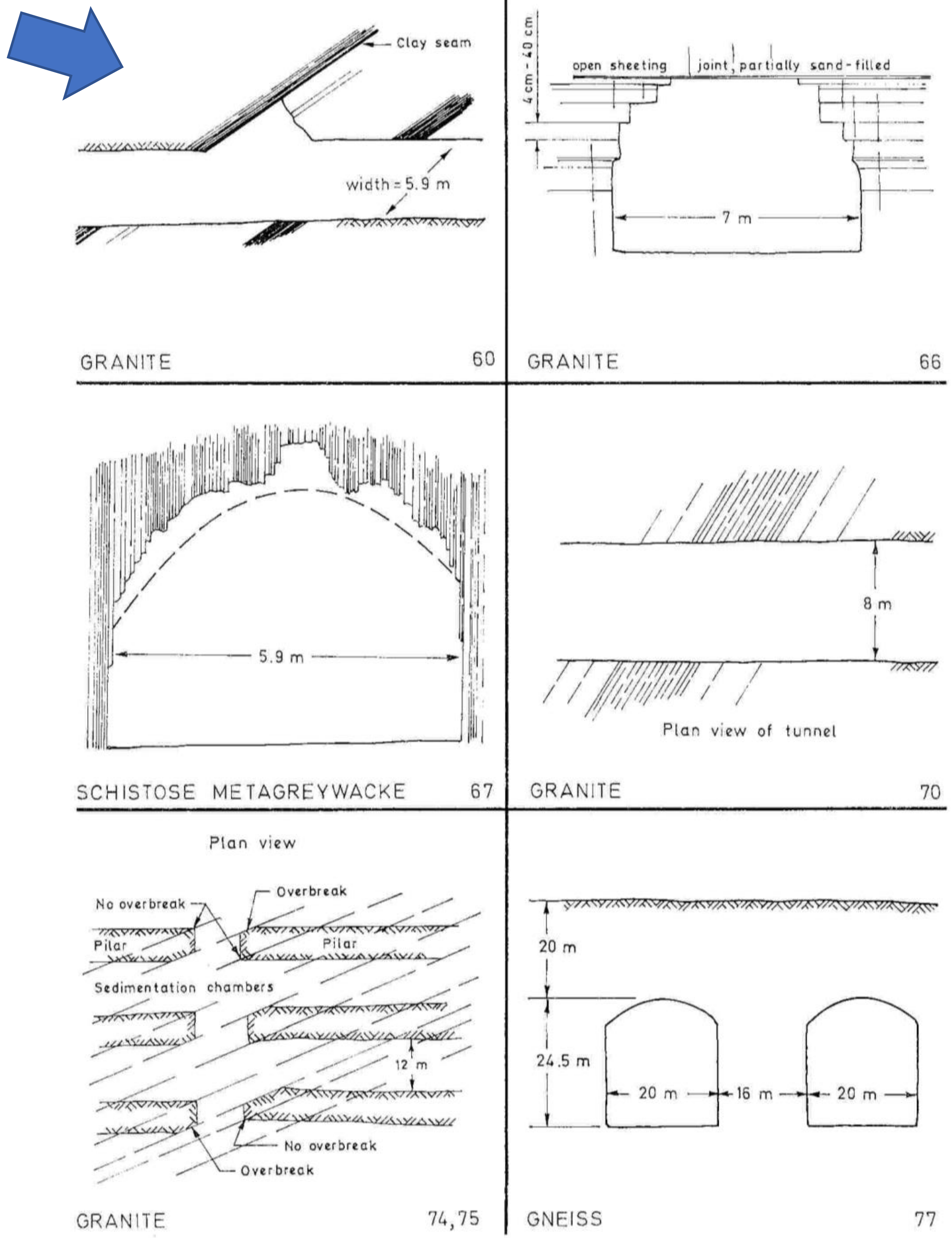


Fig. 8. Sketches of the six case records described in Table 9, after Cecil (1970)

Cecil, 1970 case records

(this selection reproduced in Barton, Lien, Lunde, 1974)

Table 8. Classification and Prediction of Support for Six of the Case Records Described by Cecil (1970)

Case No.	1. DESCRIPTION OF ROCK MASS 2. Nature of instability 3. Purpose of excavation, location, reference	SPAN m	Height m	Depth m	Support used	RQD / J_n	J_r / J_a	J_w / SRF	Q	ESR	SPAN/ESR m	Roof Support Recommendation
8	1. 50 m length of closely spaced, tight diagonal joints in leptite. Planar, smooth joints. 1 joint set, 5—30 cm, spacing. No water present. 2. Minor overbreak when blasting. 3. Tailrace tunnel, Seitevare Hydro. N. Sweden (ref. Cecil 1970).	9	9	140	None	70/2	1.0/1.0	1.0/1.0	35	1.6	5.6	Category 0
24	1. 60 m length, including a 1 m wide shear zone in mylonite. Crushed mylonite and non-softening clay seams and joint fillings. Intersecting joint set. 2 joint sets plus random, 5—30 cm spacing. Minor water inflows (<31/min). 2. Wedge shaped roof fall. 3. Headrace tunnel, Vietas Hydro, N. Sweden (ref. Cecil 1970).	12.5	6.5	60	Rock bolts, wire mesh and shotcrete	60/6	1.0/6	1.0/2.5	1.3	1.6	7.8	Category 22 =B 1 m +S (mr) 2.5—5 cm
39	1. 50 m length, shear zone in quartzite, "sugar cube" rock structure. Planar, smooth, unaltered joints. 3 joint sets, <5 cm, spacing. 5—10 l/min water inflow. 2. Major roof falls, progressive formation of dome- and vault-shaped crown. Also falls from the face. 3. Headrace tunnel, Rendal Hydro, Norway (ref. Cecil 1970).	8	6	200	Cast concrete arch, immediately after mucking out	20/15	1.0/1.0	0.66/5	0.18	1.6	5.0	Category 31 =CCA 20—30cm +B 1 m
43	1. 25 m length, 3 m wide shear zone in thinly laminated schist, swelling montmorillonitic clay seam in shear zone, some chlorite joint coatings. Planar slickensided joint walls. 1 joint set, 5—30 cm spacing. Ground water seepage along cased de-air hole may have contributed to swelling process. 2. Complete collapse of tunnel during operation of power plant. Vault-shaped crown opening. 3. Tailrace tunnel, Sällsjö Hydro, N. Sweden (ref. Cecil 1970).	9	8	110	Original 6—8 cm shotcrete failed. Permanent support after failure with cast concrete arches	20/2	0.5/12	1.0/2.5	0.17	1.6	5.6	Category 31 =CCA (sr) 30 cm +B 1 m
48	1. 15 m length, overthrust shear zone in schist, in which there was a 3 cm thick clay (non softening) and graphite seam. Shear zone was 50—100 cm wide and contained smooth, slickensided graphite-coated joint surfaces, 1 joint set, 5—30 cm spacing. Insignificant water inflow. 2. Wedge-shaped roof fall. 3. Tailrace tunnel, Bergvattnet Hydro, N. Sweden (ref. Cecil 1970)	6.5	4.5	50	Rock bolts, wire mesh and two shotcrete applications	10/2	1.0/10	1.0/5	0.10	1.6	4.1	Category 31 =B 1 m +S (mr) 5 cm
56	1. 20 m length, 10 m wide vertical shear zone in granite. Rock crushed and frequently altered to earthy-gravel. Some remnant joint surfaces coated with clay (non-softening). Rock adjacent to zone blocky and loose. Irregular slickensided joint surfaces, 5—30 cm spacing. Large water inflows after blasting carried fault zone debris into tunnel, left open voids up to 1 m wide. *Note:* Tunnel located within 10 km of a major overthrust sheet, locally vertical and low angle shear zones occur. 2. Progressive roof fall-out to form a large vault-shaped opening. 3. Headrace tunnel, Stensjöfallet Hydro, N. Sweden (ref. Cecil 1970).	5.9	4.3	100	No support immediately after blasting. Eventually two shotcrete applications	10/20	1.5/6	0.33/2.5	0.017	1.6	3.7	Category 34 =S (mr) 7.5 cm

Note: Right-hand column "Roof Support Recommendation" is obtained from Tables 11, 12, 13, and 14

Key: S = shotcrete, B = systematic bolting, sb = spot bolting, CCA = cast concrete arches, mr = mesh reinforced, sr = steel reinforced, clm = chain link mesh.

Bolt spacing is given in metres. — Shotcrete or concrete thickness is given in centimeters.

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60	1. 20 m length, 1 m wide zone of sheared granite with clay seams (non-softening) slide boundary is a thin (<1 cm) clay seam and thinly sheared material that lie in contact with massive rock. Planar, slickensided joints. 1 joint set, 5—30 cm spacing. Insignificant inflow of water. See note, case 56. 2. Wedge-shaped roof fall. 3. Headrace tunnel. Stensjöfallet Hydro. N. Sweden (ref. Cecil 1970).	5.9	4.3	85	Rock bolts, and shotcrete	80/2	0.5/6	1.0/2.5	1.3	1.6	3.7	Category 21 =B 1 m +S 2.5 cm
66	1. 80 m length, open horizontal sheeting joints in granite, partially filled with sand sized material. Planar, rough surfaced joints. 2 joint sets, 5—30 cm spacing. Insignificant water inflow. See note, case 56. 2. Overbreak above springline. 3. Access tunnel, Stensjöfallet Hydro. N. Sweden (ref. Cecil 1970).	7	4.5	15—20	Rock bolts and shotcrete	70/4	1.5/2	1.0/5	2.6	1.3	5.4	Category 21 =B 1 m +S 2.5 cm
67	1. 50 m length, close vertical jointing cutting across schistose rock structure in schistose metagreywacke. Sandy, gravelly joint fillings. Planar smooth surface joints. 1 joint set plus random (for schistocity planes), 5—30 cm spacing. Water inflows up 1000 l/min. 2. Large overbreak in intrados, some roof falls. 3. Railrace tunnel, Stensjöfallet Hydro. N. Sweden (ref. Cecil 1970).	5.9	4.8	100	Shotcrete	20/3	1.0/2	0.2/1.0	1.7	1.6	3.7	Category 21 =S 2.5 cm
70	1. 10 m length, strongly sheared granite, very tight vertical structure. Planar, rough surfaced, unaltered joints. 1 joint set, 5—30 cm spacing. Insignificant water inflow. 2. Stable, minor overbreak, no roof falls. 3. Collector tunnel, Mo i Rana Hydro. N. Norway (ref. Cecil 1970).	8	5.7	15	None	40/2	1.5/1.0	1.0/2.5	12	1.6	5.0	Category 0 Note: Very tight structure may imply higher stress, i. e. *SRF*=1.0 Hence Q=30
74 75	1. Approx. 2 km length, massive granite, widely spaced, tight, vertical joints. Planar, smooth-surfaced unaltered joints. 1 joint set, 1—3 m spacing. Insignificant water inflow. 2. No overbreak in chambers, but overbreak at intersections. 3. Waste water treatment plant, Käppala. Sweden (ref. Cecil 1970).	12	12.5	≤100	None in chambers	100/2	1.0/1.0	1.0/1.0	50	1.3	9.2	Category 0,9 =NONE or sb
					Bolts at intersections	100/2×3	1.0/1.0	1.0/1.0	16.7	1.0	12.0	Category 14 =B 1.5—2 m +clm
77	1. 300 m length, massive gneiss, few joints. Planar, rough-surfaced, unaltered joints. >3 m spacing. Insignificant water inflow. 2. Minor overbreak, no falls or slides. 3. Wine and liquor storage rooms. Stockholm (ref. Cecil 1970).	20	24.5	18	50 spot bolts in about 300 m of chamber	100/1.0	5/1.0	1.0/2.5	200	1.3	15.4	Category 0,5 =None or sb

Note: Right-hand column "Roof Support Recommendation" is obtained from Tables 11, 12, 13, and 14.

Key: S = shotcrete, B = systematic bolting, sb = spot bolting, CCA = cast concrete arches, mr = mesh reinforced, sr = steel reinforced, clm = chain link mesh.

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Table 9. Classification and Prediction of Support for Six of the Case Records Described by Cecil (1970)

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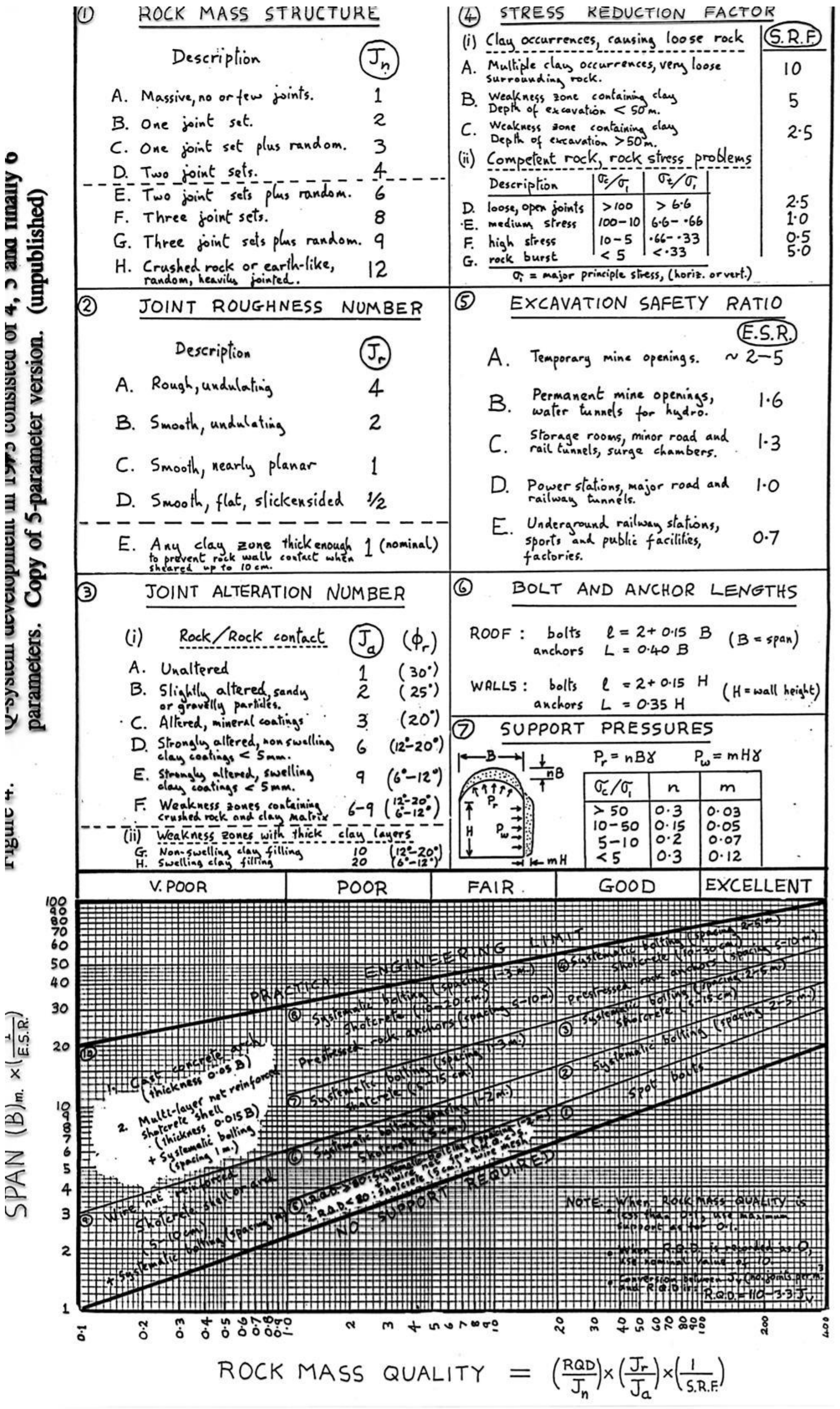
60	1. 20 m length, 1 m wide zone of sheared granite with clay seams (non-softening) slide boundary is a thin (< 1 cm) clay seam and thinly sheared material that lie in contact with massive rock. Planar, slicken-sided joints. 1 joint set, 5—30 cm spacing. Insignificant inflow of water. See note, case 56. 2. Wedge-shaped roof fall. 3. Headrace tunnel. Stensjöfallet Hydro. N. Sweden (ref. Cecil 1970).	5.9	4.3	85	Rock bolts, and shotcrete	$\frac{80}{2}$	$\frac{0.5}{6}$	$\frac{1.0}{2.5}$	1.3	1.6	3.7	Category 21 = B 1 m + S 2.5 cm

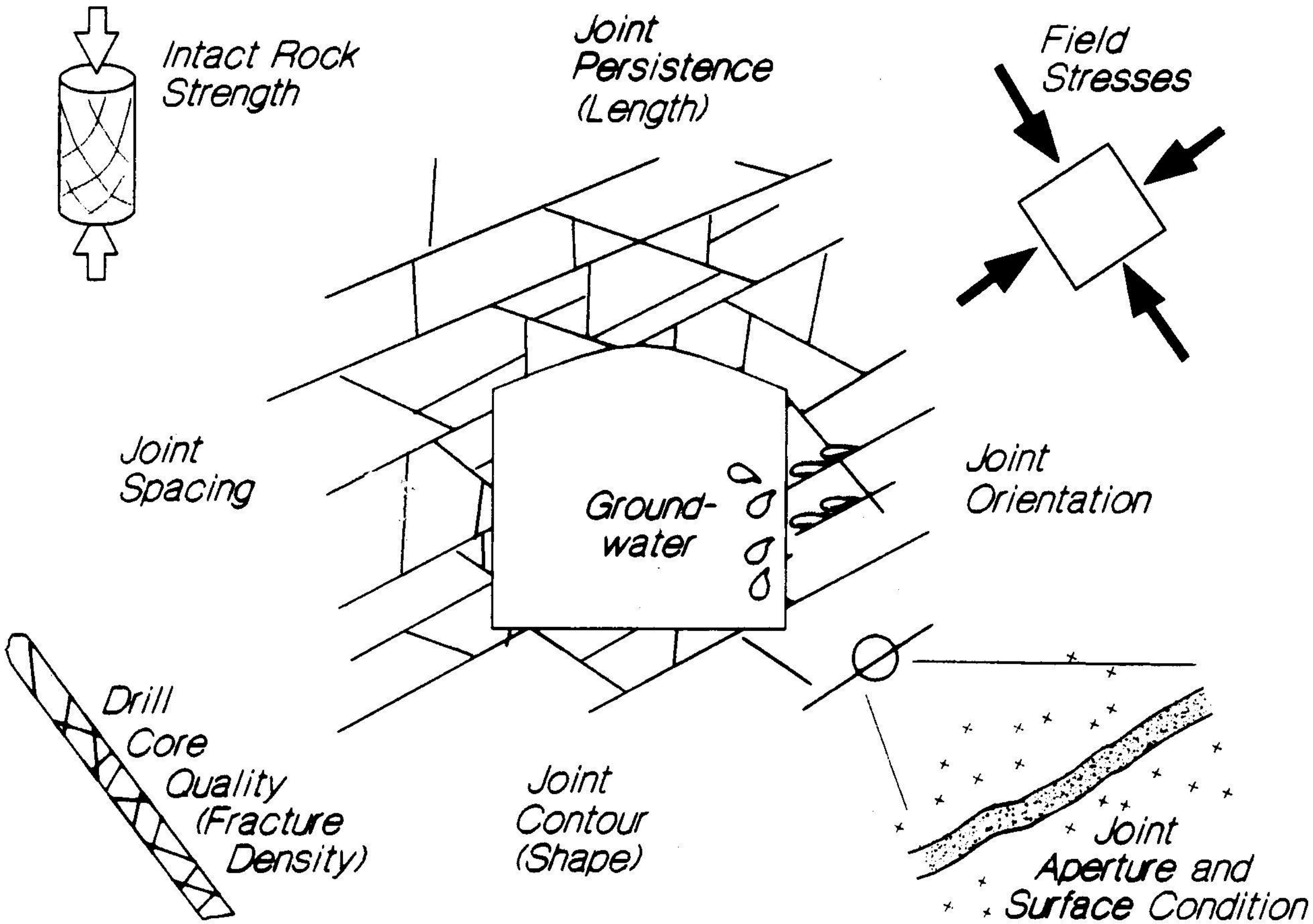
SUMMARIZED DETAIL OF ONE OF CECIL, 1970 CASE RECORDS – AND Q-SYSTEM INTERPRETATION

An early version of ‘Q’ in 1973 (Note: RQD assumed – obviously)



RQD HAS A PERMANENT ROLE IN
Q, Q_{TBM}, Q_{slope}, Q_{H2O}

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF}$$



Hutchinson and Diederichs, 1996

SO WHAT IS THE 'Q-system' ?

- *Hellenic Society Soil Mech./Geotech.*
- *engineers may not be familiar with 'Q'*

HELLENIC SOCIETY FOR SOIL MECHANICS & GEOTECHNICAL ENGINEERING

Q used here!

As a briefest introduction:

Q means *rock mass quality*.

Q consists of *ratings for six parameters*.

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$ **= ('Block size') x ('friction') x ('active stress')**

SUGAR LOAF MOUNTAIN,
RIO DE JANEIRO

TOP END OF ROCK MASS QUALITY SCALE.

$Q \approx \underline{100}/0.5 \times 4/0.75 \times 1/1$

i.e. >1000

BRAZILIAN HYDROPOWER PROJECT COLLAPSE IN FAULT

LOWEST END OF THE ROCK MASS QUALITY SCALE.

$Q \approx \underline{10}/20 \times 1/8 \times 0.5/20$

i.e. < 0.001

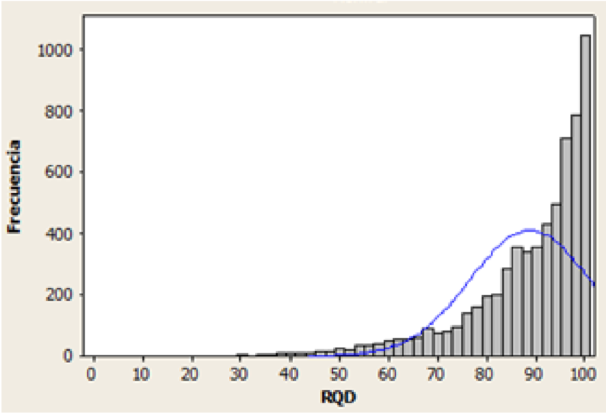
THE FIRST TWO PAIRS OF PARAMETERS HAVE DIRECT PHYSICAL MEANING:

RQD / Jn = relative block size

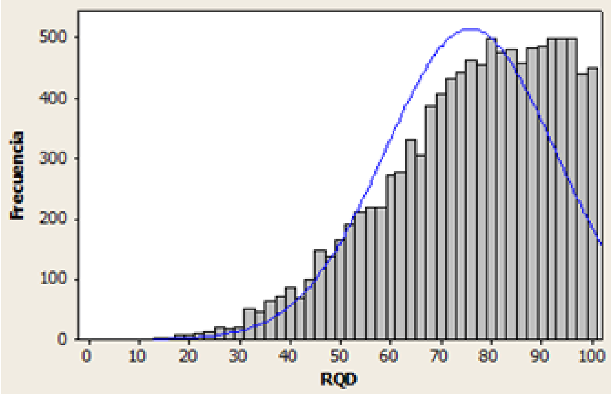
Jr / Ja = frictional strength (≈ μ)

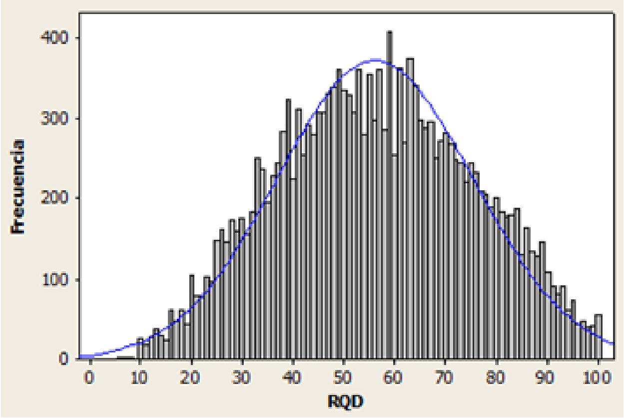
Jw / SRF = effects of water, faulting, strength/stress ratio, squeezing or swelling (an 'active stress' term)

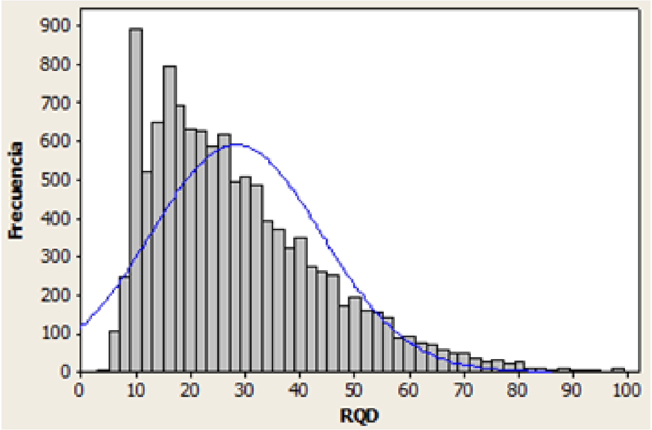
Q-classes with respective RQD distributions and Q-ranges:
0.1-1, *1-4*, 4-10, 10-40
(part of 340 km of core logging at mine, by 12 to 15 engineering geologists)



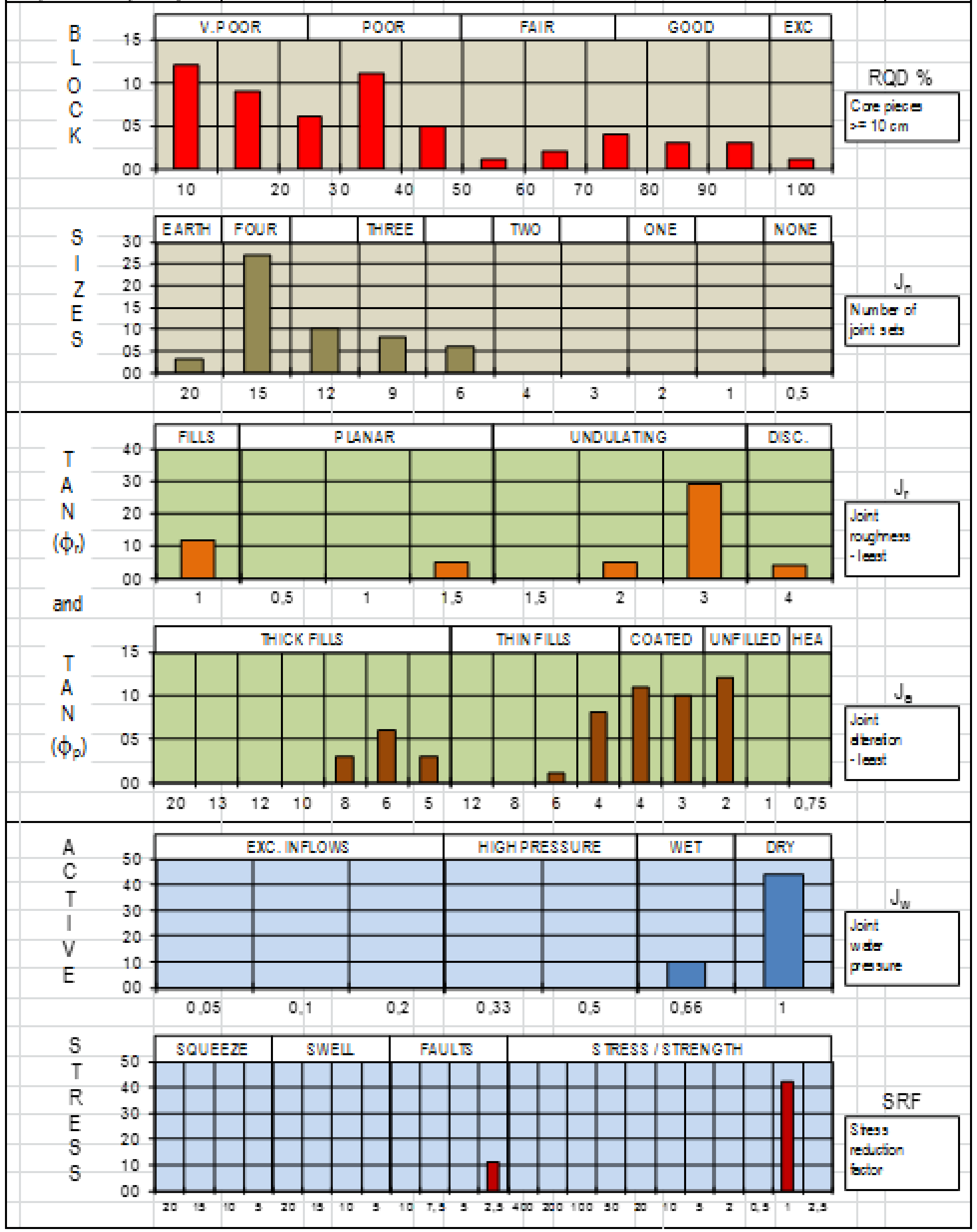
Demonstrates central role played by RQD in (> 40 km of core)







Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,0	/	6,0	*	0,66	/	2,5	=	0,029
Q (typical max)=	75	/	6,0	*	4,0	/	2,0	*	1,00	/	1,0	=	25,0
Q (mean value)=	38	/	12,8	*	2,4	/	3,9	*	0,94	/	1,3	=	1,29
Q (most frequent)=	10	/	15,0	*	3,0	/	2,0	*	1,00	/	1,0	=	1,00



I ROCK MASS STRUCTURE

1	RQD	Deere et al., 1967)		block { Q
2	J_n	=	joint set number	size { Q
3	F	=	joint frequency (per metre)	
4	J_v	=	volumetric joint count (Palmström, 1982)	
5	S	=	joint spacing (in metres)	
6	L	=	joint length (in metres)	
7	w	=	weathering grade (ISRM, 1978)	
8	α/ß	=	dip/dip direction of joints (Schmidt diagram)	

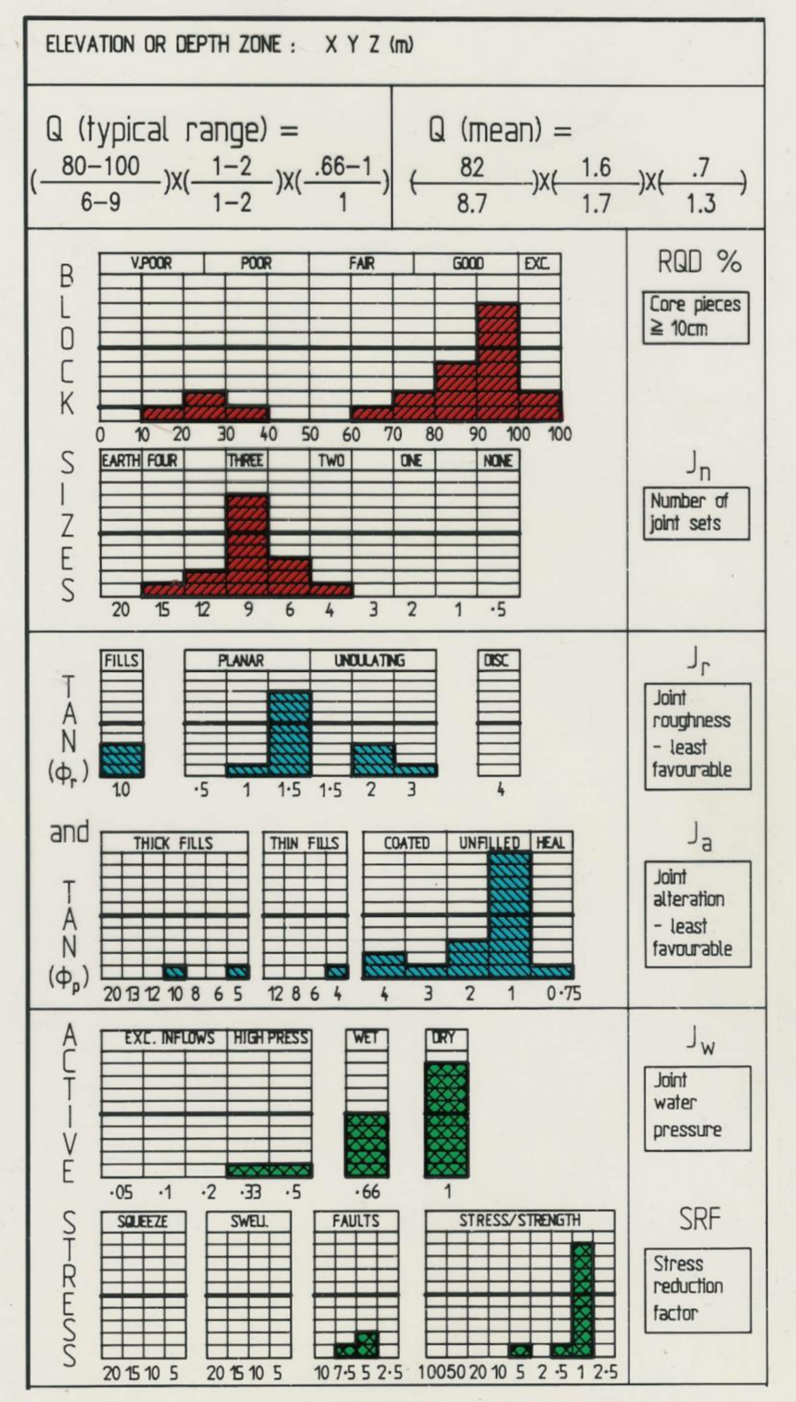
II JOINT CHARACTER

9	J_r	=	joint roughness number	shear { Q
10	J_a	=	joint alteration number	strength { Q
11	JRC	=	joint roughness coefficient	
12	a/L	=	roughness amplitude of asperities per unit length (mm/m)	
13	JCS	=	joint wall compressive strength	
14	ϕ_r	=	residual friction angle	
15	r,R	=	Schmidt rebound values for joint and rock surfaces	

III WATER, STRESS, STRENGTH

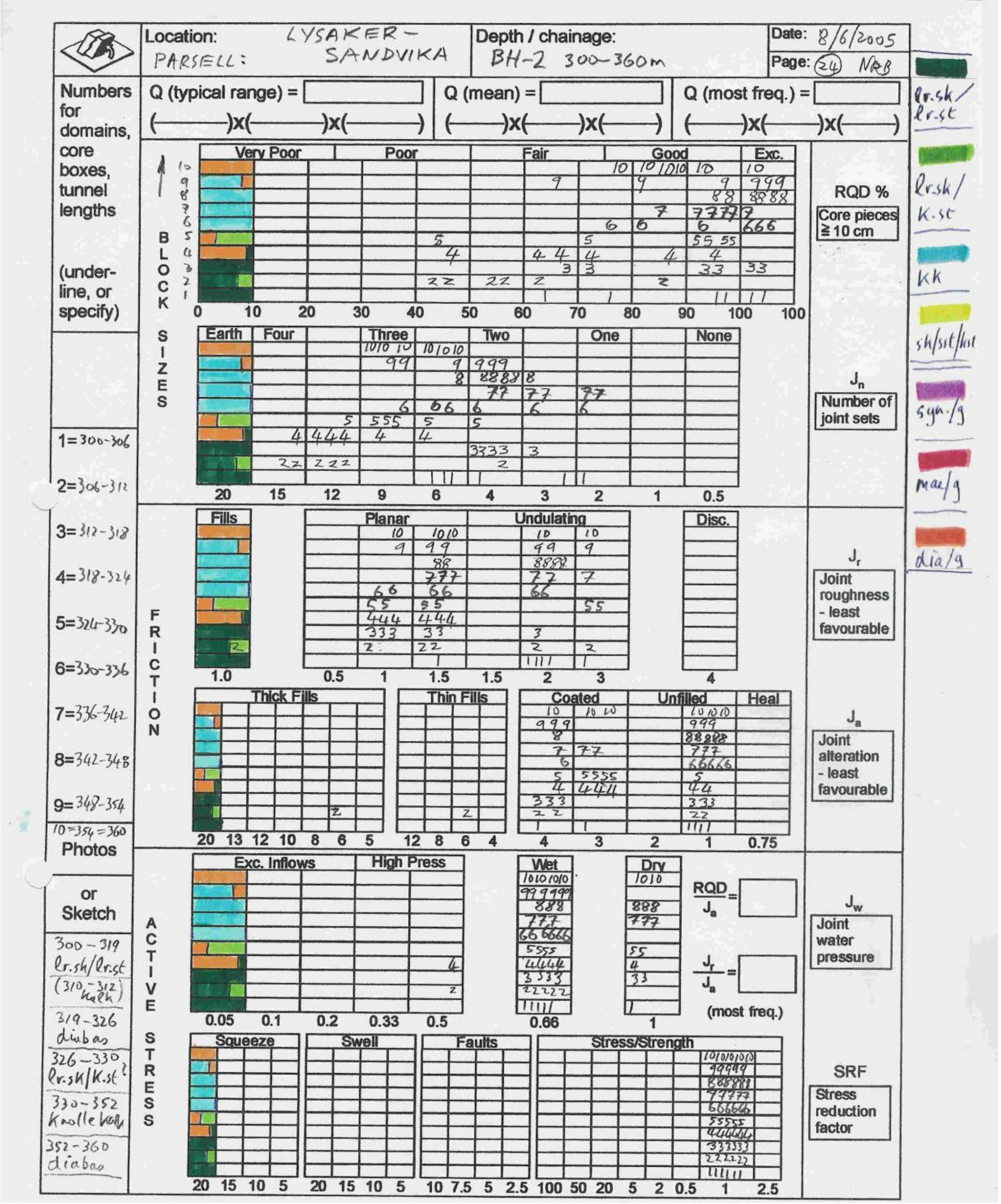
16	J_w	=	joint water reduction factor	active { Q
17	SRF	=	stress reduction factor	stress { Q
18	K	=	rock mass permeability (m/s)	
19	σ_c	=	compressive strength	
20	σ_1	=	major principal stress	

Q IS ONLY PART OF A ROCK MASS DESC-RIPTION EXERCISE

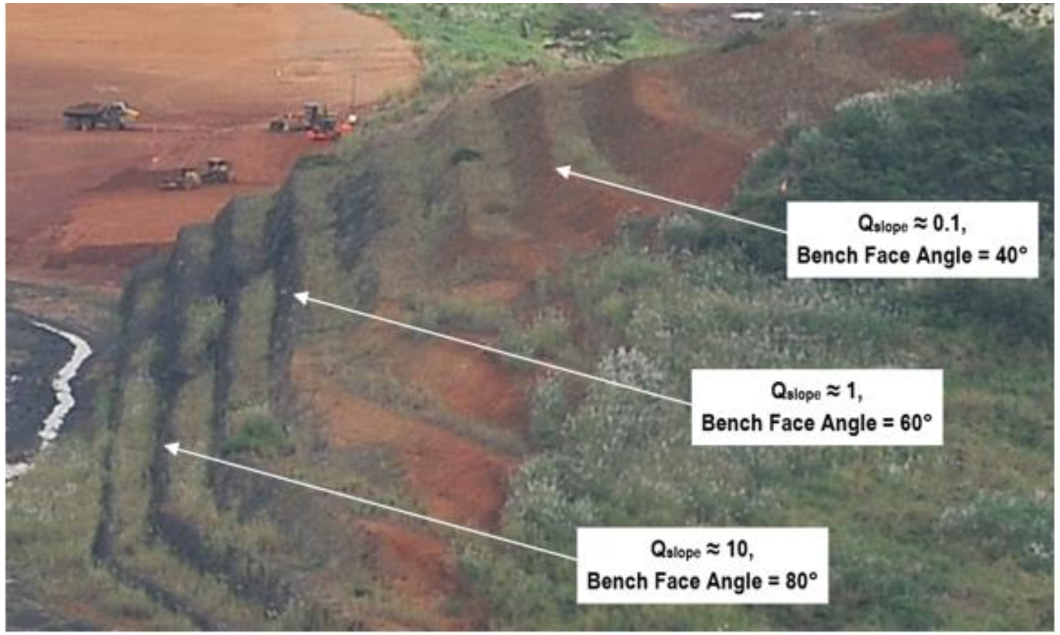


Q-histogram method of recording data.

RQD is frequently the most variable parameter



Q-slope



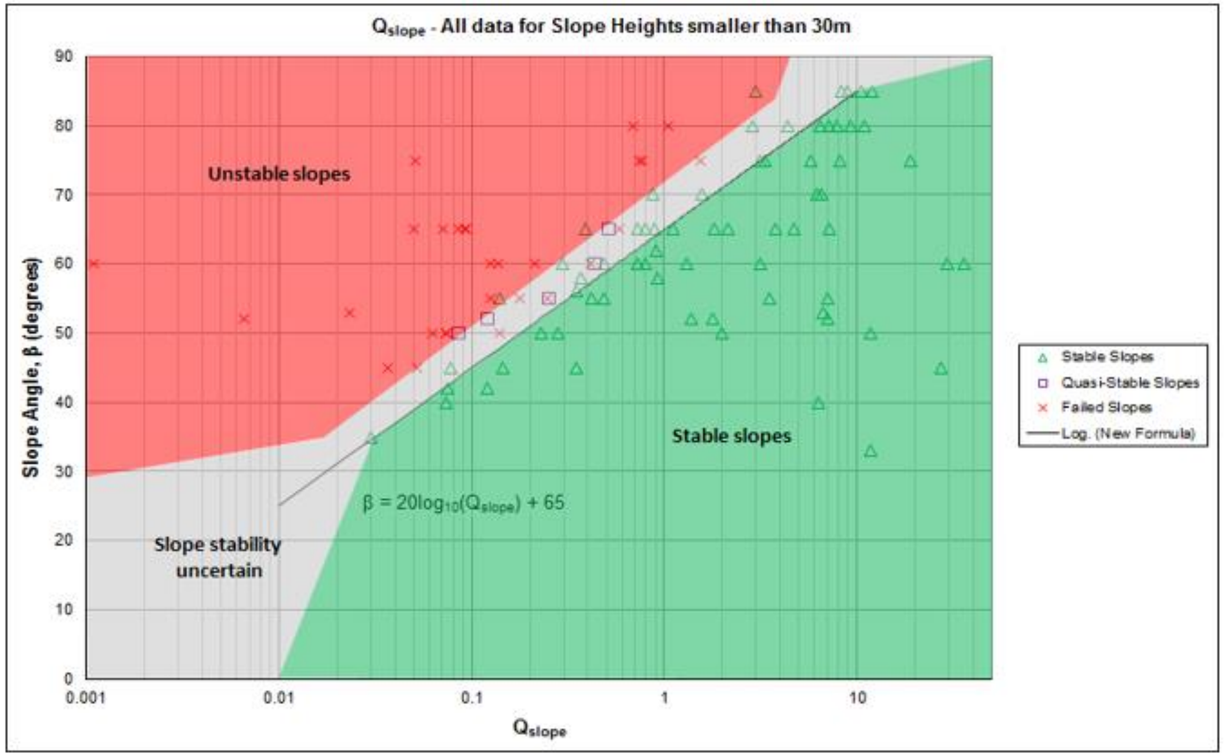
Q-SLOPE METHOD

(Barton and Bar, 2015)

Q-slope = 0.01 : slope angle ≈ 25°
Q-slope = 0.1 : slope angle 45°
Q-slope = 1.0 : slope angle 65°
Q-slope = 10 : slope angle 85°

$$Q_{slope} = \frac{RQD}{J_n} x \left(\frac{J_r}{J_a}\right)_0 x \frac{J_{wice}}{SRF_{slope}}$$

$$\beta = 20\,log_{10}\,Q_{slope} + 65°$$

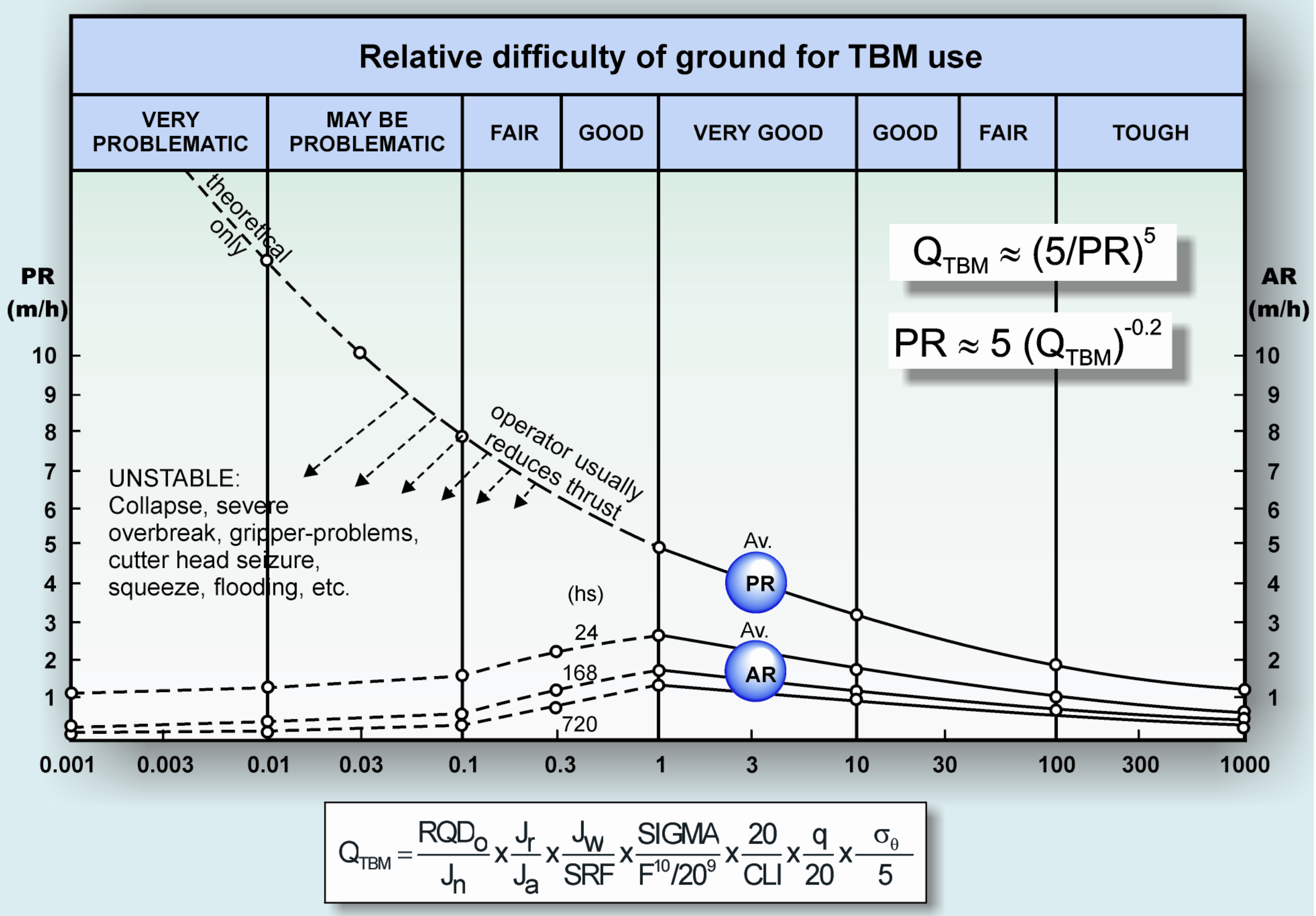


Case Study 3: Q-slope mining application

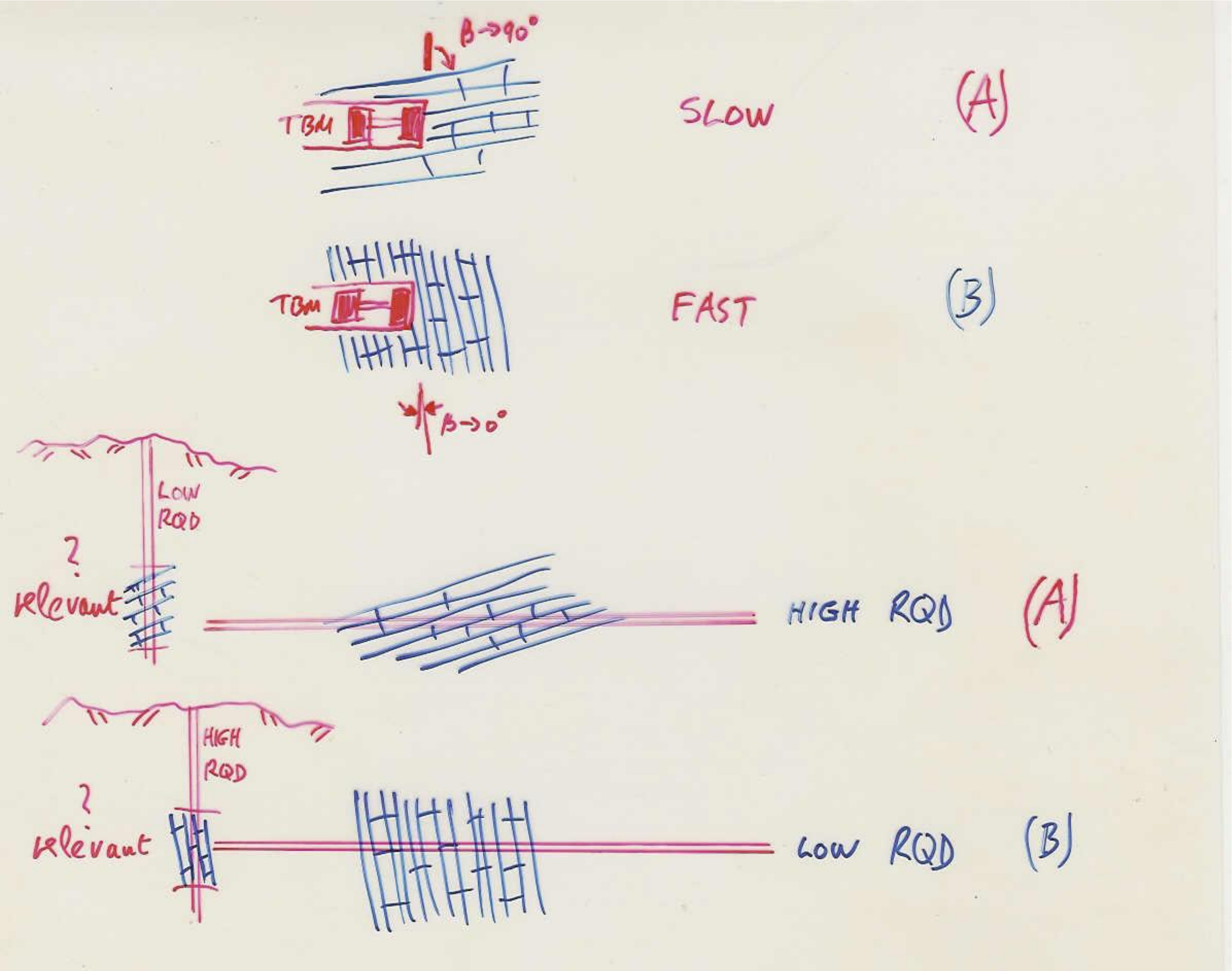
Local	RQD (%)	Jn	Jr	Ja	0-factor	Jwice	SRFa	SRFb	SRFc	Q-slope	β (slope angle °)
1	10-25	6	1	4	0.5	0.5	2.5	1	N/A	0.0729	**42**
2	10-25	6	1	3	0.75	0.5	2.5	2	N/A	0.1458	**48**
3	25-50	9	2	3	0.75	0.5	2.5	2	N/A	0.4166	**57**

- RQD improves with depth
- Orientation factor improves with depth (bedding)

QTBM



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



Important to use RQD as a directional parameter (when needed)

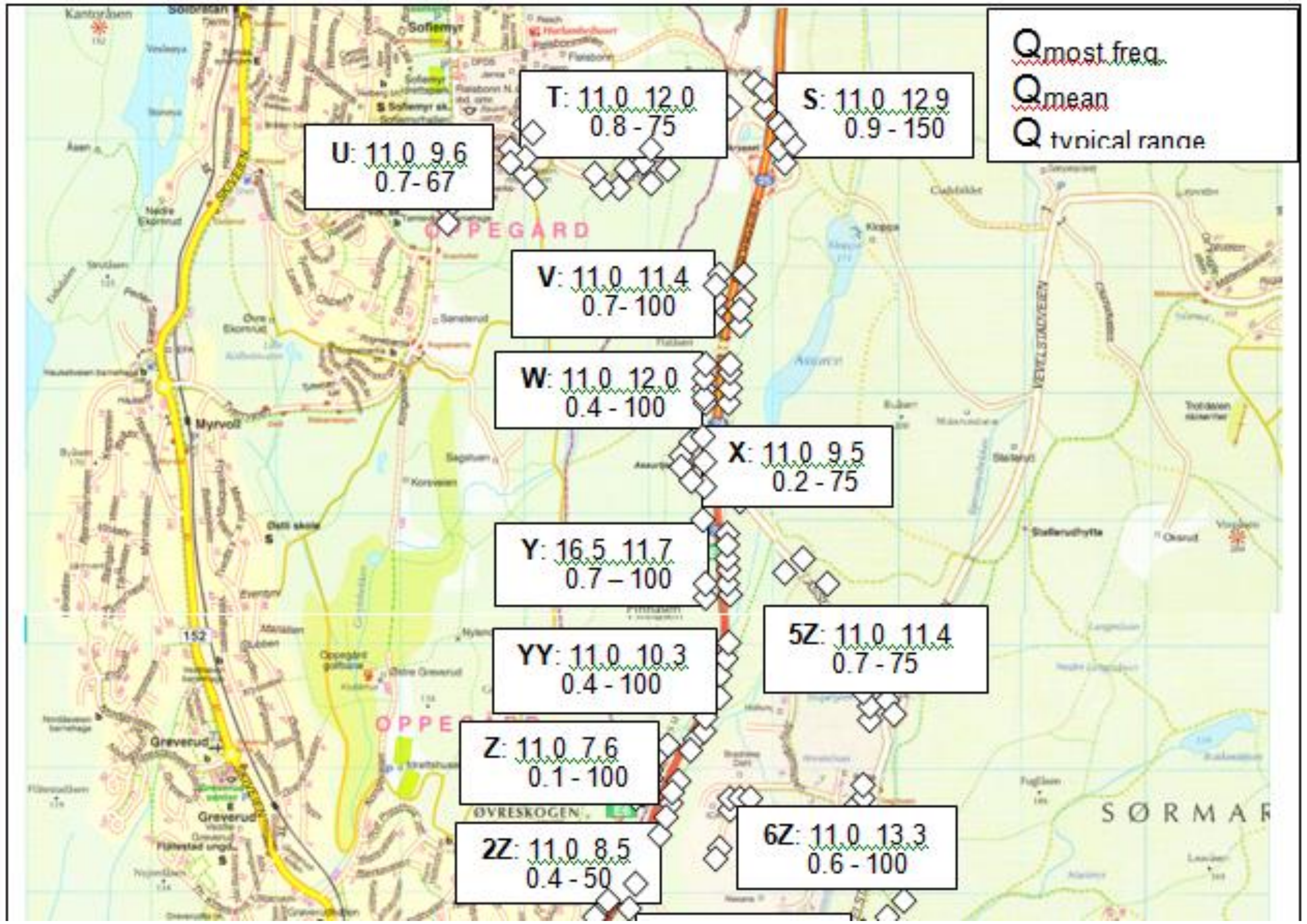


Figure A20. Locations U1 to U8. Sofiemyr, mostly near Brannstasjon.

A selection of the 300+ locations which were Q-logged

Summing the raw data

Location: TUNNEL-SOUTH JBV ÅSLAND–LANGHUS | Depth / chainage: ROCK EXPOSURES LOGGED | Date: 30-8-09 | Page: 40

Numbers for domains, core boxes, tunnel lengths (under-line, or specify)

All areas logged for T-S.

1=
2=
3=
4=
5=
6=

Q (typical range) = 0·1 — 100 $\left(\frac{75-100}{4-15}\right) \times \left(\frac{1-4}{1-5}\right) \times \left(\frac{0.5-1.0}{1.0}\right)$

Q (mean) = 11·1 $\left(\frac{98}{8.4}\right) \times \left(\frac{1.7}{1.3}\right) \times \left(\frac{0.75}{1.0}\right)$

Q (most freq.) = 11·0 $\left(\frac{100}{9}\right) \times \left(\frac{1.5}{1.0}\right) \times \left(\frac{0.66}{1.0}\right)$

RQD % (Core pieces ≥ 10 cm)

	Very Poor			Poor		Fair			Good		Exc.
	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	100
Σ				2	6	18	46	123	297	650	4807
HQR				1	1		1 2	6 2 2	15 6 6	27 23 15	176 190 137
TSU						1	1	6 3 1	12 14 9	29 40 20	221 213 240
VWX							2 2	3 6 6	14 13 13	28 27 31	225 222 218
Y5Z YY						2	1 1 4	4 4 7	13 10 18	30 34 32	192 221 202
Z6Z 2Z					3 1	5 1 2	8 3 3	11 5 7	17 13 14	27 31 36	199 216 208
7Z8Z3Z				1	1	3	4 3	1 9 7	11 14 12	23 27 29	235 181 219
11Z10Z4Z						3 1	2 4 3	7 10 6	12 15 14	24 34 32	115 204 214
12Z9Z							1	2 4	8 11	23 34	147 220
13Z						1	1	4	13	34	187

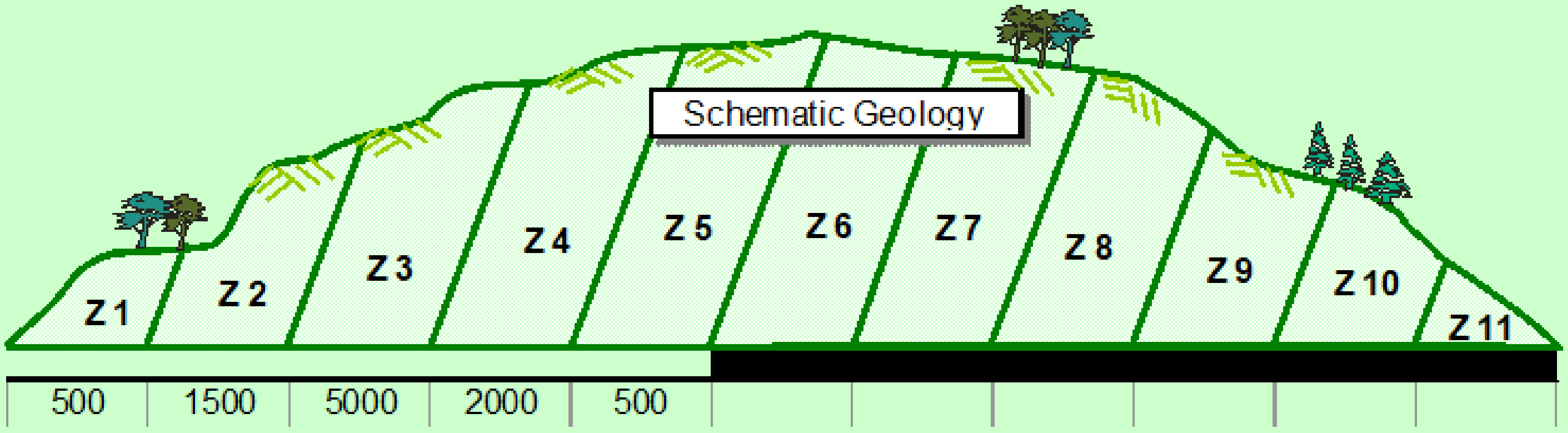
J_n (Number of joint sets)

	Earth	Four		Three		Two		One		None
	20	15	12	9	6	4	3	2	1	0.5
Σ		378	576	2966	1426	587	47	10		
HQR		5 2	11 5 8	152 45 48	51 61 70	6 93 34	19			
TSU		8 56	14 14 35	170 116 165	61 83 12	17 32 2	15	10		
VWX		16 9 8	32 18 24	121 109 165	89 85 58	12 49 15				
Y5Z YY		8 11 7	21 26 27	87 154 119	91 60 92	33 16 25	3			
Z6Z 2Z		19 11 15	42 35 27	122 99 194	68 73 32	19 50 2	2			
7Z8Z3Z		11 91 13	31 19 28	126 78 111	47 48 61	52 4 57	3			
11Z10Z4Z		16 15 25	17 32 42	71 191 148	43 30 48	13 2 7				
12Z9Z		32	11 35	91 153	59 46	16 4	3			
13Z			22	131	58	27	2			

J_r (Joint roughness - least favourable)

	Fills	Planar			Undulating			Disc.
	1.0	0.5	1	1.5	1.5	2	3	4
Σ	46		496	3675	2	1240	430	119
HQR	2		24 7 13	136 171 79		35 32 60	17 5 12	11 10
TSU			26 17 14	184 159 166		41 61 65	16 33 13	3 11
VWX	4 5		15 18 14	123 146 157	2	92 62 69	36 44 23	2
Y5Z YY	5		24 20 22	167 153 173		30 70 47	8 27 19	11 3 4
Z6Z 2Z	10 4		16 28 27	166 133 197		63 56 31	10 29 14	5 20
7Z8Z3Z	6		28 26 32	178 174 172		54 30 50	10 4 8	10 6 8
11Z10Z4Z	2 2 6		13 44 27	88 189 135		32 30 80	17 5 22	8
12Z9Z			5 22	79 184		70 41	21 23	5
13Z			14	170		39	14	2

Input-data screen for assumed Class 1 rock mass



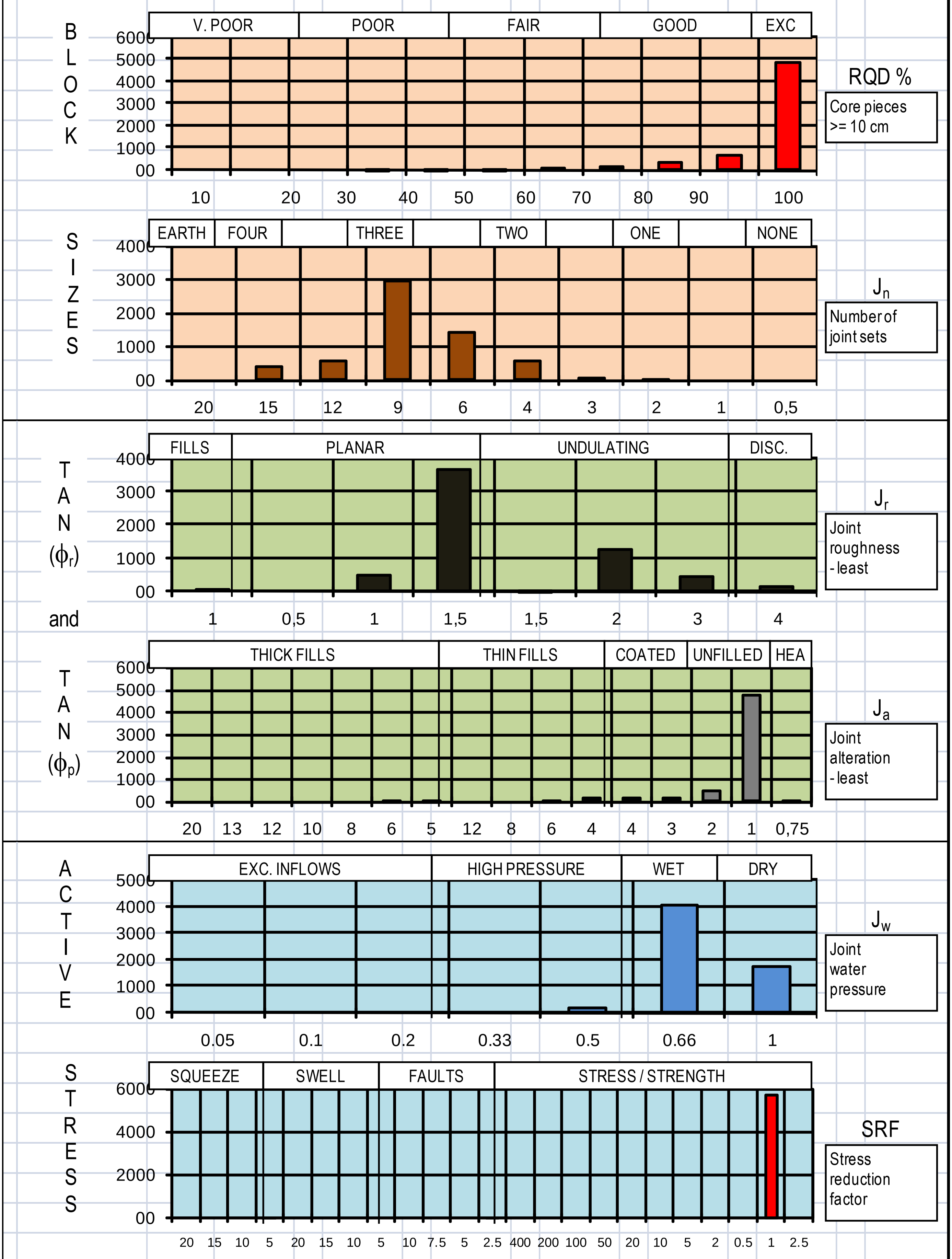
ZONE	5	LITHOLOGY	*Class 1 granitic gneiss*	ZONE LENGTH	*500*

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	2.0	3.0	1.0	1.00	1.0	-0.19	100.0	2.8	

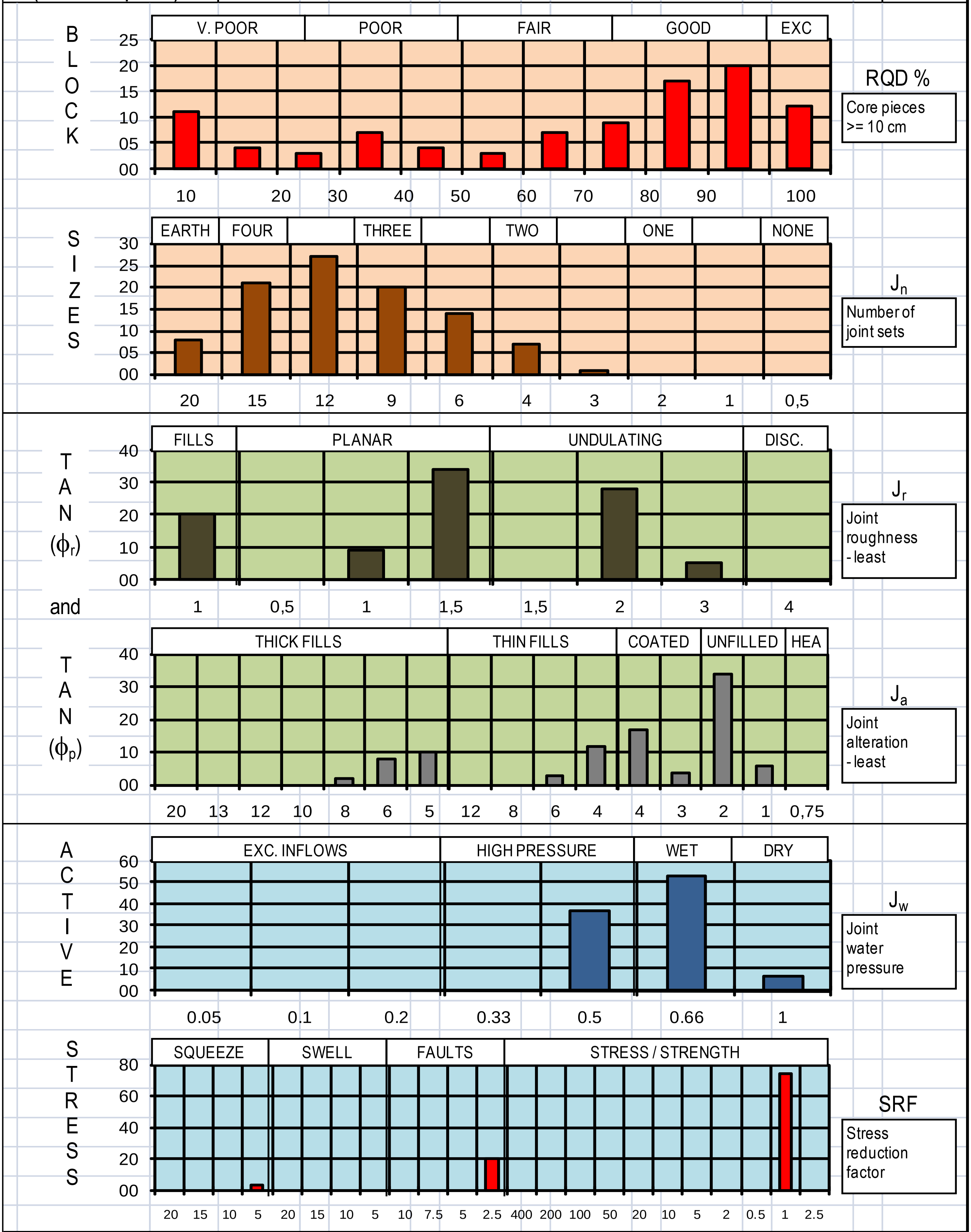
$\beta°$	σ_c (MPa)	I_{50} (MPa)	F (tf)	CLI	q %	σ_θ (MPa)	D (m)	n %
	250.0		32.0	5.0	35.0	8.0	10.0	1.0

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 logging for TUNNEL-SOUTH, therefore excluding core and weakness zones.	Borehole No. : Rock slopes	Drawn by NB&A	Date 31.8.09
	Depth zone (m) near-surface	Checked nrb	
		Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	20.0	*	1.0	/	8.0	*	0.50	/	5.0	=	**0.006**
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	1.0	=	**100.0**
Q (mean value)=	67	/	11.2	*	1.6	/	3.5	*	0.62	/	1.5	=	**1.16**
Q (most frequent)=	95	/	12.0	*	1.5	/	2.0	*	0.66	/	1.0	=	**3.92**



	Rev.	Report No.	Figure No.
JBV OSLO-SKI		NB&A #1	AA8
Q-histogram trends for selected core with weakness zones or faults: aggregate of seven holes.	Borehole No. : Seven holes	Drawn by NB&A	Date 1.9.09
	Depth zone (m) Range 18-144m	Checked nrb	
		Approved	

QH2O

Q_c	0.1	1	10	100
Lugeon	10	1	0.1	0.01
K(m/s) ≈	10^{-6}	10^{-7}	10^{-8}	10^{-9}
V_p (km/s)	2.5	3.5	4.5	5.5

Typical trends (of permeability) if no clay.

No clay present:

$L \approx 1/Q_c$

For hard, jointed, clay-free, rock masses)

(1 Lugeon ≈ 10^{-7} m/s ≈ 10^{-14} m^2 for water at 20°C)

Q_c = RQD/Jn x **Jr/Ja** x Jw/SRF x σ_c/100

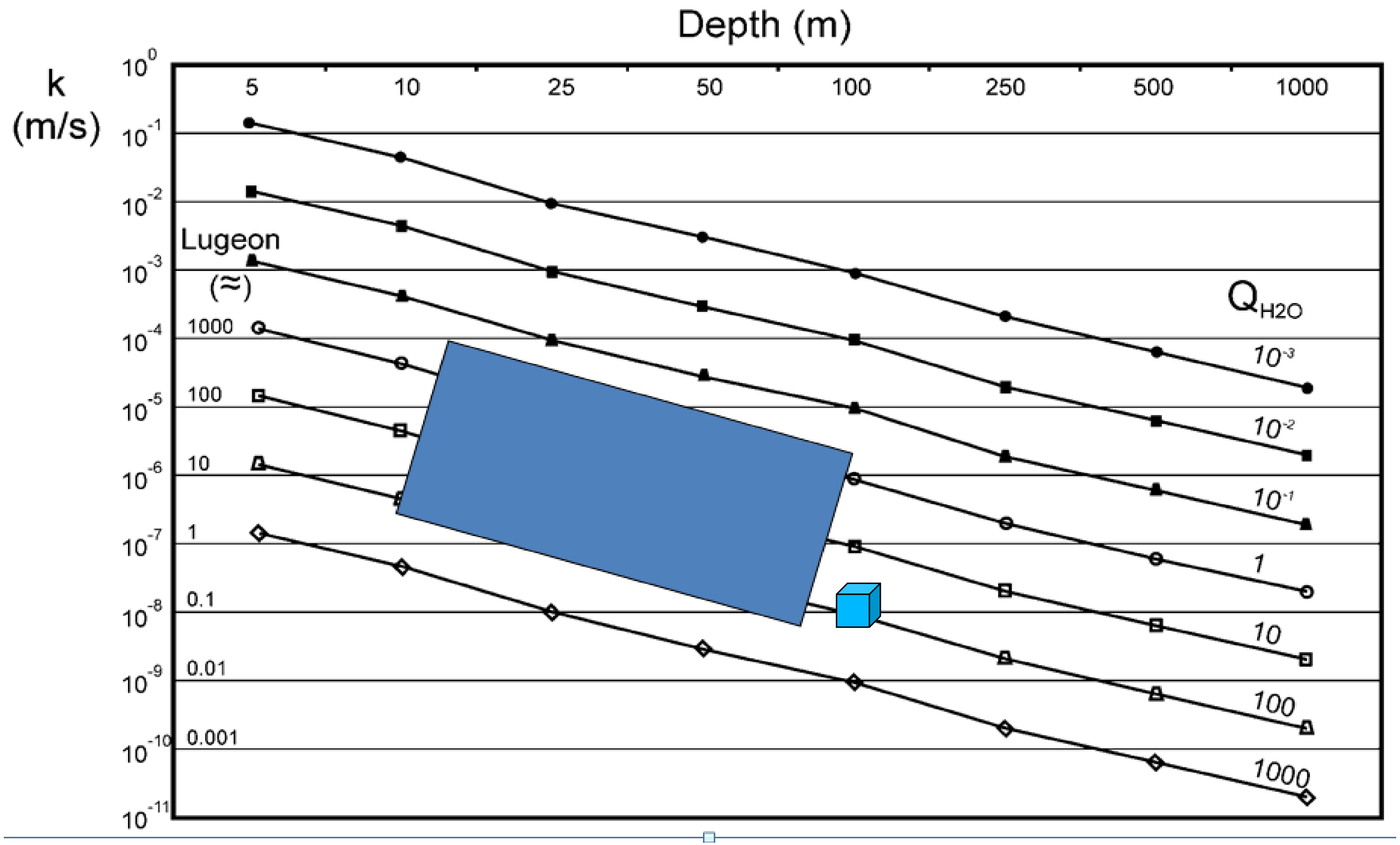
(standard equation, normalized by σ_c/100)

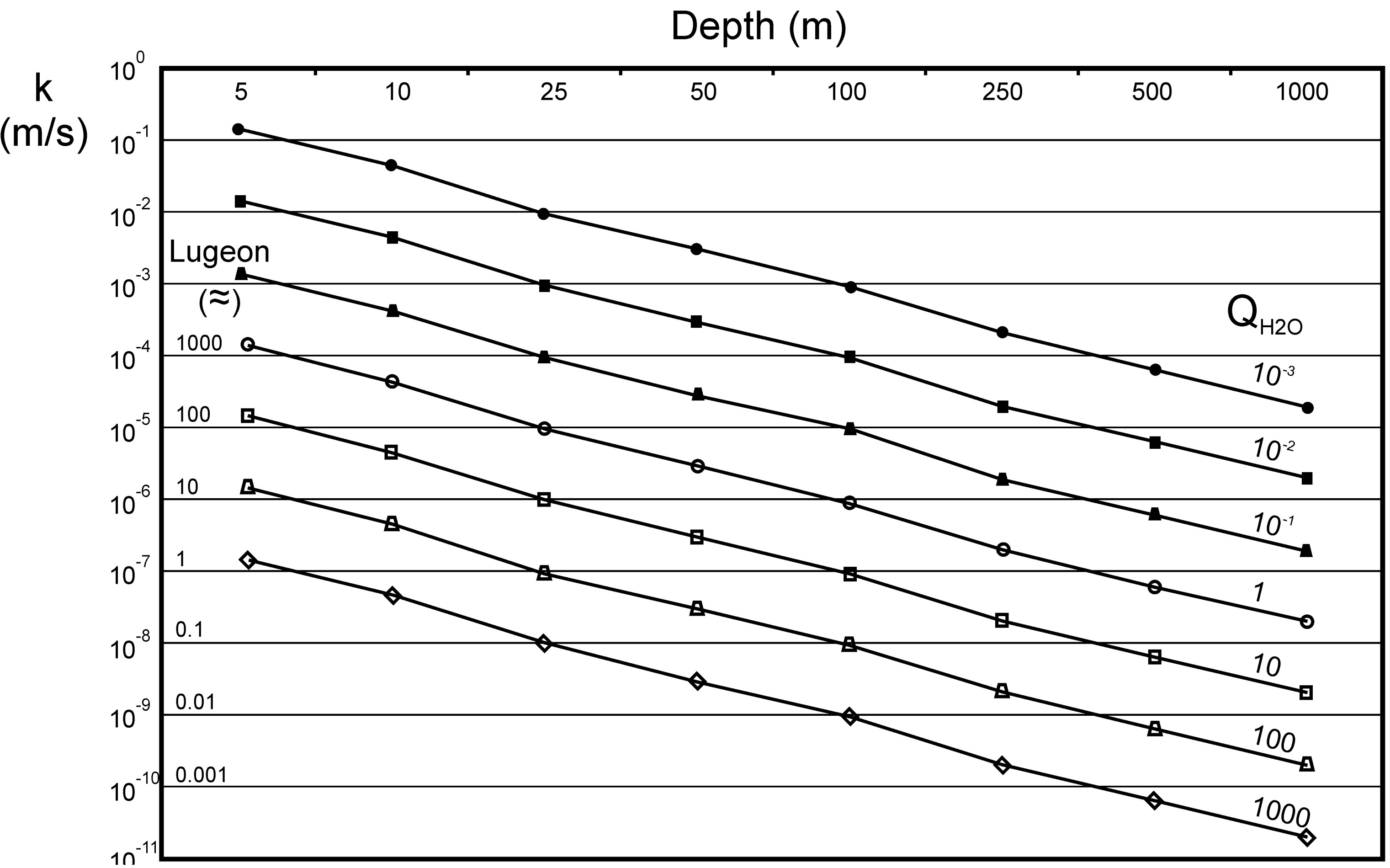
General case, with or without clay, with depth or stress allowance, *and consideration of* ***joint wall strength JCS***

Q_{H2O} = RQD/Jn x *Ja/Jr* x Jw/SRF x 100/JCS

$K \approx 0.002 / (Q_{H20} D^{5/3})$ m/s

USUAL RANGE OF K at DAM SITES





Example of Q_{H2O} estimation: Weak, well-jointed rock at 100 m depth with a low assumed joint-wall-compression-strength JCS of 10 MPa:

Regular Q-value =

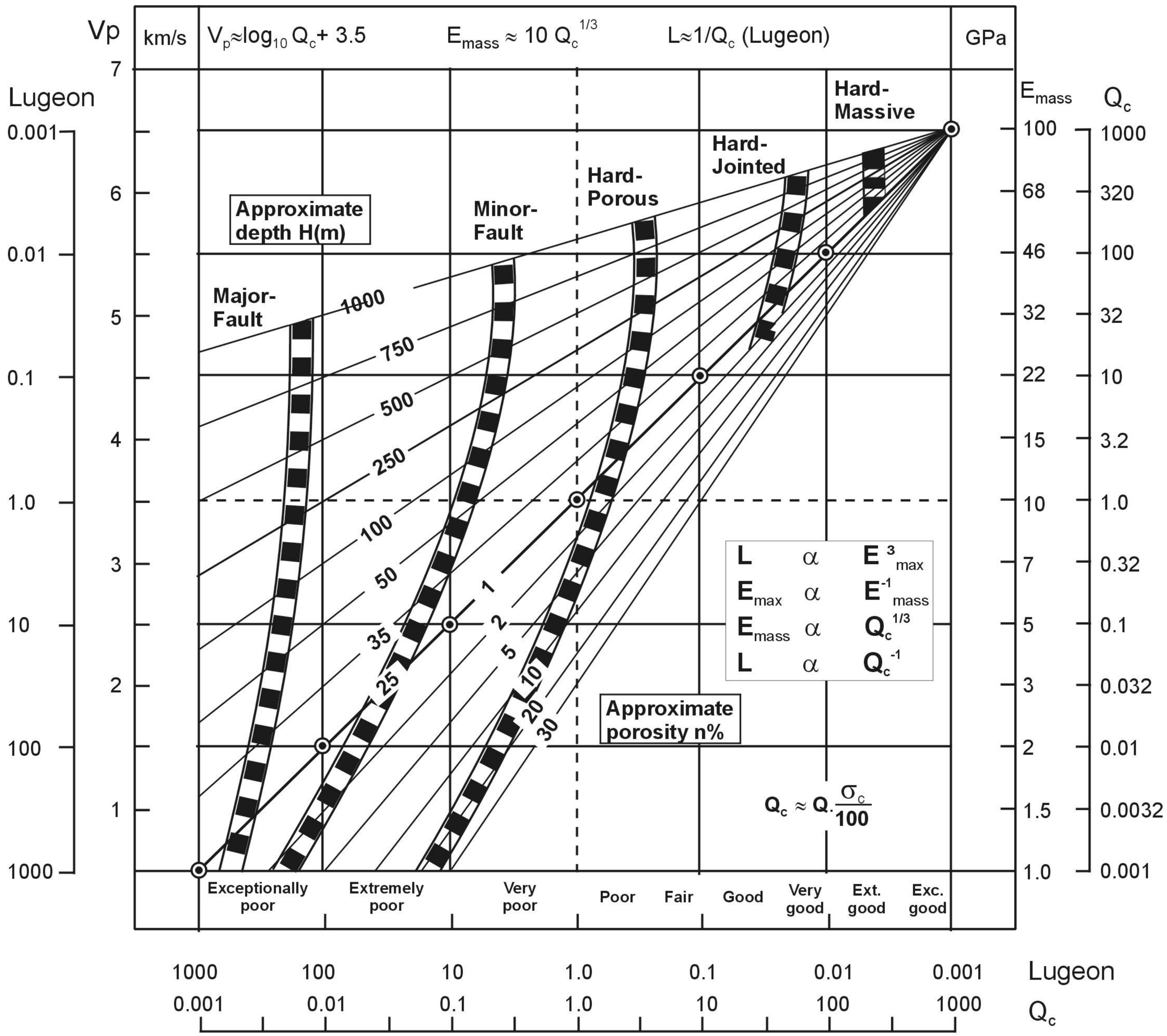
$$\frac{50}{9}\times\frac{1.5}{4}\times\frac{0.66}{1}$$

= 1.4, i.e. 'poor quality'

$$Q_{H_2O} = \frac{50}{9}\times\frac{4}{1.5}\times\frac{0.66}{1}\times\frac{100}{10} = 98$$

$$K \approx \left(\frac{2}{1000\times 98\times 100^{5/3}}\right) = 9\times 10^{-9}\ \text{m/s}$$

(Quite low permeability despite the extensively jointed nature of this rock mass, due to nearly closed, compressible, clay-coated joint walls).



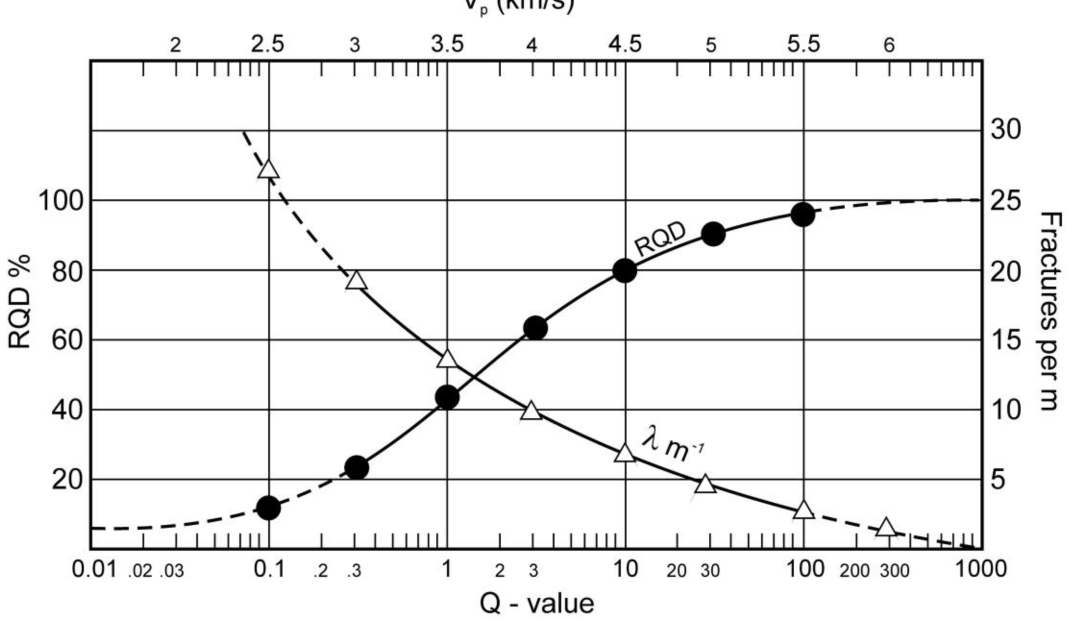
(Barton, 2006)

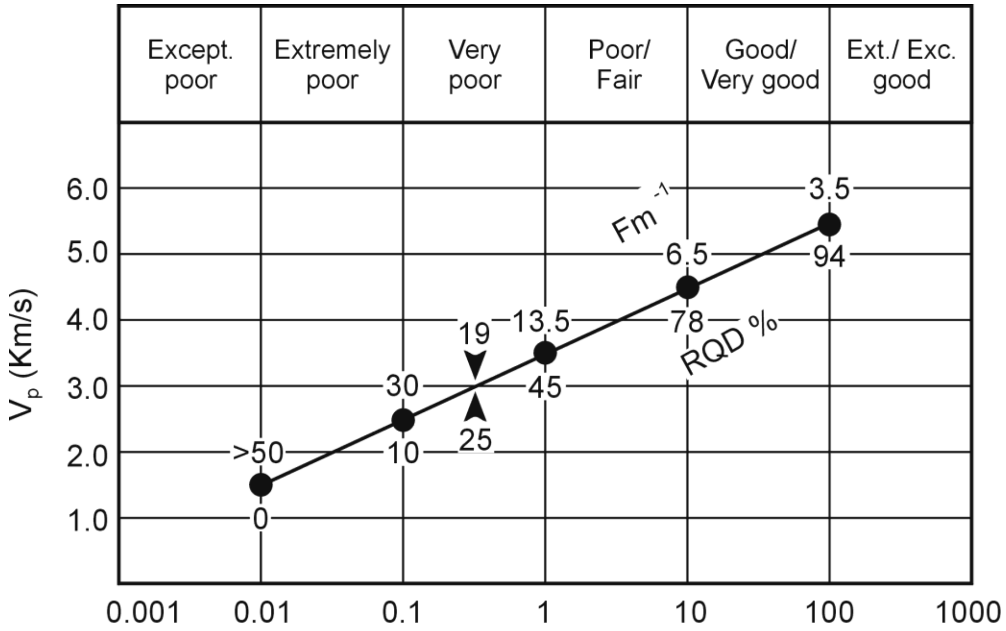
Attempts at an integrated rock-mass model

(RQD is of course embedded in Qc)

RQD and seismic velocity V_p

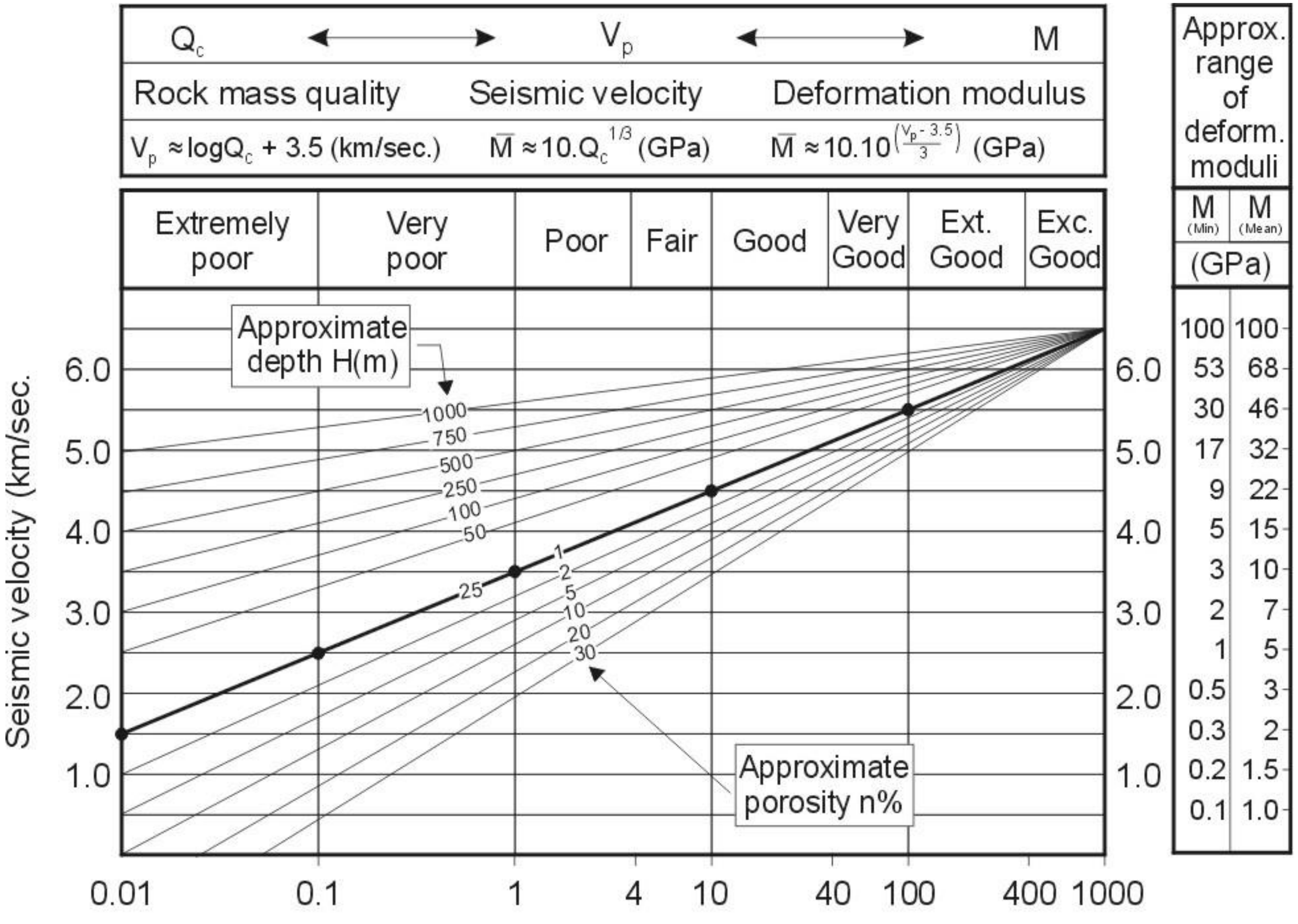
Sjøgren et al. 1979: RQD/Fm-1/Vp
NB added Q-value scale, 1995: hard rocks.
(120 km ref. seis., 2.2km core)





ROCK MASS QUALITY $Q = \frac{RQD}{Jn} x \frac{Jr}{Ja} x \frac{Jw}{SRF}$

Below: NB, 1995: general case



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

HOEK-BROWN

GSI-BASED ESTIMATION

(AN ALTERNATIVE, WITH ***RQD*** INCLUDED)

$$E_m(GPa) = \left(1-\frac{D}{2}\right)\sqrt{\frac{\sigma_{ci}}{100}} \times 10^{(GSI-10)/40}$$

$$\sigma'_{cm} = \sigma_{ci} \times \frac{(m_b+4s-a(m_b-8s))\ (m_b/4+s)^{a-1}}{2(1+a)\ (2+a)}$$

$$\varphi' = a\sin\left[\frac{6am_b(s+m_b\sigma'_{3n})^{a-1}}{2(1+a)(2+a)+6am_b\ (s+m_b\sigma'_{3n})^{a-1}}\right]$$

$$c' = \frac{\sigma_{ci}[(1+2a)s+(1-a)m_b\sigma'_{3n}]\ (s+m_b\sigma'_{3n})^{a-1}}{(1+u)\ (2+a)\sqrt{1+(6am_b(s+m_b\sigma'_{3n})^{a-1})/((1+a)\ (2+a))}}$$

where

$$\sigma_{3n} = \sigma'_{3\ \max}/\sigma_{ci} \quad (+\mathrm{GSI}+a+s+m_b \text{ relations})$$

$$E_m \approx 10 \times Q_c^{1/3}$$

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

$$\varphi \approx \tan^{-1}\left(\frac{J_r}{J_a} \times \frac{J_w}{1}\right)$$

$$c \approx \left(\frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100}\right)$$

FOR THOSE WHO ARE SUSPICIOUS OF BLACK-BOX EQUATIONS – THERE ARE TRANSPARENT ALTERNATIVES……***also with RQD!***

CC and FC from $Q_c = Q \times \sigma_c / 100$:

Cut Q_c into two halves → 'c' and 'φ'

$Q_c = RQD/Jn \times Jr/Ja \times Jw / SRF \times \sigma_c / 100)$

CC = cohesive strength (the component of the rock mass requiring shotcrete)

FC = frictional strength (the component of the rock mass requiring bolting).

$$CC = \frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100}$$

$$FC = \tan^{-1}\left(\frac{Jr}{Ja} \times Jw\right)$$

	$c' = \dfrac{\sigma_{ci}\left[(1+2a)s+(1-a)m_b\sigma'_{3n}\right]\left(s+m_b\sigma'_{3n}\right)^{a-1}}{(1+u)(2+a)\sqrt{1+\left(6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}\right)\Big/\left((1+a)(2+a)\right)}}$
CC	$"c" \approx \left(\dfrac{RQD}{J_n}\times\dfrac{1}{SRF}\times\dfrac{\sigma_c}{100}\right)$
	$\phi' = \operatorname{asin}\left[\dfrac{6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}{2(1+a)(2+a)+6am_b\left(s+m_b\sigma'_{3n}\right)^{a-1}}\right]$
FC	$"\phi" \approx \tan^{-1}\left(\dfrac{J_r}{J_a}\times\dfrac{J_w}{1}\right)$

GSI-based algebra for 'c' and 'ϕ'

contrasted with

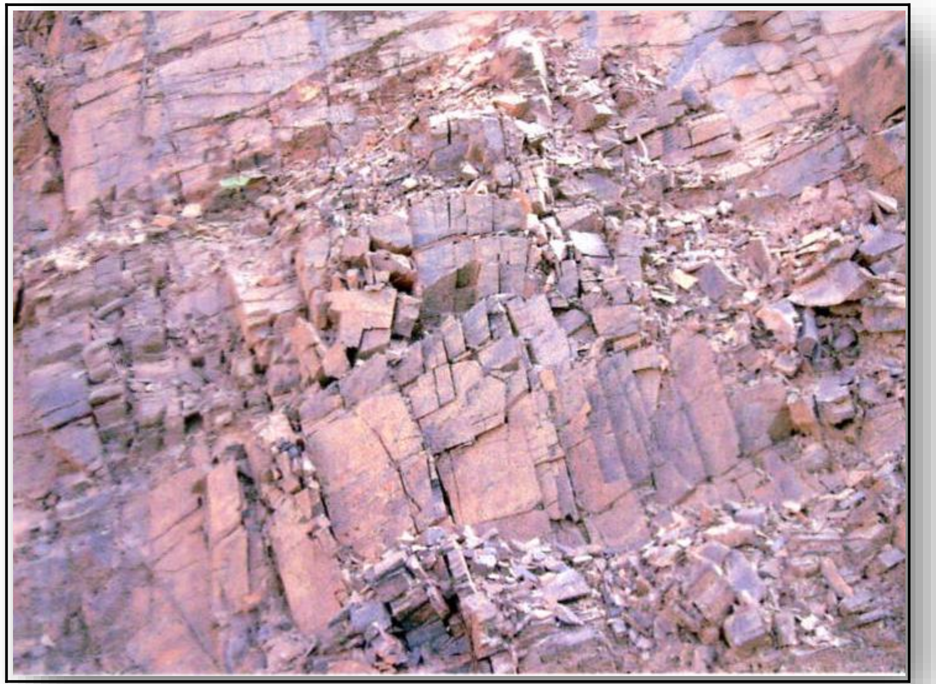
Q-based 'empiricism'

Note: shotcrete needed when low CC, bolting needed when low FC.

RQD	J_n	J_r	J_a	J_w	SRF	Q	σ_c	Q_c	*FC*°	*CC* MPa	V_p km/s	E_{mass} GPa
100	2	2	1	1	1	100	100	100	63°	50	5.5	46
90	9	1	1	1	1	10	100	10	45°	10	4.5	22
60	12	1.5	2	0.66	1	2.5	50	1.2	26°	2.5	3.6	10.7
30	15	1	4	0.66	2.5	0.13	33	0.04	9°	0.26	2.1	3.5

Four rock masses with successively reducing character: *lower RQD*, more joint sets, more weathering, lower UCS, more clay.

Low CC –shotcrete preferred



Low FC – bolting preferred