3. LINKING Q TO USEFUL PARAMETERS FOR DESIGN

CORE LOGGING EXAMPLES – PRIOR TO PARAMETER ESTIMATION

SKB (Sweden) – from a potential site for high level nuclear waste

Simpevarp – jointed rock example

IDEAL CORE HANDLING CONDITIONS

SKB’S SIMPEVARP

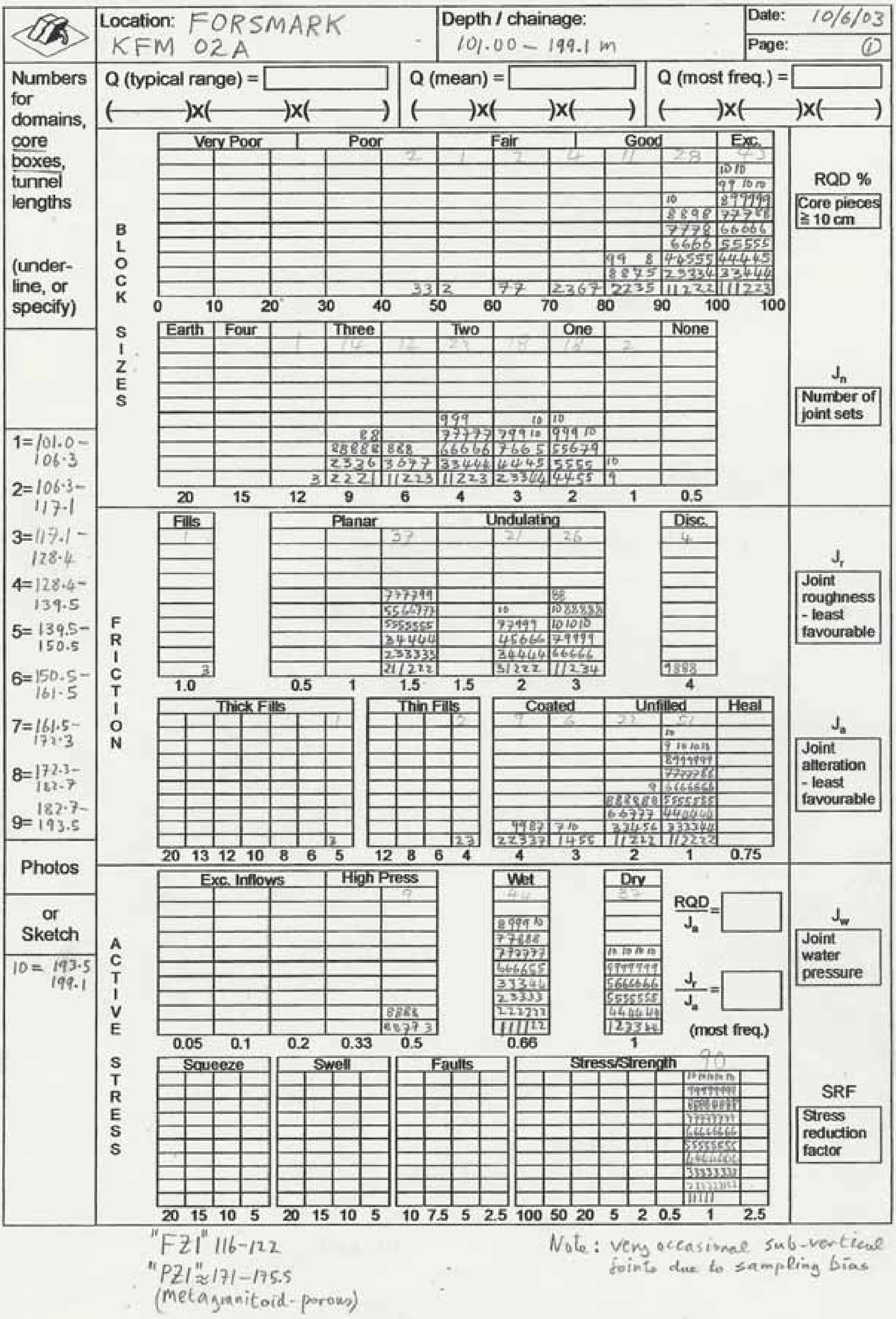
KSH 01 A and KSH 02

(these are 1000m deep holes)

KSH02 916.09-921.65
Låda 163
919.09
921.65
911.56
Låda 162
KSH02 921.65-927.37
Låda 164
927
922.12
925.12
927.37


KSH01A LÅDA 62
426,44 – 431,25
430,92
431,10
431,25


824,10
825,13 ↑F
F
835,13 – 830,10
KSH
827,10
830,10↑



Location: FORSMARK KFM 02A

Depth / chainage: 101.00 – 199.1 m

Date: 10/6/03

Page: ①

Q (typical range) = ☐ (—)x(—)x(—)

Q (mean) = ☐ (—)x(—)x(—)

Q (most freq.) = ☐ (—)x(—)x(—)

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

1= 101.0 – 106.3
2= 106.3 – 117.1
3= 117.1 – 128.4
4= 128.4 – 139.5
5= 139.5 – 150.5
6= 150.5 – 161.5
7= 161.5 – 172.3
8= 172.3 – 182.7
9= 182.7 – 193.5
10= 193.5 – 199.1

Photos or Sketch

BLOCK SIZES

RQD % (Core pieces ≥ 10 cm)

Very Poor		Poor			Fair		Good		Exc.
				2	1	7	4	11	28 / 43

Scale: 0 10 20 30 40 50 60 70 80 90 100 100

J_n (Number of joint sets)

Earth	Four		Three		Two		One		None
		1	14	12	23	18	18	2	
20	15	12	9	6	4	3	2	1	0.5

FRICTION

J_r (Joint roughness - least favourable)

Fills	Planar			Undulating			Disc.
1			37		21	26	4
1.0	0.5	1	1.5	1.5	2	3	4

J_a (Joint alteration - least favourable)

Thick Fills							Thin Fills				Coated		Unfilled		Heal
						1				2	9	6	22	51	
20	13	12	10	8	6	5	12	8	6	4	4	3	2	1	0.75

ACTIVE STRESS

J_w (Joint water pressure)

Exc. Inflows			High Press		Wet	Dry
				9	44	37
0.05	0.1	0.2	0.33	0.5	0.66	1

$\frac{RQD}{J_n}$ = ☐

$\frac{J_r}{J_a}$ = ☐ (most freq.)

SRF (Stress reduction factor)

Squeeze				Swell				Faults				Stress/Strength							
																		90	
20	15	10	5	20	15	10	5	10	7.5	5	2.5	100	50	20	5	2	0.5	1	2.5

"FZI" 116-122
"PZI" ≈ 171-175.5
(metagranitoid - porous)

Note: very occasional sub-vertical joints due to sampling bias


441.06 – 446.5
441.71


2 2m 3 4 INOX 5 6 7 SWEDEN 8 9 10 1 2 3 4 5 6 7 8 9 20 1


600
601

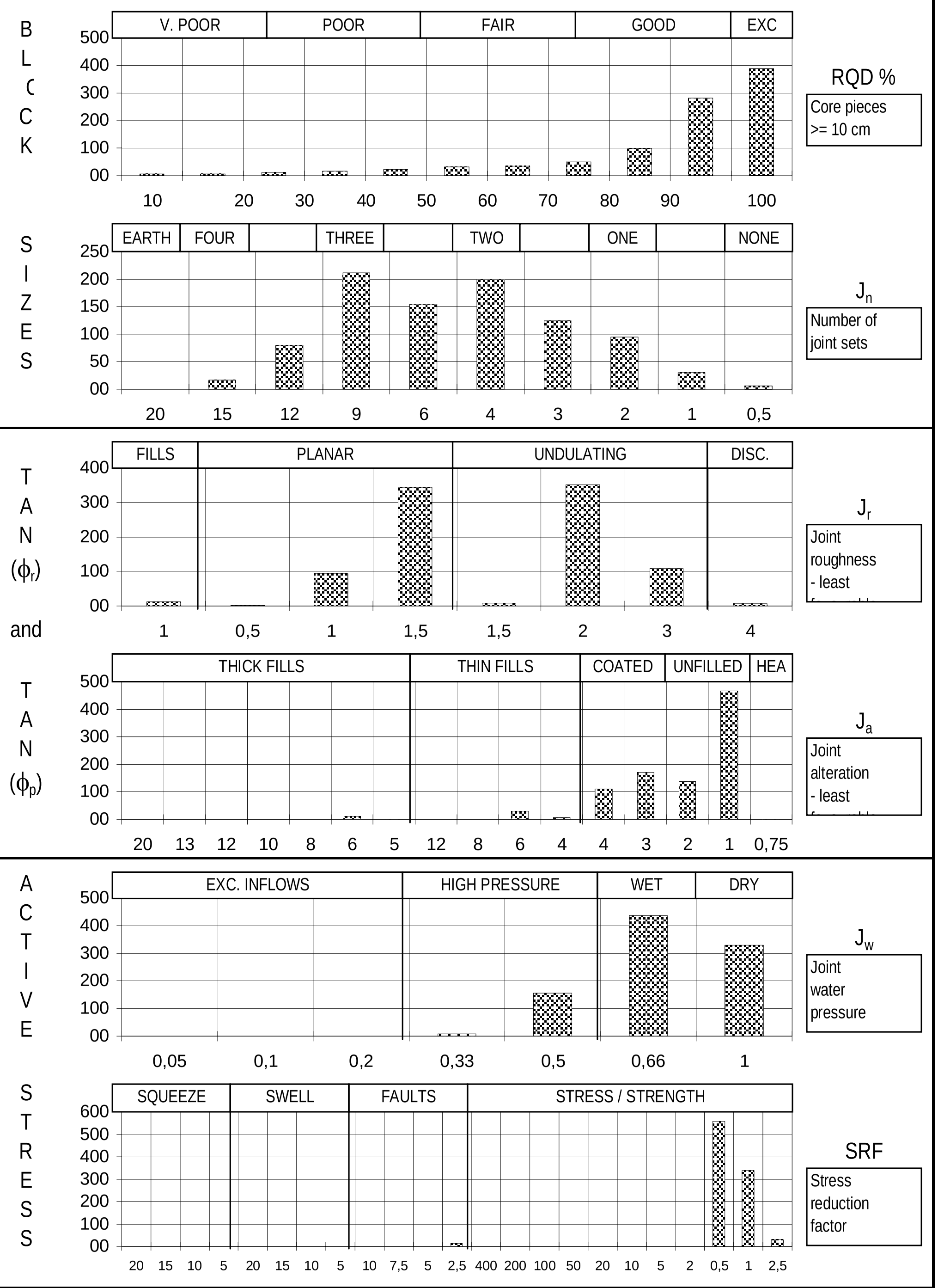

80
806.15 –
807
la. 143


568.97

833,10
ylomi
833
17
833 | 17

962
962.15

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	45	/	12,0	*	1,0	/	6,0	*	0,50	/	1,0	=	0,313
Q (typical max)=	100	/	1,0	*	3,0	/	1,0	*	1,00	/	0,5	=	600,0
Q (mean value)=	88	/	5,9	*	1,8	/	2,1	*	0,75	/	0,8	=	12,54
Q (most frequent)=	100	/	9,0	*	2,0	/	1,0	*	0,66	/	0,5	=	29,33



SKB SIMPEVARP candidate site KSH 01A, 01B

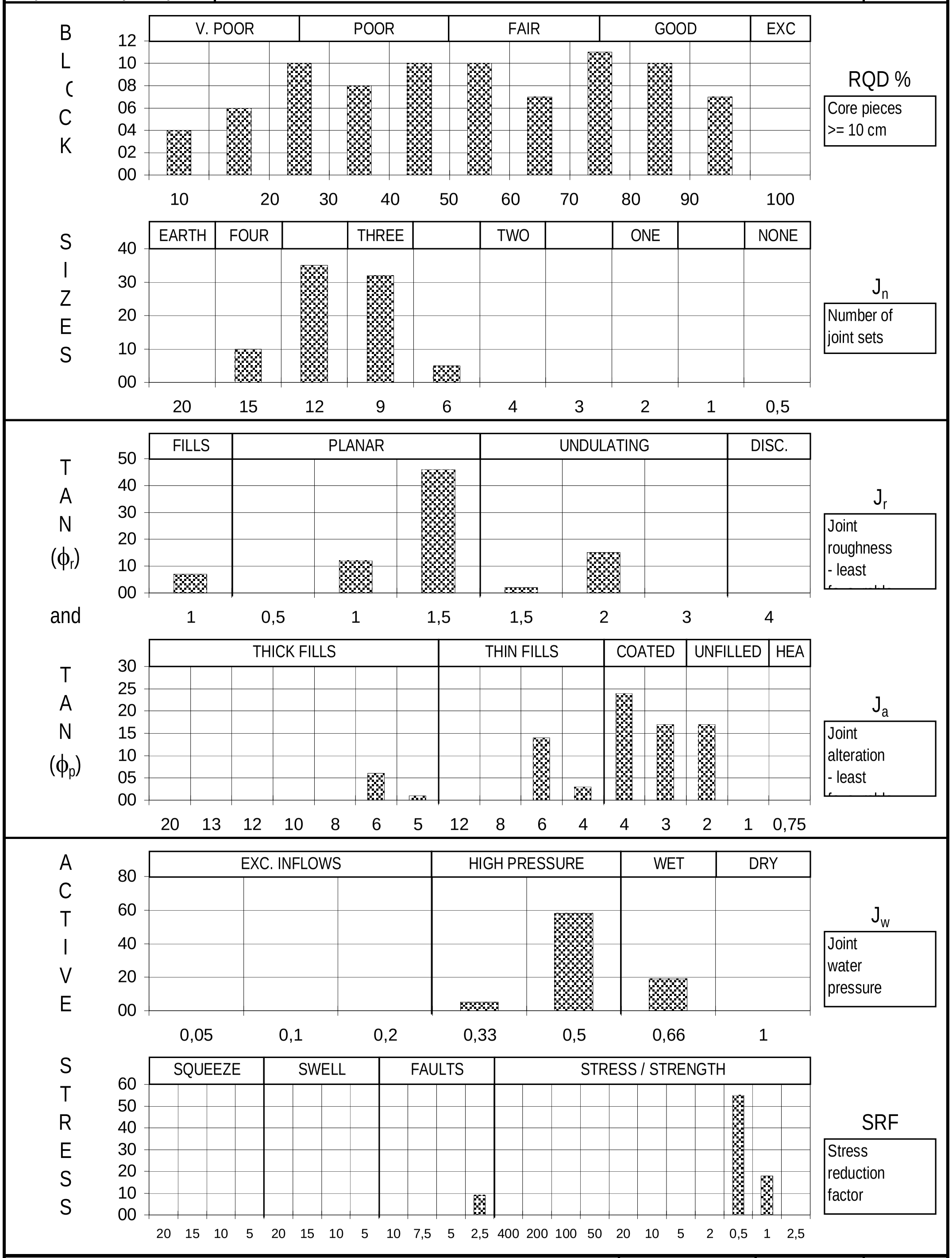
KSH 01A and 01B : overall quality of both cores, from 1.3 to 1003.0m (includes seven more fractured zones)

Rev.
Report No. NB&A
Figure No.
Borehole No. : KSH 01 A+B
Drawn by nrb
Date
Depth zone (m) 1.3-1000.3
Checked nrb
Logg 1,0
Approved
20th May 2003

Variations with depth for the 'background rock mass' of KSH 01 A and B (minus 7 x FZ)

Depth down hole	$Q_{most\ frequent}$	Q_{mean}	$Q_{typ.\ min.}$	$Q_{typ.\ max.}$
1.3-100.8 m	24.8	6.3	0.9	75
100.8-199.9 m	31.4	12.9	2.6	100
199.9-302.9 m	13.9	6.0	0.3	75
302.9-398.8 m	31.4	16.8	1.8	150
398.8-500.1 m	15.8	15.3	2.7	150
500.1-600.6 m	49.5	17.9	4.0	200
600.6-699.5 m	62.7	14.0	2.3	200
699.5-798.8 m	133	48.3	2.6	600
798.8-901.2 m	133	59.4	7.1	300
901.2-1003.0 m	150	71.7	13.9	1200

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	10	/	15,0	*	1,0	/	6,0	*	0,33	/	2,5	=	0,015
Q (typical max)=	95	/	6,0	*	2,0	/	2,0	*	0,66	/	0,5	=	20,9
Q (mean value)=	54	/	10,8	*	1,5	/	3,9	*	0,53	/	0,8	=	1,20
Q (most frequent)=	75	/	12,0	*	1,5	/	4,0	*	0,50	/	0,5	=	2,34



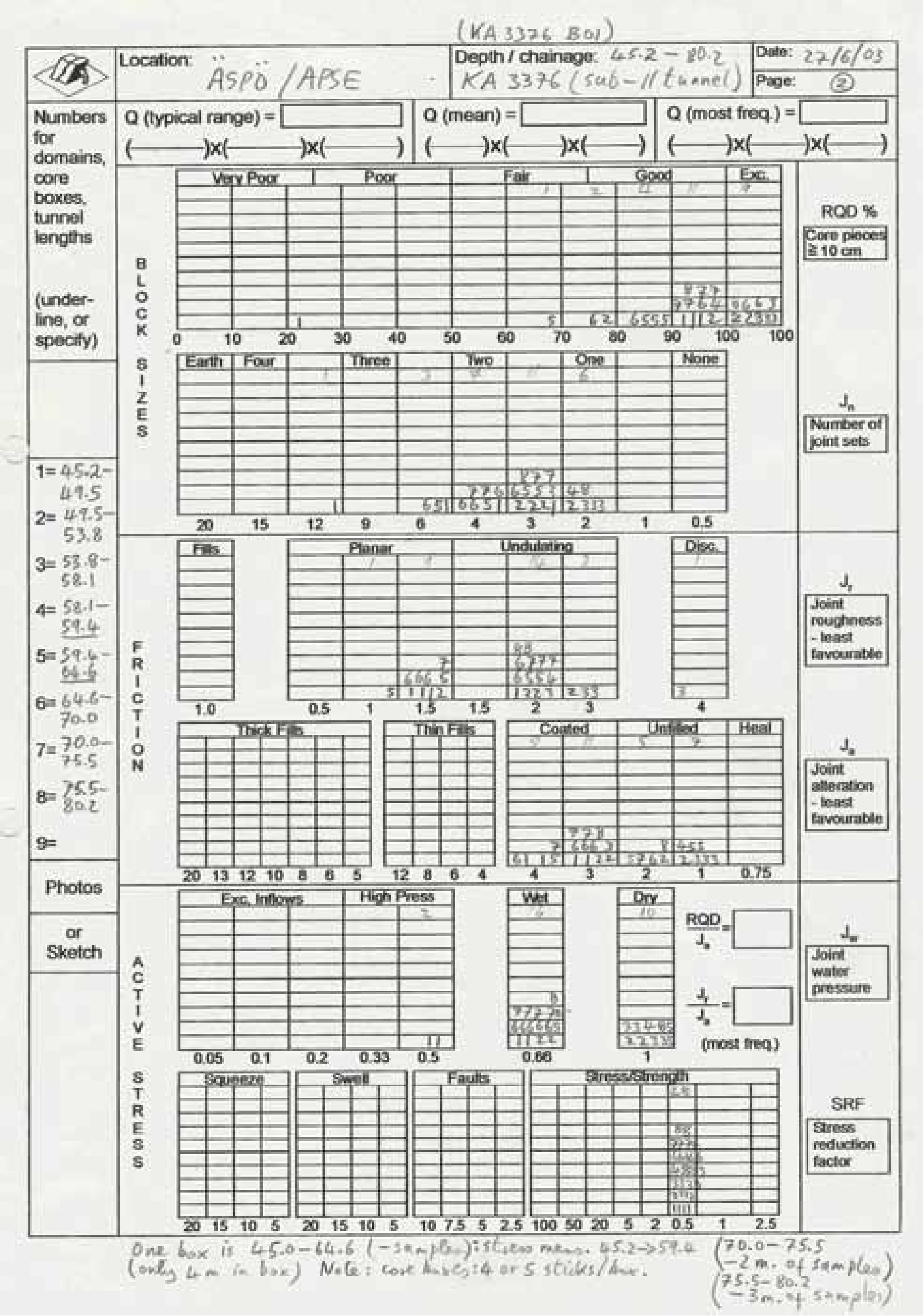
SKB SIMPEVARP candidate site	Rev.	Report No. NB&A	Figure No.
KSH 01A and B : overall quality of seven identified fracture	Borehole No. : KSH 01A and B	Drawn by	Date
zones : 1) 138.5-154.5, 2) 247.7-253.0, 3) 407.0-409.5,	Depth zone (m) various	Checked nrb	
4) 420-437, 5) 541-570, 6) 619-637, and 7) 725-730	Logg 1,0 ## 21st May 2003	Approved nrb	

Q-statistics for KSH 01 A and B’s four principal fracture(d) zones identified from Q-parameter changes.

Fracture(d) zone	Depth (m)	$Q_{most\ frequent}$	Q_{mean}	$Q_{typ.\ min.}$	$Q_{typ.\ max.}$
FZ 1	138.5 -154.5	5.3	2.2	0.3	7.0
FZ 4	420 – 437	3.8	1.4	0.02	24.8
FZ 5	541 – 570	2.3	1.3	0.02	20.9
FZ 6	619 – 637	2.7	1.1	0.04	10.5

EXAMPLE OF PARAMETER ESTIMATION AT SKB's 'APSE' tunnel


164.99
166.52



(KA 3376 B01)

Location: ÄSPÖ / APSE

Depth / chainage: 45.2 – 80.2 KA 3376 (sub-// tunnel)

Date: 27/6/03

Page: ②

Q (typical range) = ( )x( )x( )

Q (mean) = ( )x( )x( )

Q (most freq.) = ( )x( )x( )

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

1= 45.2–49.5
2= 49.5–53.8
3= 53.8–58.1
4= 58.1–59.4
5= 59.4–64.6
6= 64.6–70.0
7= 70.0–75.5
8= 75.5–80.2
9=

Photos or Sketch

BLOCK SIZES

Very Poor | Poor | Fair | Good | Exc.

0 10 20 30 40 50 60 70 80 90 100 100

RQD % — Core pieces ≥ 10 cm

Earth | Four | Three | Two | One | None

20 15 12 9 6 4 3 2 1 0.5

J_n — Number of joint sets

FRICTION

Fills | Planar | Undulating | Disc.

1.0 0.5 1 1.5 1.5 2 3 4

J_r — Joint roughness - least favourable

Thick Fills | Thin Fills | Coated | Unfilled | Heal

20 13 12 10 8 6 5 12 8 6 4 4 3 2 1 0.75

J_a — Joint alteration - least favourable

ACTIVE STRESS

Exc. Inflows | High Press | Wet | Dry

0.05 0.1 0.2 0.33 0.5 0.66 1

$\frac{RQD}{J_n}$ =

$\frac{J_r}{J_a}$ = (most freq.)

J_w — Joint water pressure

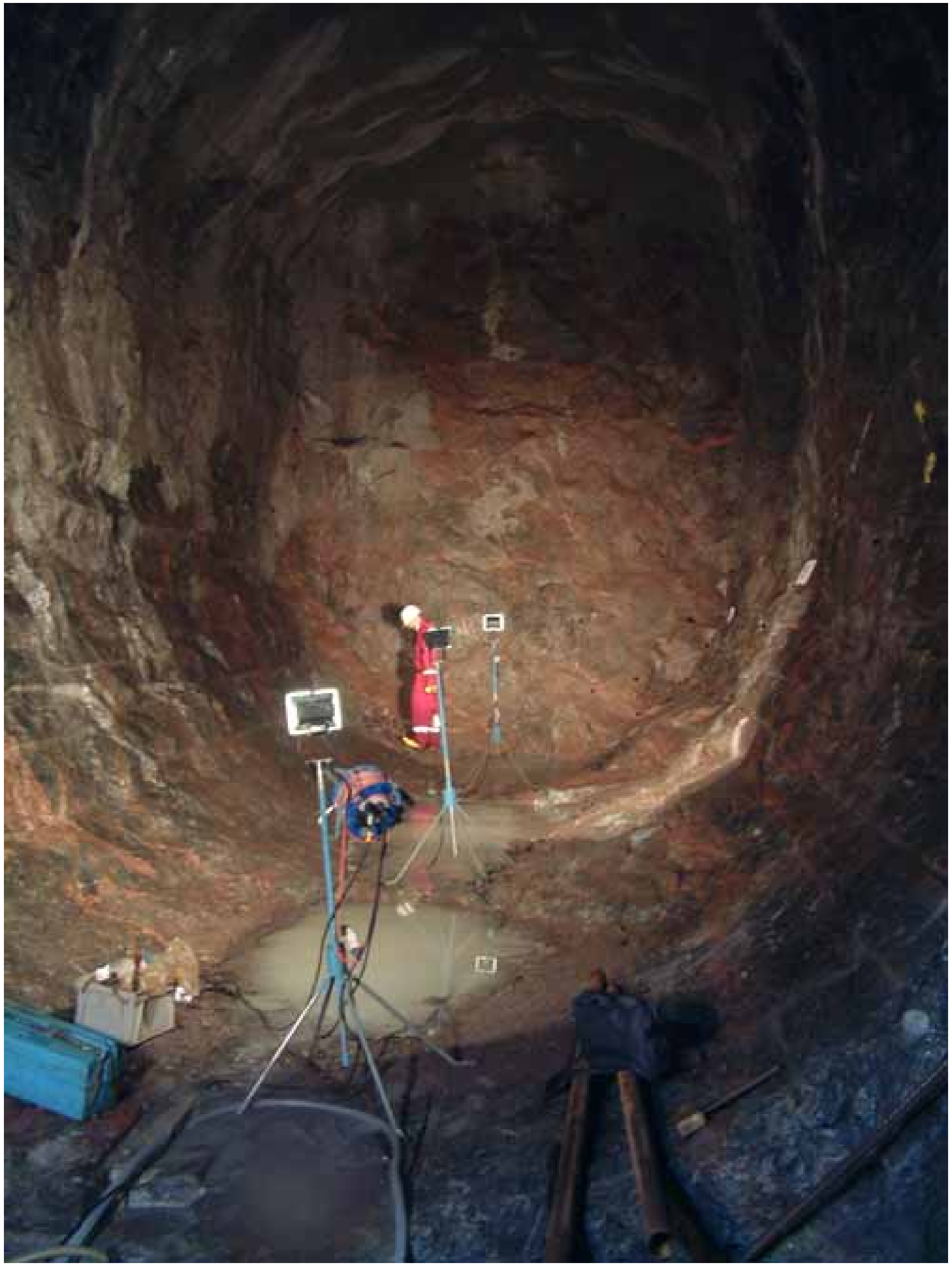
Squeeze | Swell | Faults | Stress/Strength

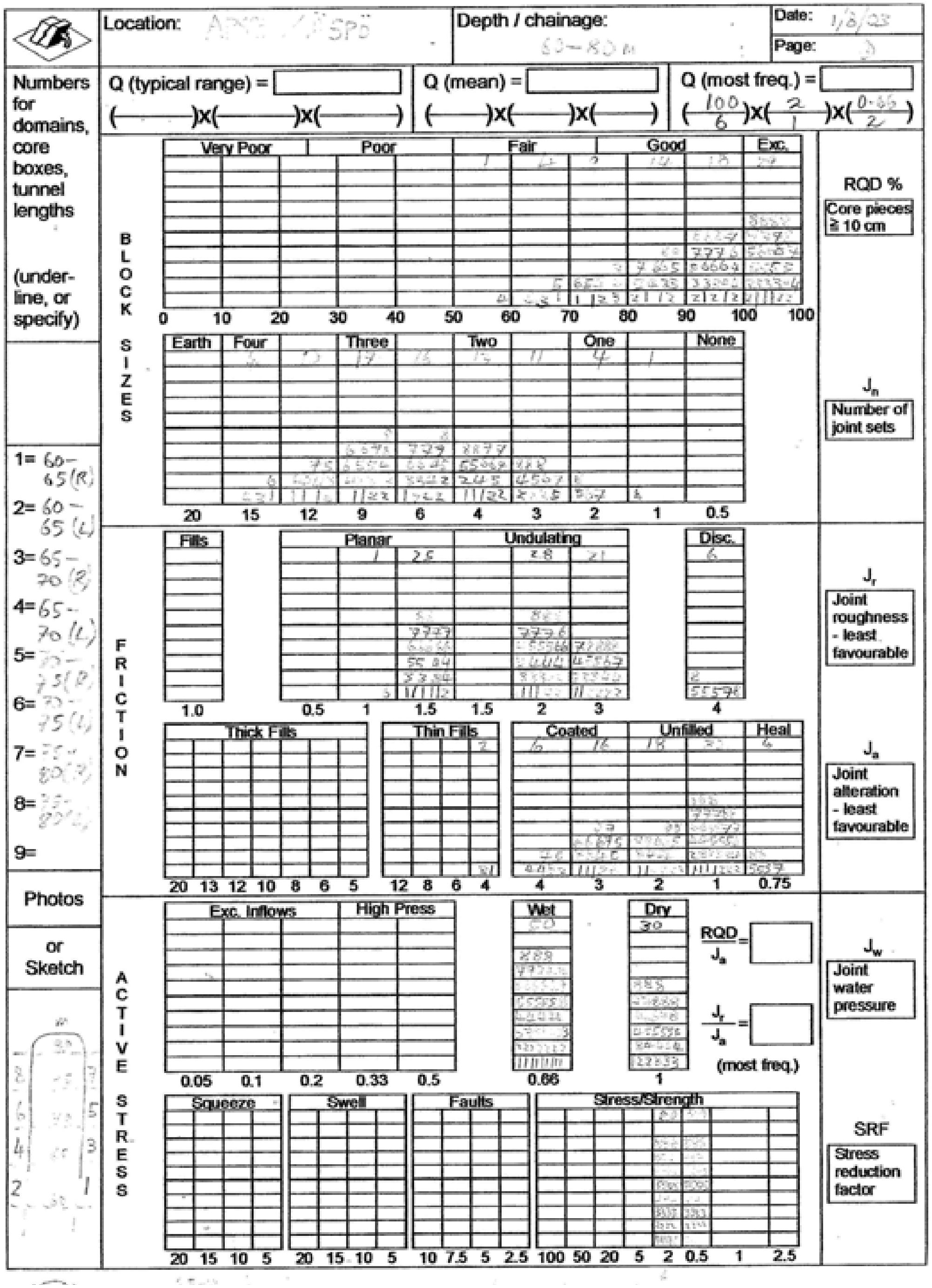
20 15 10 5 20 15 10 5 10 7.5 5 2.5 100 50 20 5 2 0.5 1 2.5

SRF — Stress reduction factor

One box is 45.0–64.6 (–samples): stress meas. 45.2→59.4 (only 4 m in box) Note: core boxes: 4 or 5 sticks/box.

(70.0–75.5 –2 m. of samples)
(75.5–80.2 –3 m. of samples)





Location: [illegible] SP5

Depth / chainage: 60–80 m

Date: 1/8/23

Page: 2

Q (typical range) = ☐ (——)x(——)x(——)

Q (mean) = ☐ (——)x(——)x(——)

Q (most freq.) = ☐ $\left(\frac{100}{6}\right)\times\left(\frac{2}{1}\right)\times\left(\frac{0.66}{2}\right)$

Numbers for domains, core boxes, tunnel lengths

(under-line, or specify)

1= 60–65 (R)

2= 60–65 (L)

3= 65–70 (R)

4= 65–70 (L)

5= 70–75 (R)

6= 70–75 (L)

7= 75–80 (R)

8= 75–80 (L)

9=

Photos

or Sketch

BLOCK SIZES

RQD %

Core pieces ≥ 10 cm

Very Poor		Poor			Fair			Good		Exc.
					1	4	2	14	18	29
0	10	20	30	40	50	60	70	80	90	100

J$_n$

Number of joint sets

Earth	Four		Three		Two		One		None
	6	12	17	16	15	11	4	1	
20	15	12	9	6	4	3	2	1	0.5

FRICTION

J$_r$

Joint roughness - least favourable

Fills	Planar			Undulating			Disc.
		1	25		28	21	6
1.0	0.5	1	1.5	1.5	2	3	4

J$_a$

Joint alteration - least favourable

Thick Fills							Thin Fills				Coated		Unfilled		Heal
										2	6	16	18	30	6
20	13	12	10	8	6	5	12	8	6	4	4	3	2	1	0.75

ACTIVE STRESS

J$_w$

Joint water pressure

Exc. Inflows		High Press			Wet	Dry
					60	30
0.05	0.1	0.2	0.33	0.5	0.66	1

$\frac{RQD}{J_a}$ = ☐

$\frac{J_r}{J_a}$ = ☐

(most freq.)

SRF

Stress reduction factor

Squeeze				Swell				Faults				Stress/Strength							
20	15	10	5	20	15	10	5	10	7.5	5	2.5	100	50	20	5	2	0.5	1	2.5

APPLICATION OF ‘500m’ Q_c – V_p equation

(C. Andersson, SKB)

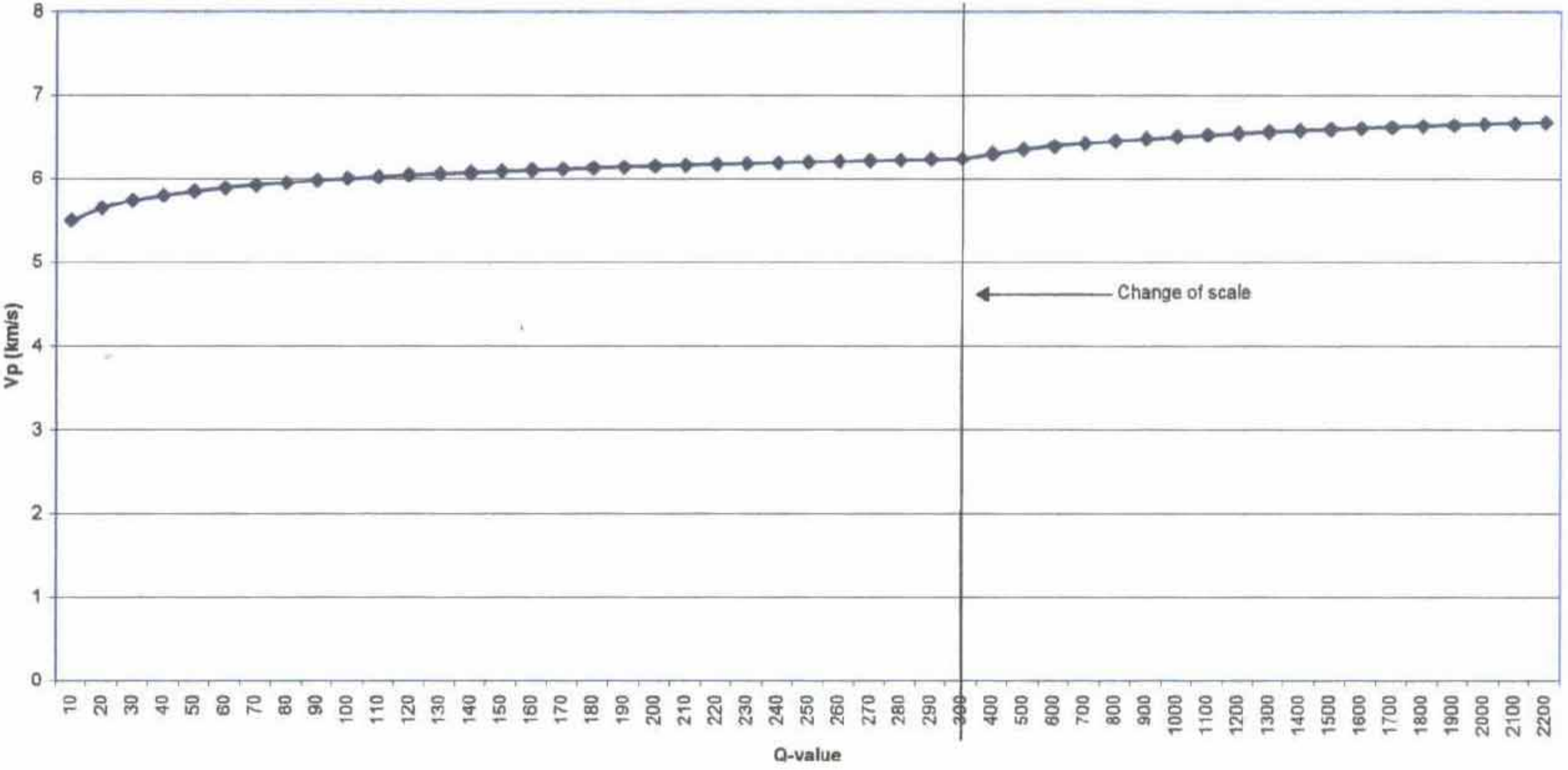
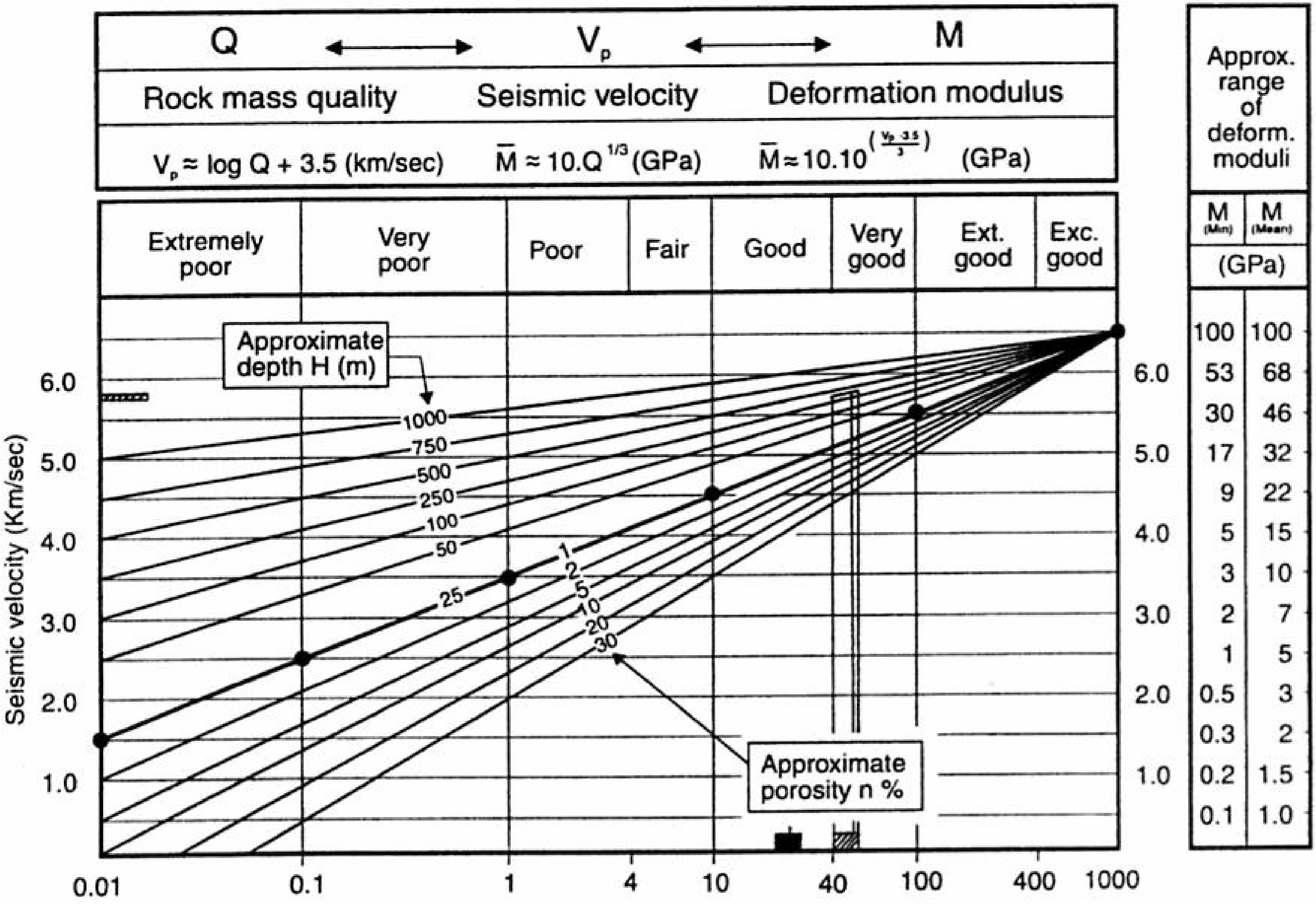


Figure 8. Plot of Vp versus Q-value using equation $Vp=5+0.5\log Q_c$



M (Min)	M (Mean)
(GPa)	
100	100
53	68
30	46
17	32
9	22
5	15
3	10
2	7
1	5
0.5	3
0.3	2
0.2	1.5
0.1	1.0

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

APPLICATION OF ‘500m’ Q_c – E_{mass} equation
(C. Andersson, SKB)

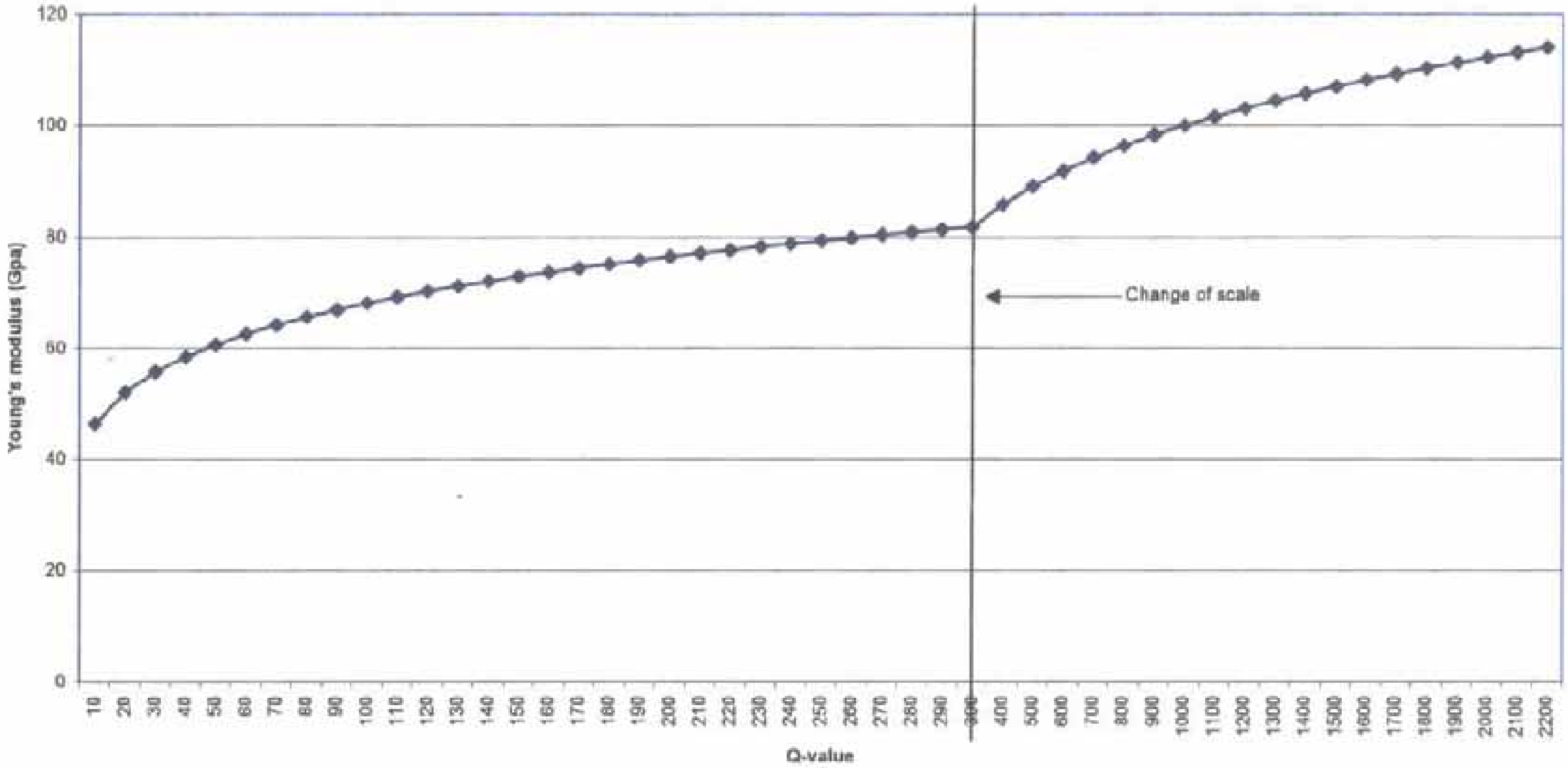


Figure 10. Plot of Young's modulus versus Q-value using equation: $E_{mass} = 10^{(4.5+0.5\log Q)/3}$

APPLICATION OF Q – deformation equation
(C. Andersson, SKB)

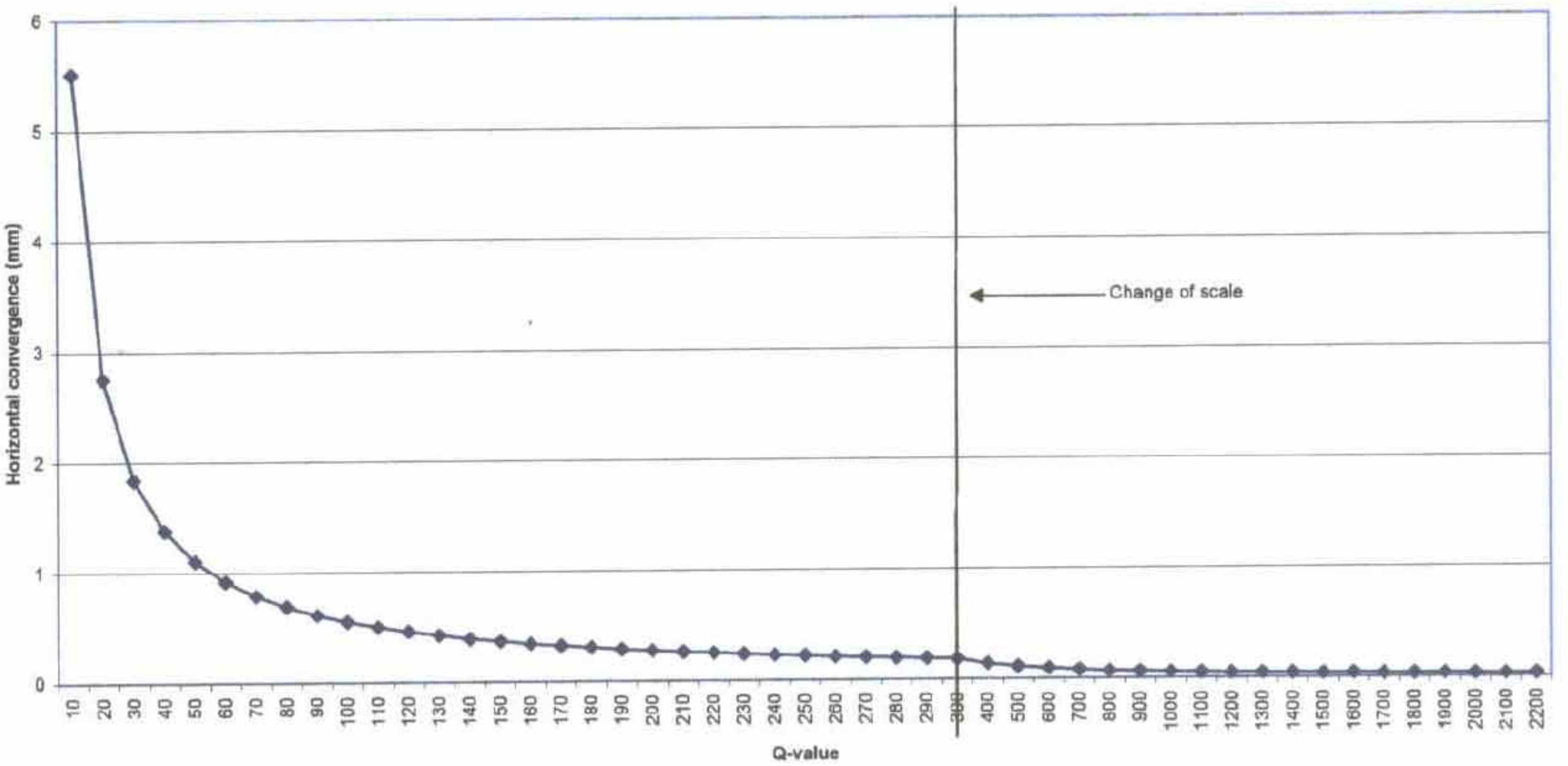
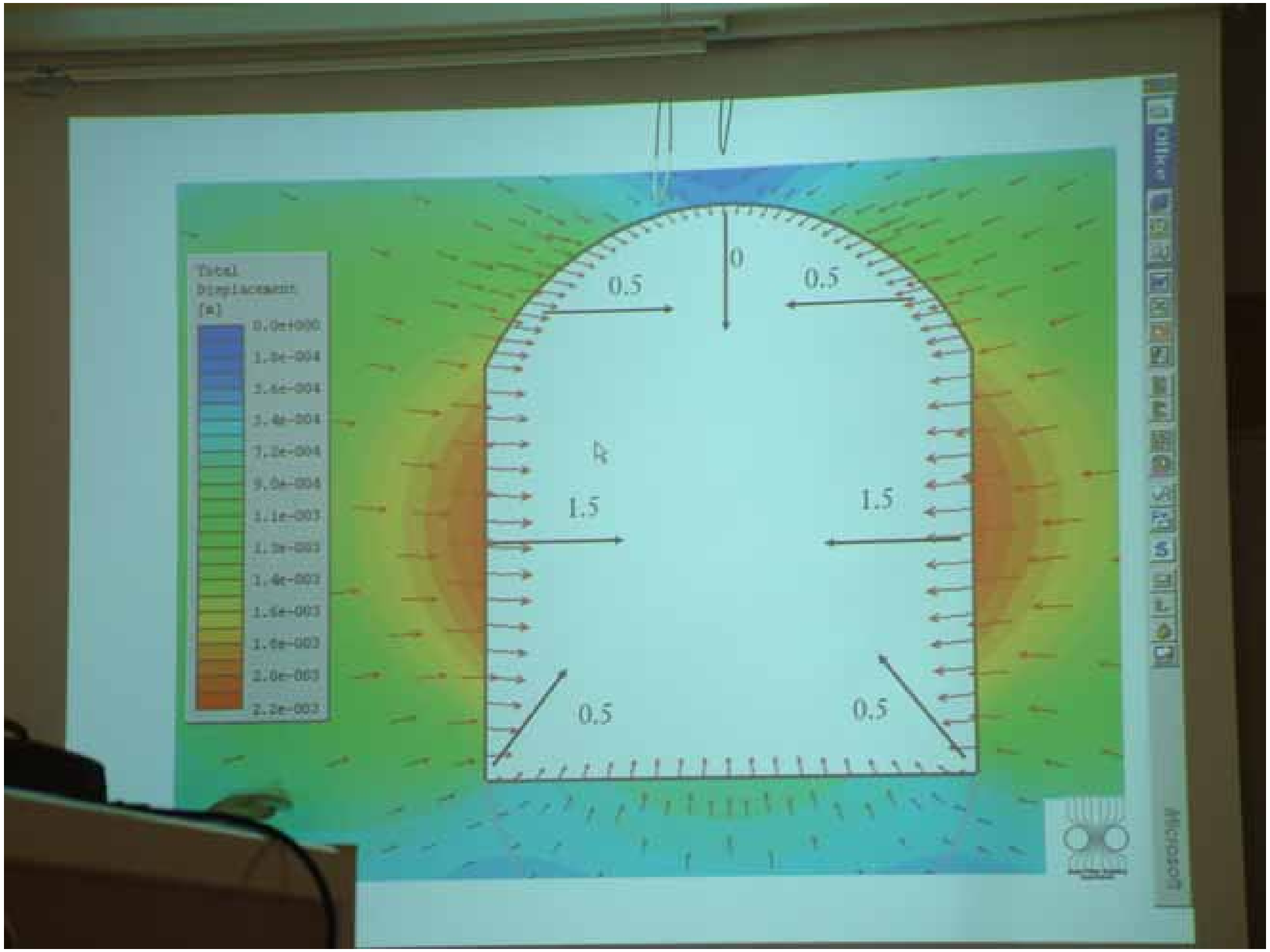


Figure 9. Plot of horizontal deformations versus Q-value using equation: $\Delta h = 2\times HEIGHT/100Q(\sigma_H/\sigma_c)$. Used parameters: Height = 7500, σ_H = 27 MPa, σ_c = 200 MPa.


Total
Displacement
[m]
0.0e+000
1.8e-004
3.6e-004
5.4e-004
7.2e-004
9.0e-004
1.1e-003
1.3e-003
1.4e-003
1.6e-003
1.8e-003
2.0e-003
2.2e-003
0
0.5
0.5
1.5
1.5
0.5
0.5
Microsoft

CORE LOGGING

OF

FAULTS

AND

WEATHERED ROCK


3865
3700
3660
3595
3565
3510
3474
3424
3330
3282
3220

LOOK OUT FOR THE PLANAR, RUST STAINED OR CLAY-BEARING JOINTS WHEN LOGGING

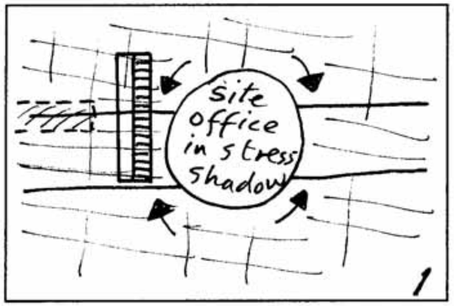

SM-ML4-17
34.50
31.60
23.00
25.00

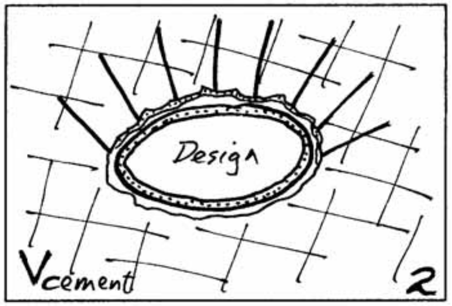
THE PRICE PAYED FOR TUNNELLING TOO HIGH IN THE WEATHERING PROFILE

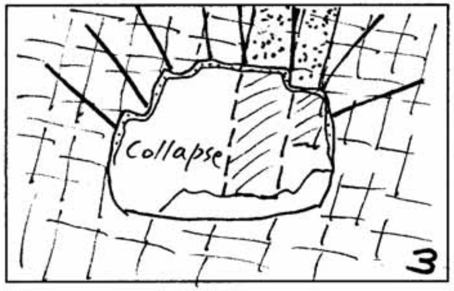

SM-ML4-17
30.10
22.00
17.00
13.00
12.00
11.00

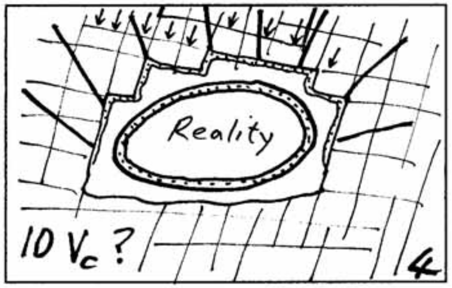
SAME PROJECT

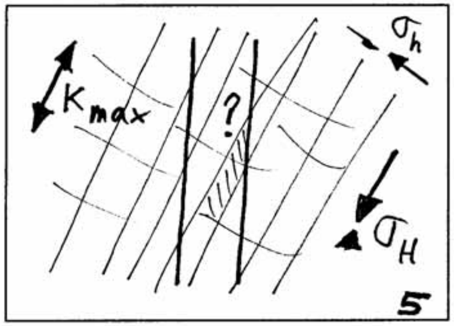
TOO MUCH OVER-BREAK – REQUIRES PRE-GROUTING

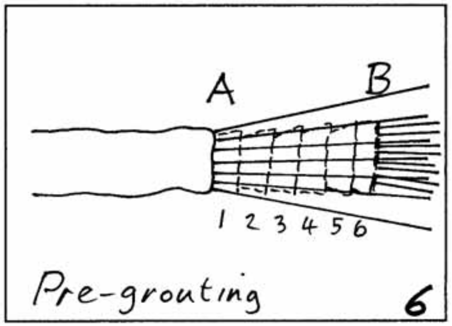

site office in stress shadow
1

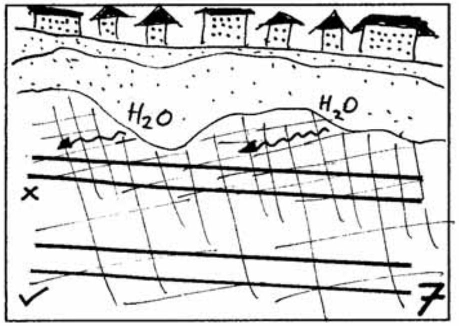

Design
Vcement
2

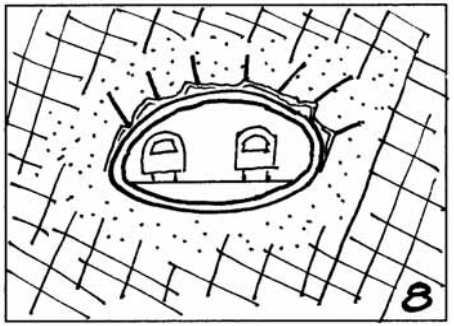

Collapse
3


Reality
10 Vc ?
4

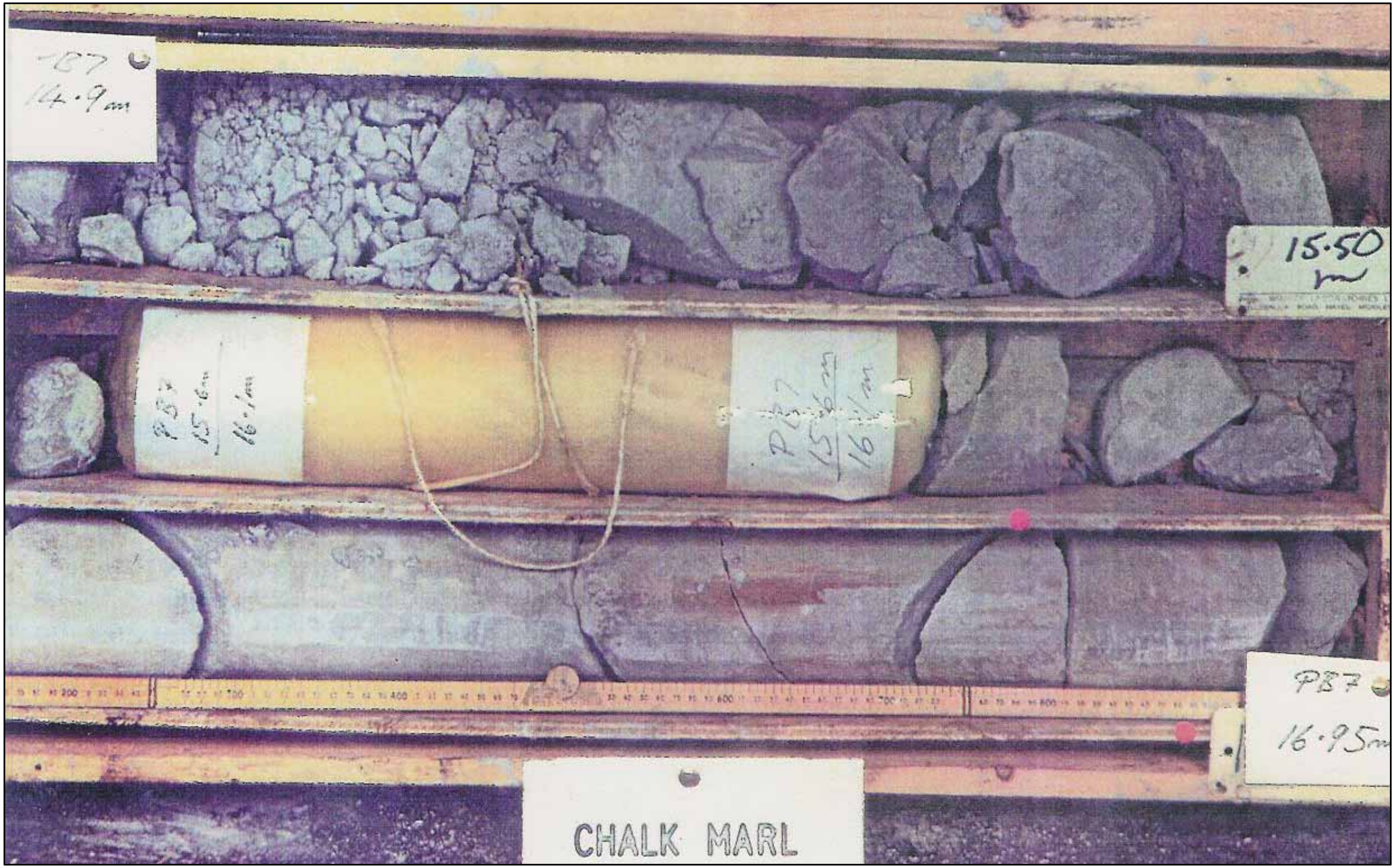

σh
K max
?
σH
5


A
B
1 2 3 4 5 6
Pre-grouting
6

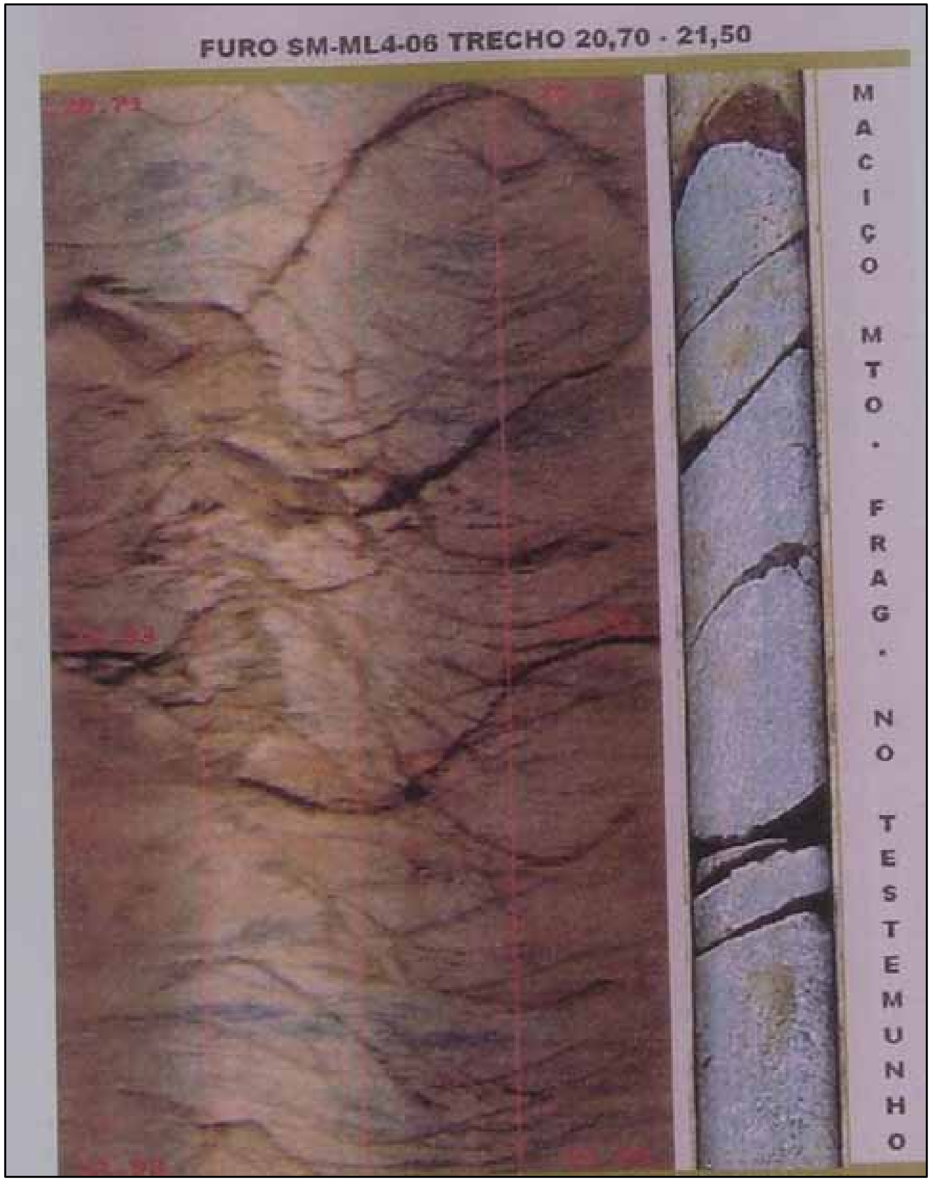

H2O
H2O
×
✓
7


8

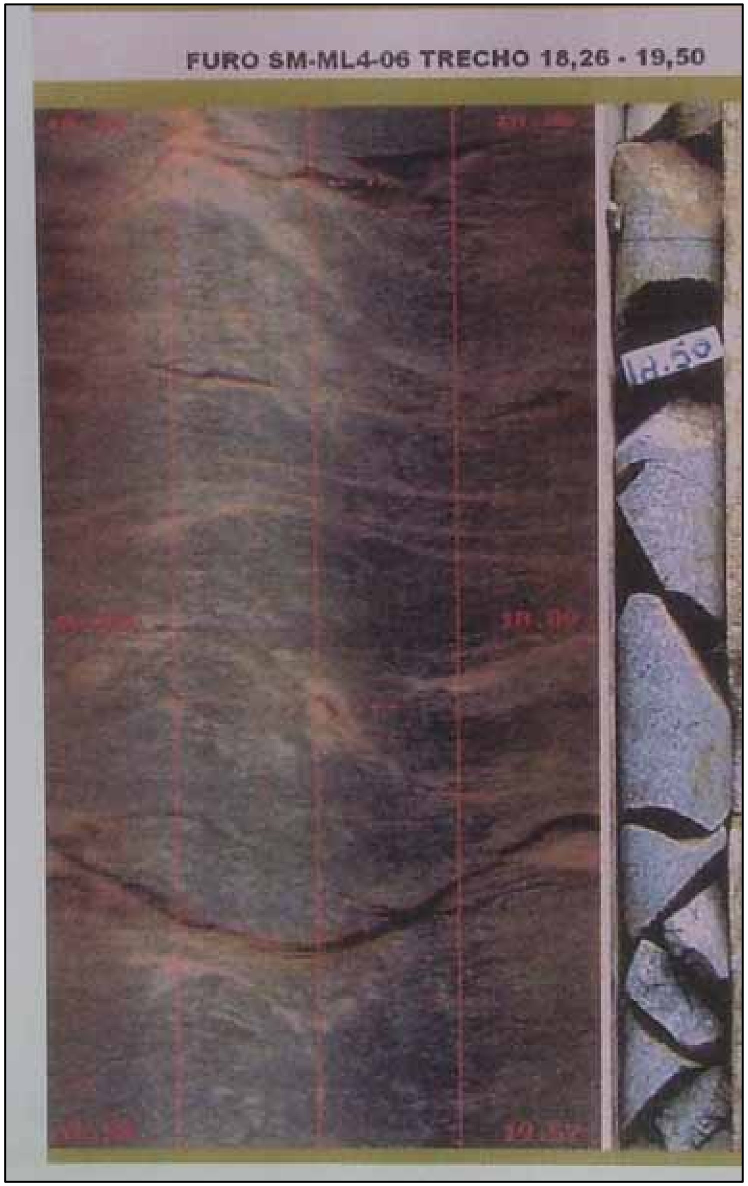

10,50
9,10
6,20
7,70
2,10 A12,10
4,95 A8,10


PB7
14·9m
15·50 m
PB7
15·6m
16·1m
PB7
15·6m
16·1m
PB7
16·95m
CHALK MARL

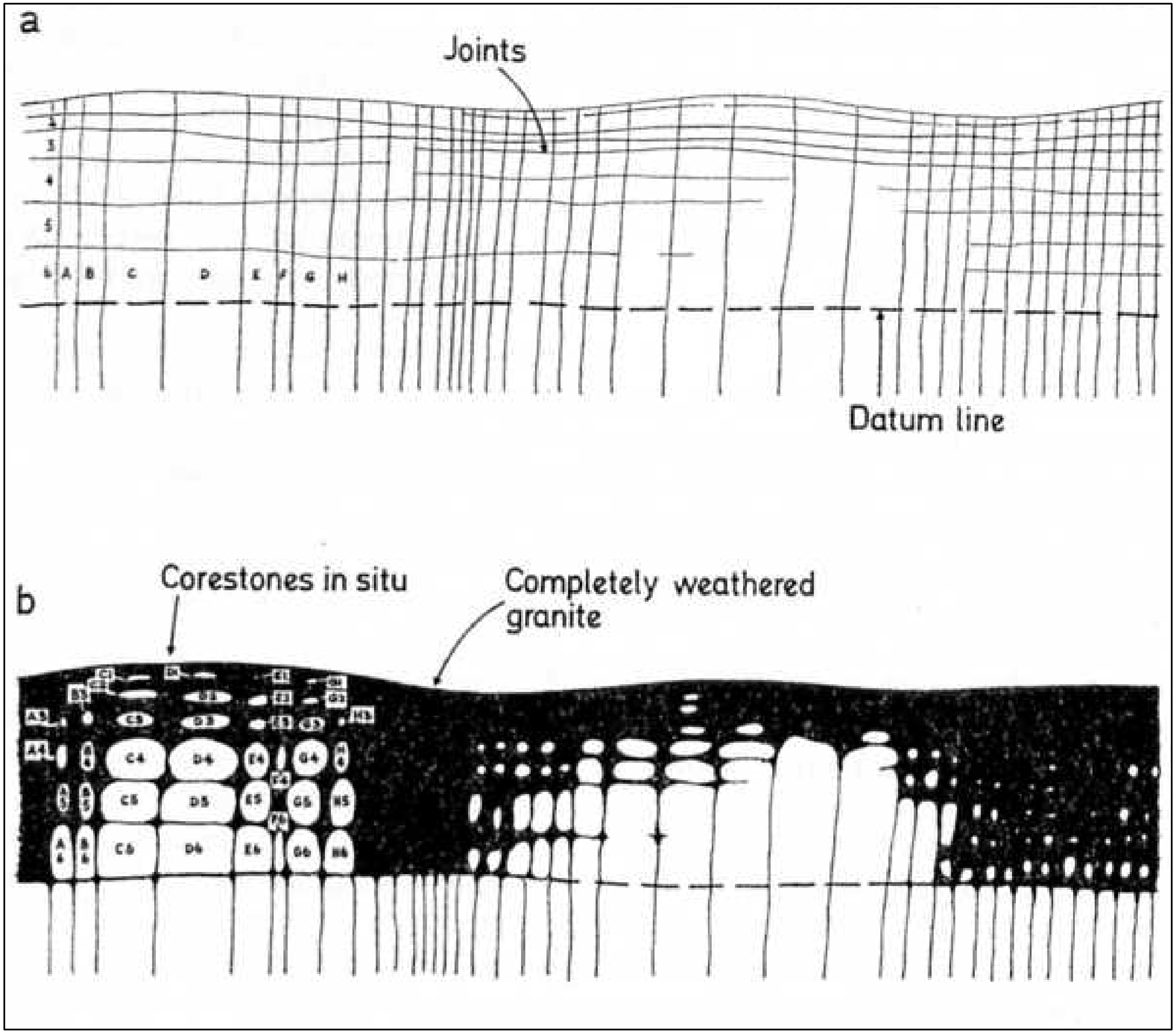

MACIÇO MTO. FRAG. NO TESTEMUNHO



FURO SM-ML4-06 TRECHO 20,70 - 21,50
MACIÇO MTO. FRAG. NO TESTEMUNHO



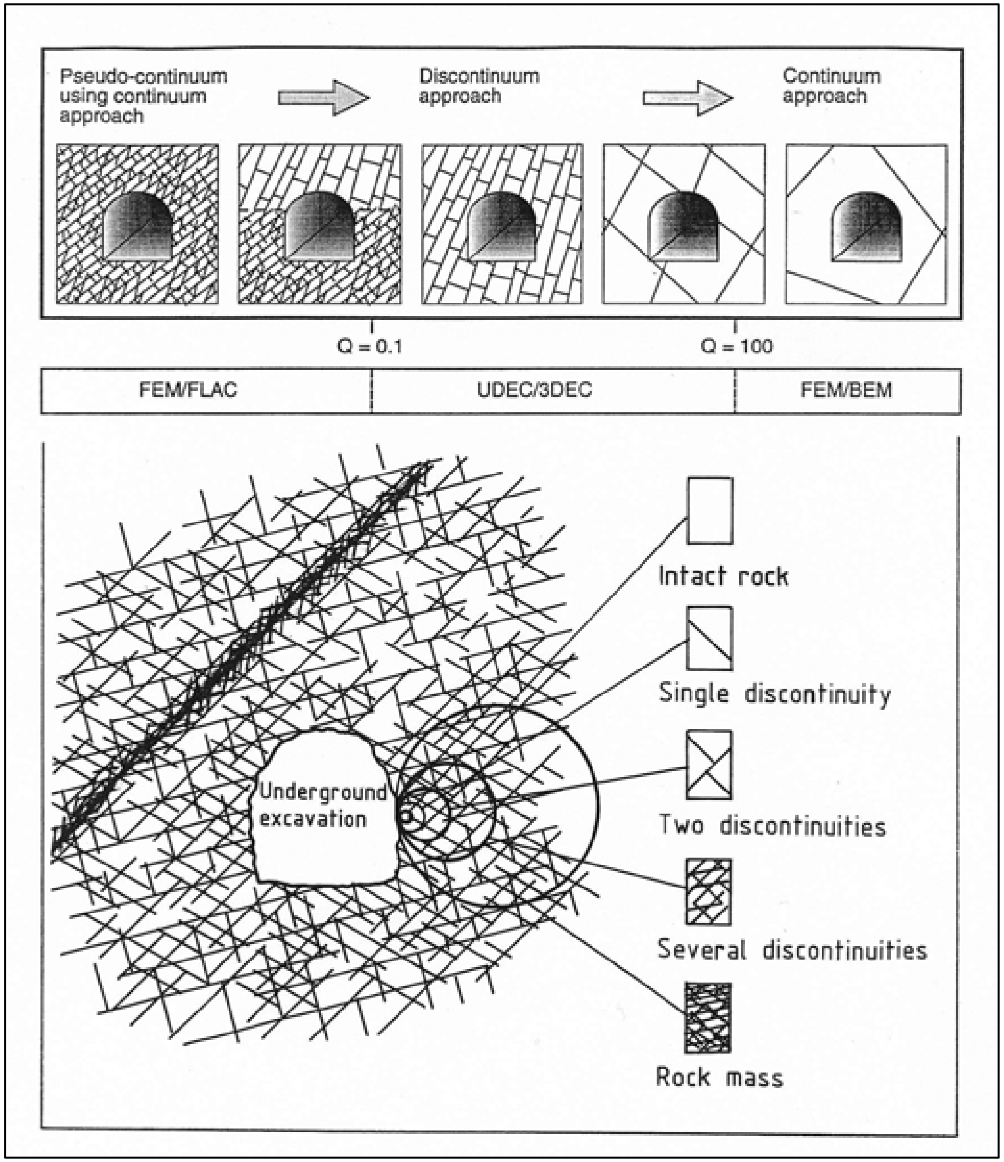
FURO SM-ML4-06 TRECHO 18,26 - 19,50
18.50

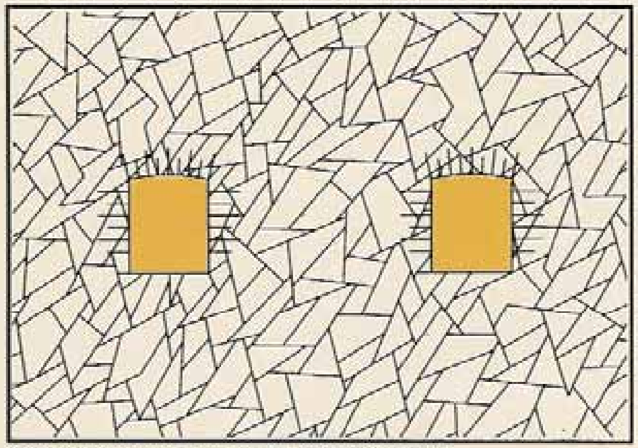

a
Joints
2
3
4
5
6
A
B
C
D
E
F
G
H
Datum line
b
Corestones in situ
Completely weathered granite
A4
A5
C4
D4
E4
G4
C5
D5
E5
G5
H5
C6
D6
E6
G6
H6

DEFORMATION MODULI FOR NUMERICAL MODELS

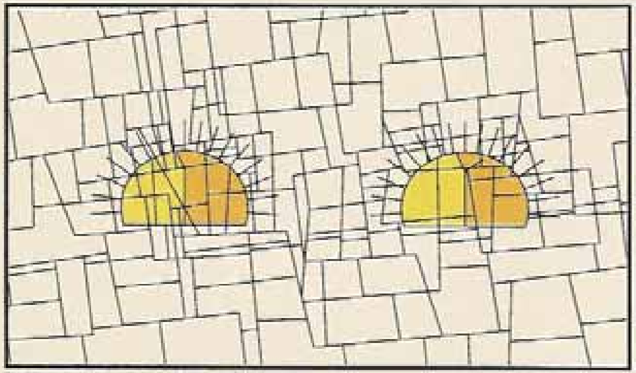
e.g.

UDEC-BB, FLAC, PHASES

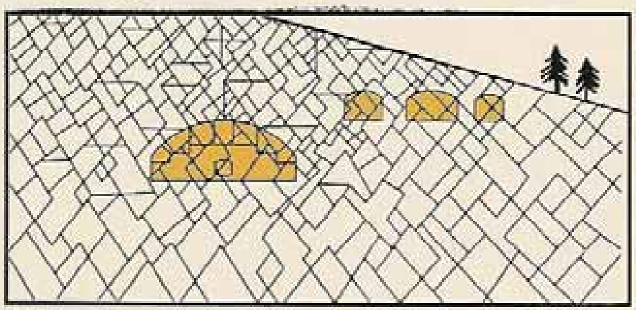

Pseudo-continuum using continuum approach
Discontinuum approach
Continuum approach
Q = 0.1
Q = 100
FEM/FLAC
UDEC/3DEC
FEM/BEM
Underground excavation
Intact rock
Single discontinuity
Two discontinuities
Several discontinuities
Rock mass



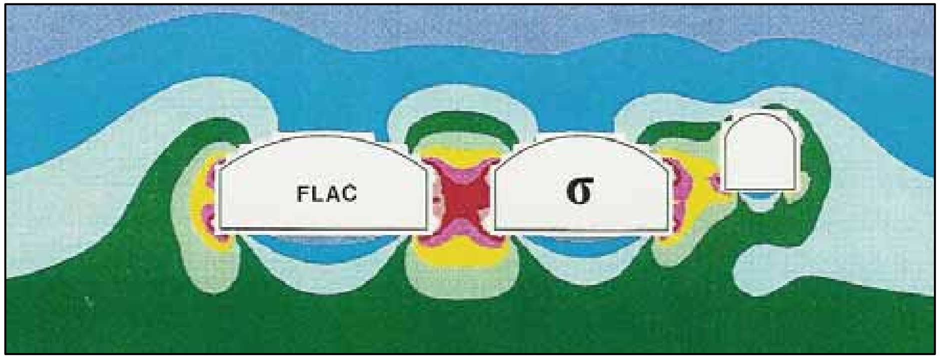
Radioactive waste caverns, UK Nirex Ltd.
England (For Owners)

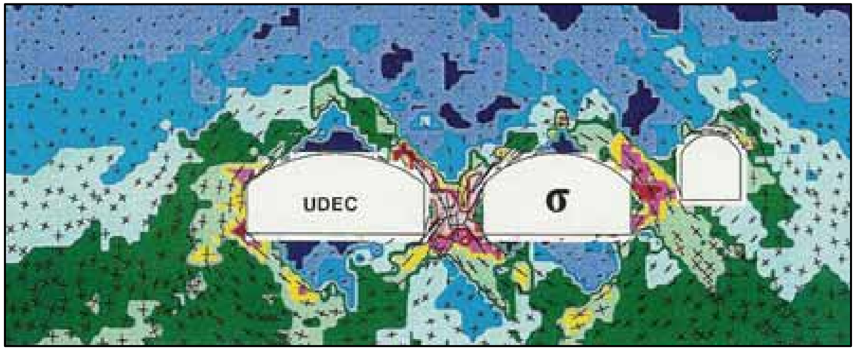


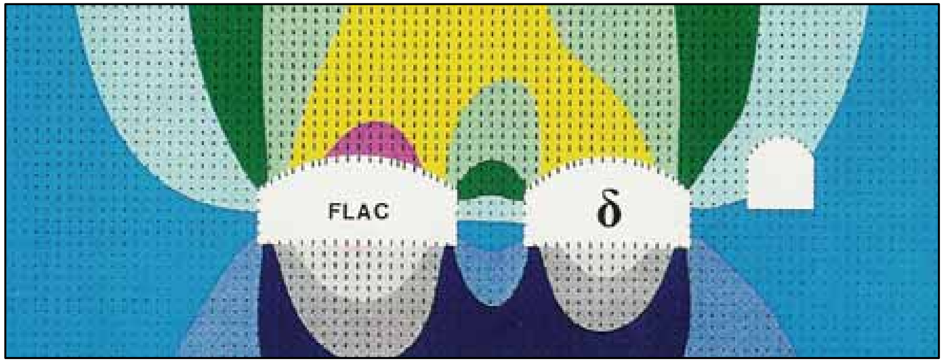
Motorway tunnels, 16m span
Hong Kong (For Contractors)

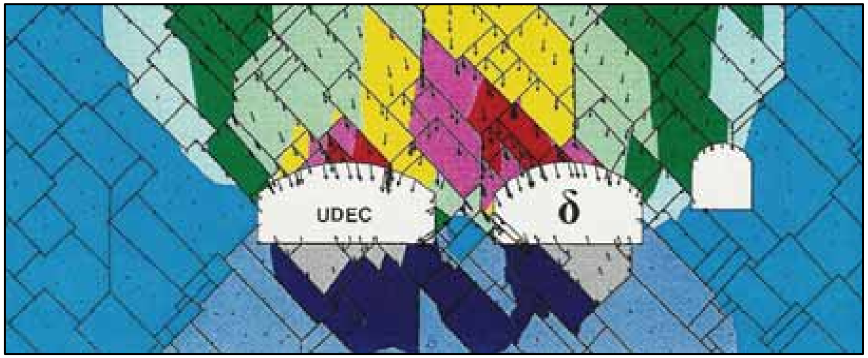


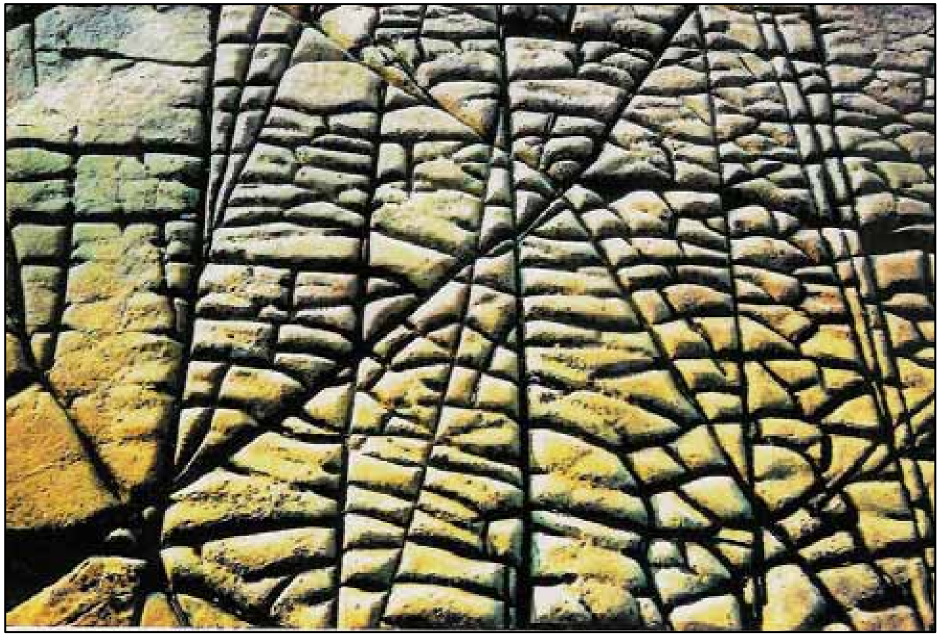
Gjøvik Olympic Mountain Hall, 62m span
Norway (For Consultants)


FLAC
σ

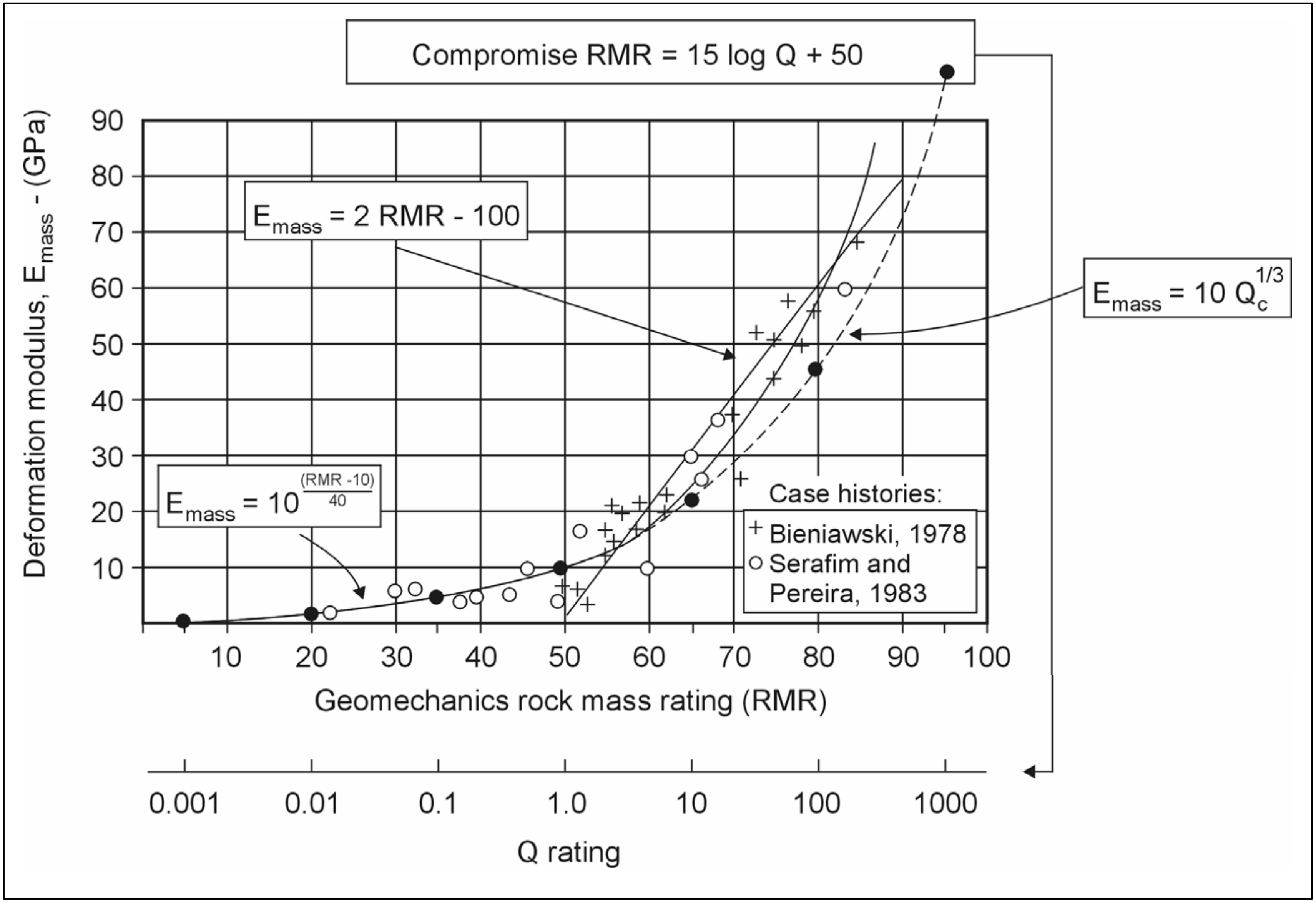

UDEC
σ


FLAC
δ


UDEC
δ



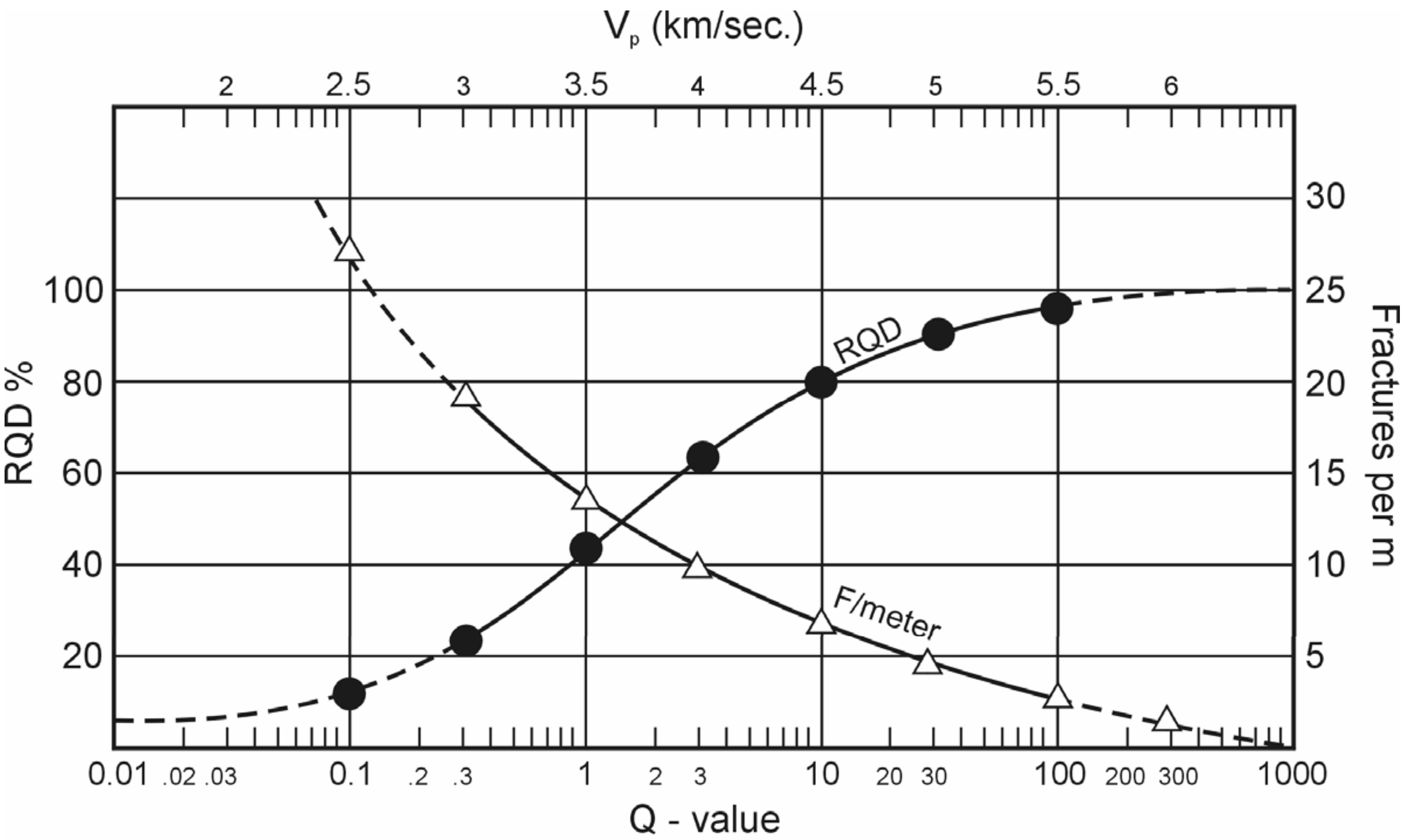
DISCRETE ELEMENT MODELLING REQUIRES ‘PRIORITIZING’ OF MAJOR JOINTS.
BUT MODULUS EFFECT OF UNMODELLED JOINTS NEEDS ALSO TO BE CAPTURED.


Compromise RMR = 15 log Q + 50
E_{mass} = 2 RMR - 100
$E_{mass} = 10\ Q_c^{1/3}$
$E_{mass} = 10^{\frac{(RMR-10)}{40}}$
Case histories:
+ Bieniawski, 1978
○ Serafim and Pereira, 1983
Deformation modulus, E_{mass} - (GPa)
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
Geomechanics rock mass rating (RMR)
0.001
0.01
0.1
1.0
10
100
1000
Q rating

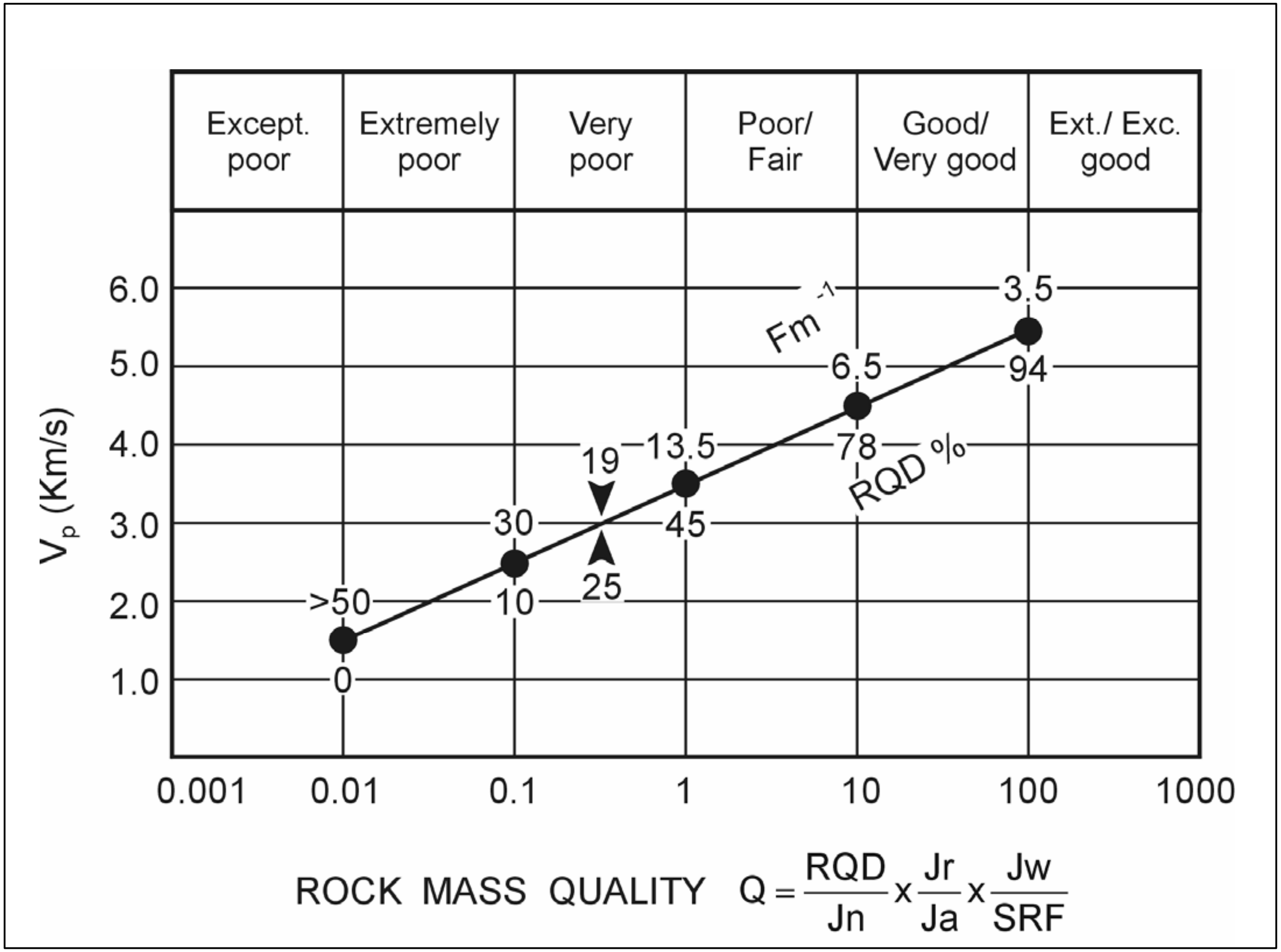
- *In the case of correlating Q-values to engineering/ geophysical parameters like E_{mass} (deformation modulus) or to V_p (P-wave seismic velocity) the term* $Q_c = Q\ x\sigma_c/100$ *is used.*

- *The six-order of magnitude Q range of 0.001 to 1000* (approx.) and the larger range of Q_c *correlate fairly simply, to the huge, real world, range of rock mass properties.*

PREDICTING V_p AND E_{MASS} FROM Q, or Q_c VALUE

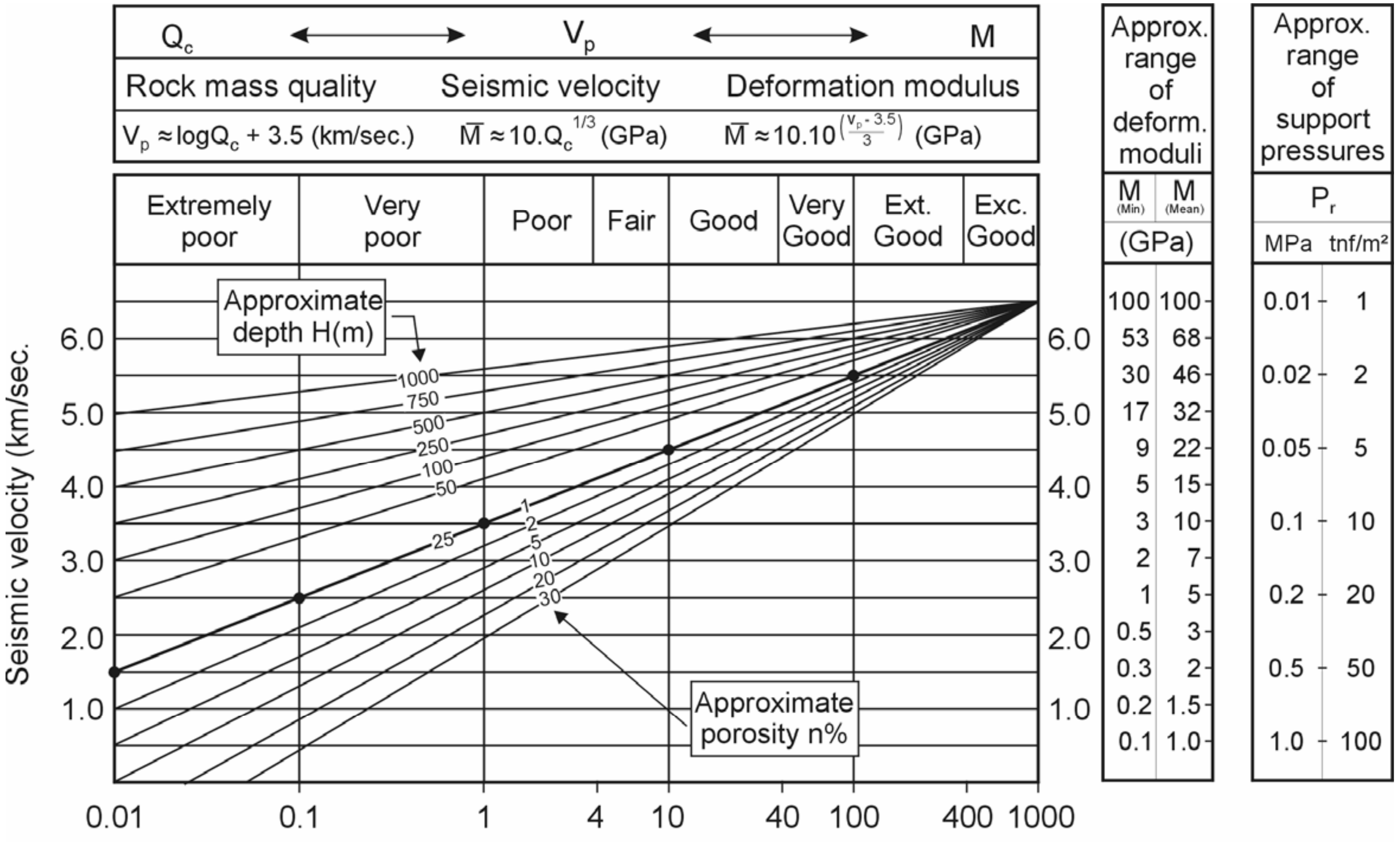


(After Sjøgren et al. 1979, with Barton, 1995 addition of Q)

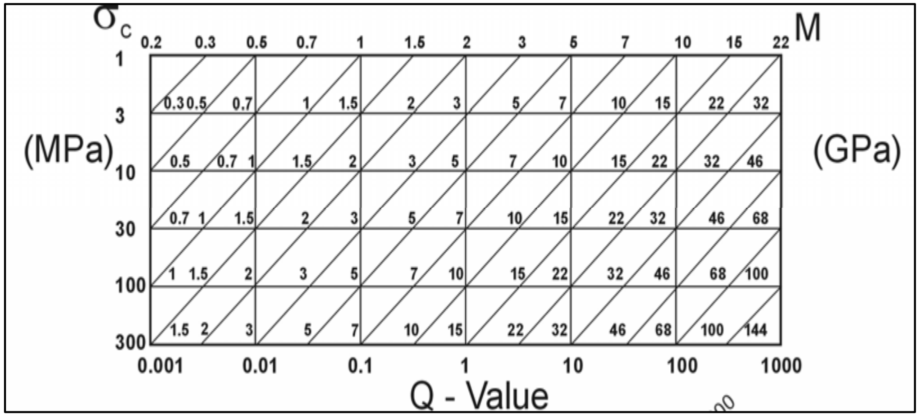


(As with all Sjøgren data: hard rock, near-surface)

AN INTEGRATED MODEL: Q_c – V_p – E_{mass} - P_r



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



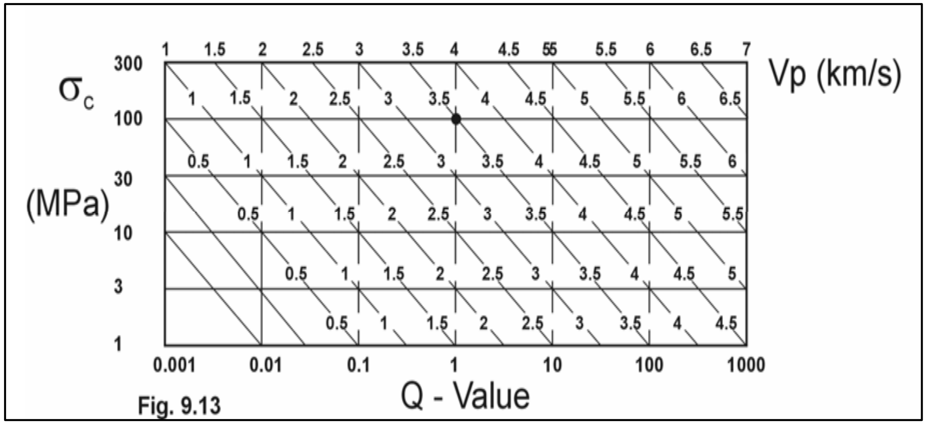
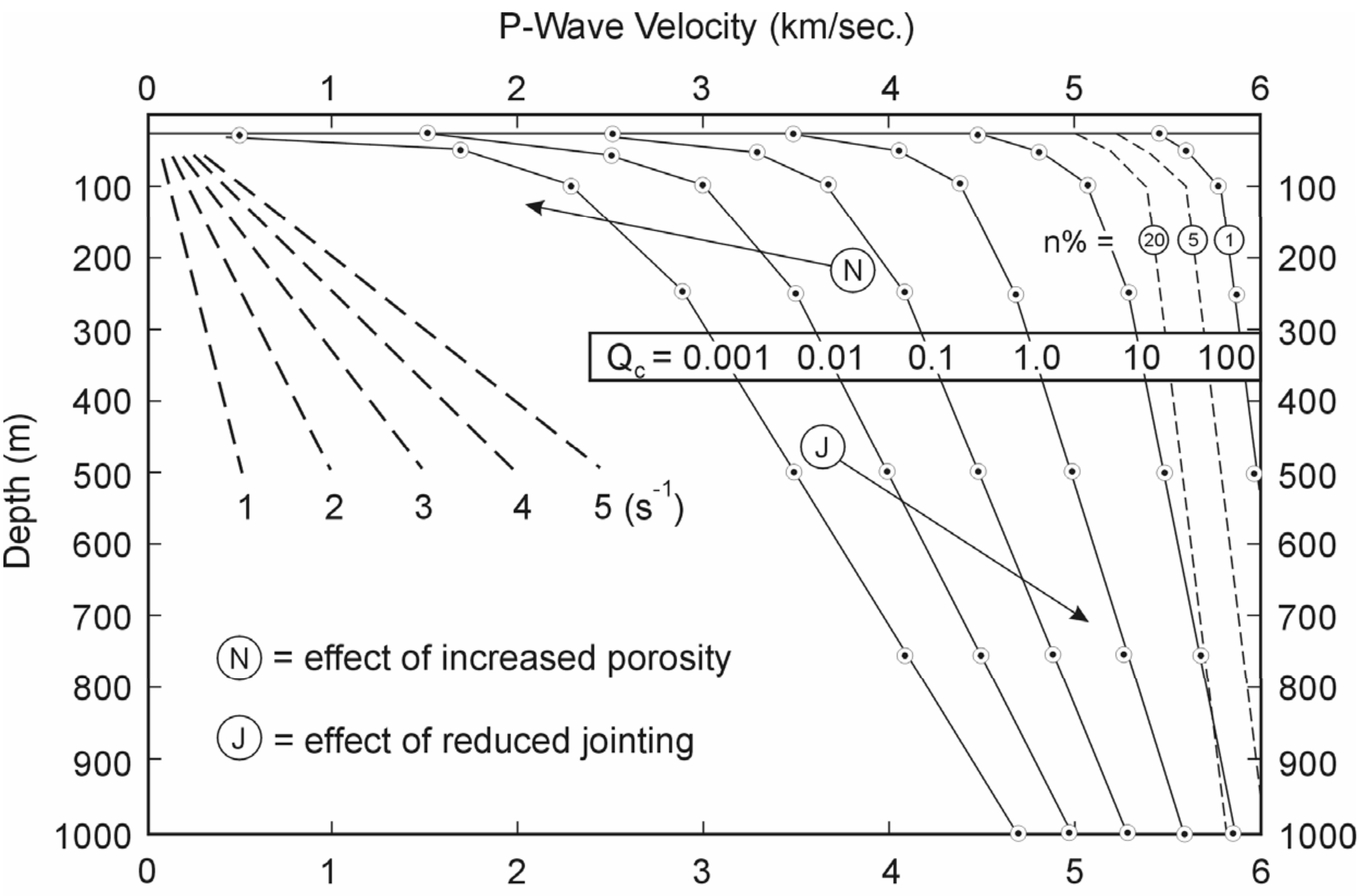
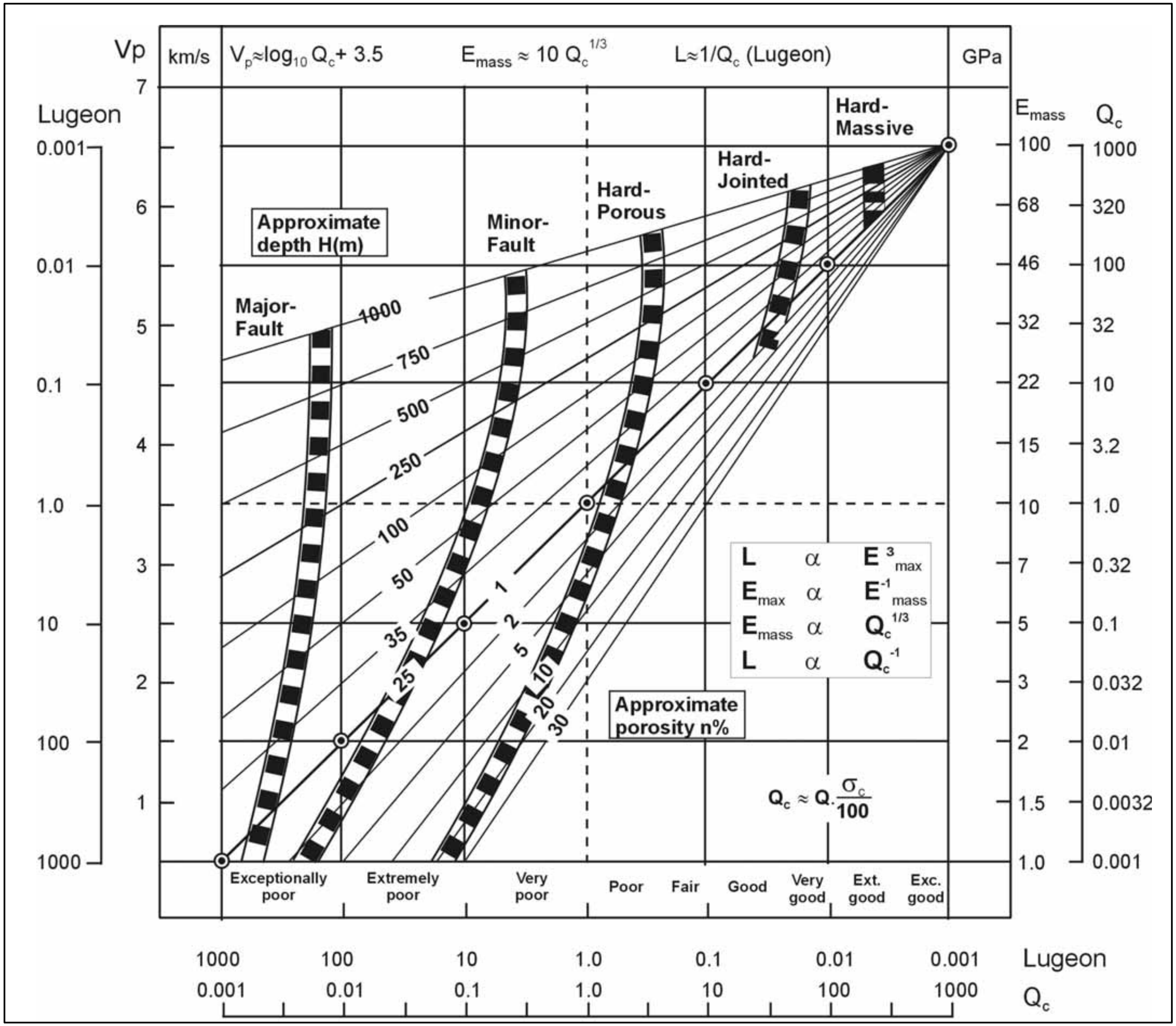


Fig. 9.13

WITH NO CORRECTION FOR DEPTH (OR STRESS) – as central diagonal in previous figure – nominal depth 25m


P-Wave Velocity (km/sec.)
0
1
2
3
4
5
6
Depth (m)
100
200
300
400
500
600
700
800
900
1000
1
2
3
4
5 (s⁻¹)
N
J
n% =
20
5
1
Qc = 0.001
0.01
0.1
1.0
10
100
N = effect of increased porosity
J = effect of reduced jointing


Vp
km/s
$V_p \approx \log_{10} Q_c + 3.5$
$E_{mass} \approx 10\, Q_c^{1/3}$
$L \approx 1/Q_c$ (Lugeon)
GPa
Lugeon
0.001
0.01
0.1
1.0
10
100
1000
7
6
5
4
3
2
1
Emass
100
68
46
32
22
15
10
7
5
3
2
1.5
1.0
Qc
1000
320
100
32
10
3.2
1.0
0.32
0.1
0.032
0.01
0.0032
0.001
Hard-Massive
Hard-Jointed
Hard-Porous
Minor-Fault
Major-Fault
Approximate depth H(m)
1000
750
500
250
100
50
35
25
1
2
5
10
20
30
Approximate porosity n%
L α E 3 max
Emax α E -1 mass
Emass α Qc 1/3
L α Qc -1
$Q_c \approx Q.\frac{\sigma_c}{100}$
Exceptionally poor
Extremely poor
Very poor
Poor
Fair
Good
Very good
Ext. good
Exc. good
1000
100
10
1.0
0.1
0.01
0.001
Lugeon
0.001
0.01
0.1
1.0
10
100
1000
Qc

CC and FC

A recent discovery (Barton, 2002) is that the Q-value consists of the product of the cohesive strength (the component of the rock mass requiring shotcrete or mesh or concrete support), and the frictional strength (the component of the rock mass requiring bolting).

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

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

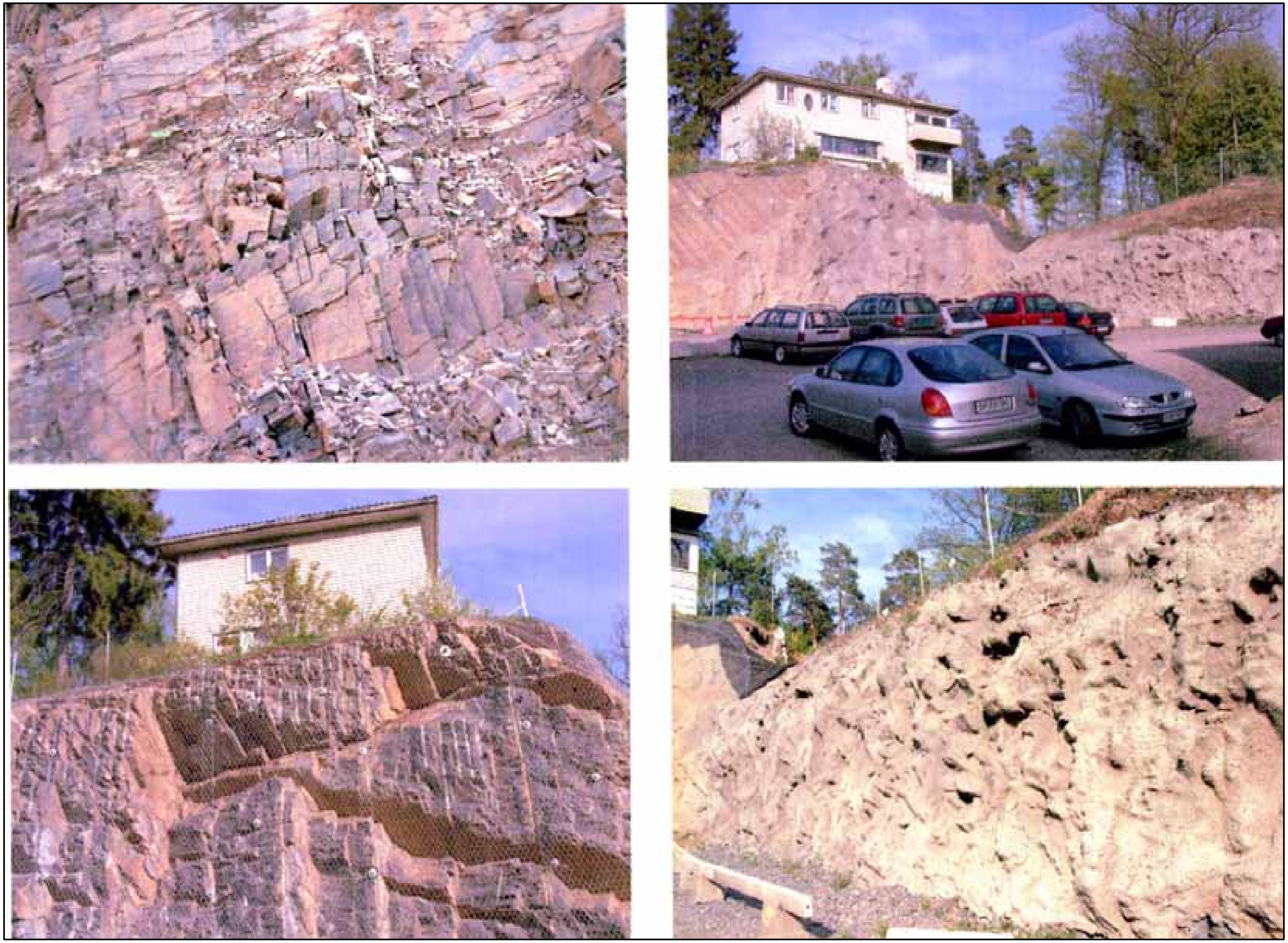
Unpredicted degrees of weathering have a directly negative effect on both these strength (or weakness) components and therefore also on the support requirements.

Table of Q-parameters with declining quality (resembling weathering) (Barton, 2002).

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
10	20	1	6	0.5	5	0.008	10	0.0008	5°	0.01	0.4	0.9

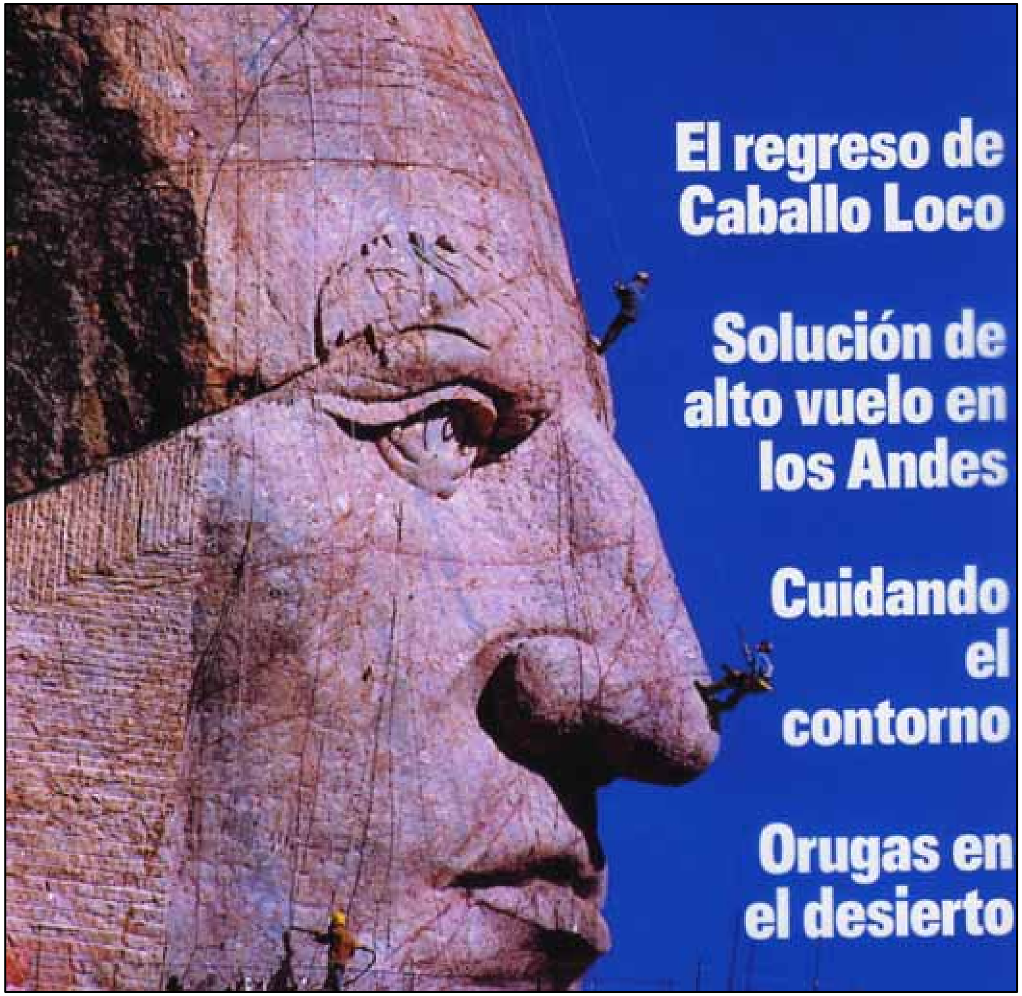
Rock masses with low CC-values require more shotcrete,

Rock masses with low FC-values require more rock bolts



LOW CC **MEDIUM FC**

LOW CC IN ARCH, AND INSUFFICIENT SHOTCRETE THICKNESS CAUSED (REGRETTABLY) THE INSTANT DEATH OF A TUNNEL WORKER


El regreso de Caballo Loco

Solución de alto vuelo en los Andes

Cuidando el contorno

Orugas en el desierto

MINING AND CONSTRUCTION MAGAZINE

HIGH CC **HIGH FC**

$$Q = \frac{100}{0.5} \times \frac{4}{0.75} \times \frac{1.0}{5} = 213$$

SRF = 5 (near-surface)

COMPARISON OF SOME GSI and Q EQUATIONS

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

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

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

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

where $\sigma_{3n} = \sigma'_{3\max}/\sigma_{ci}$

(+GSI + a + s + m_b relations)

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

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

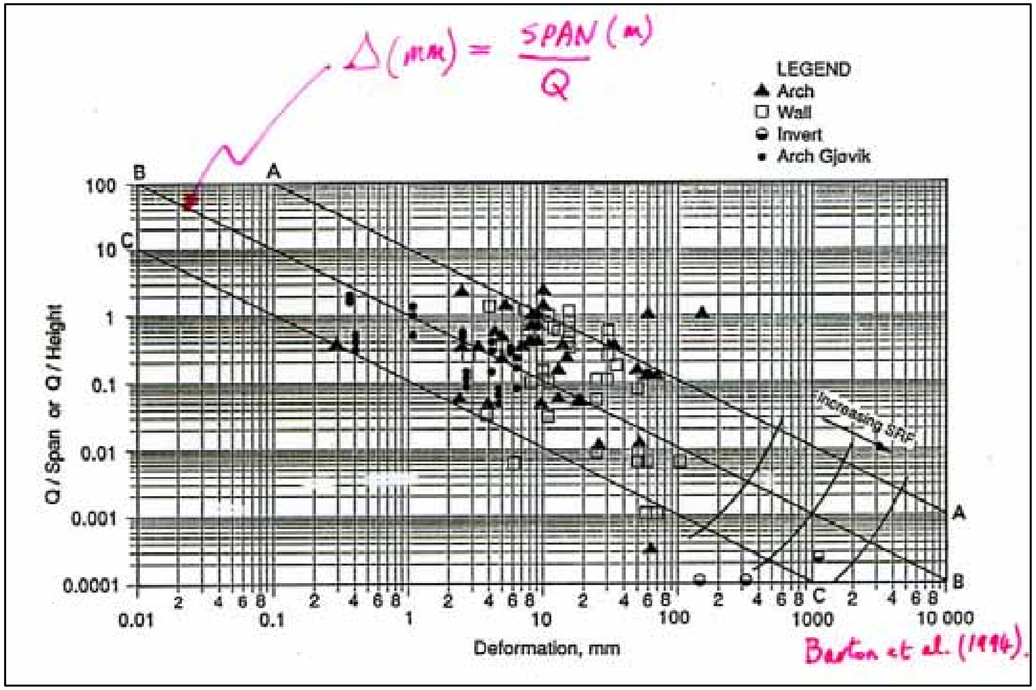
$$"\phi" \approx \tan^{-1}\left(\frac{J_r}{J_a} \times \frac{J_w}{1}\right)$$

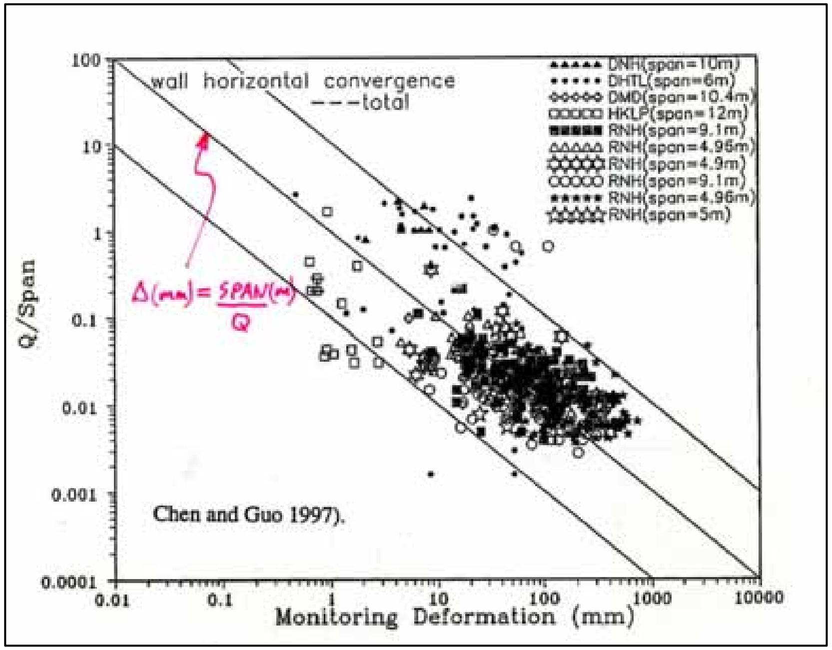
$$"c" \approx \left(\frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100}\right)$$

(no “stress” term yet)

($\sigma_c = \sigma_{ci}$)

DEFORMATION AND CLOSURE PREDICTION WITH Q





Chen and Guo collected hundreds of fresh data from difficult tunnelling projects in Taiwan, using the same plotting format of log Q/SPAN and log *convergence*.

MORE ACCURACY – BY CONSIDERING ‘COMPETENCE FACTOR’

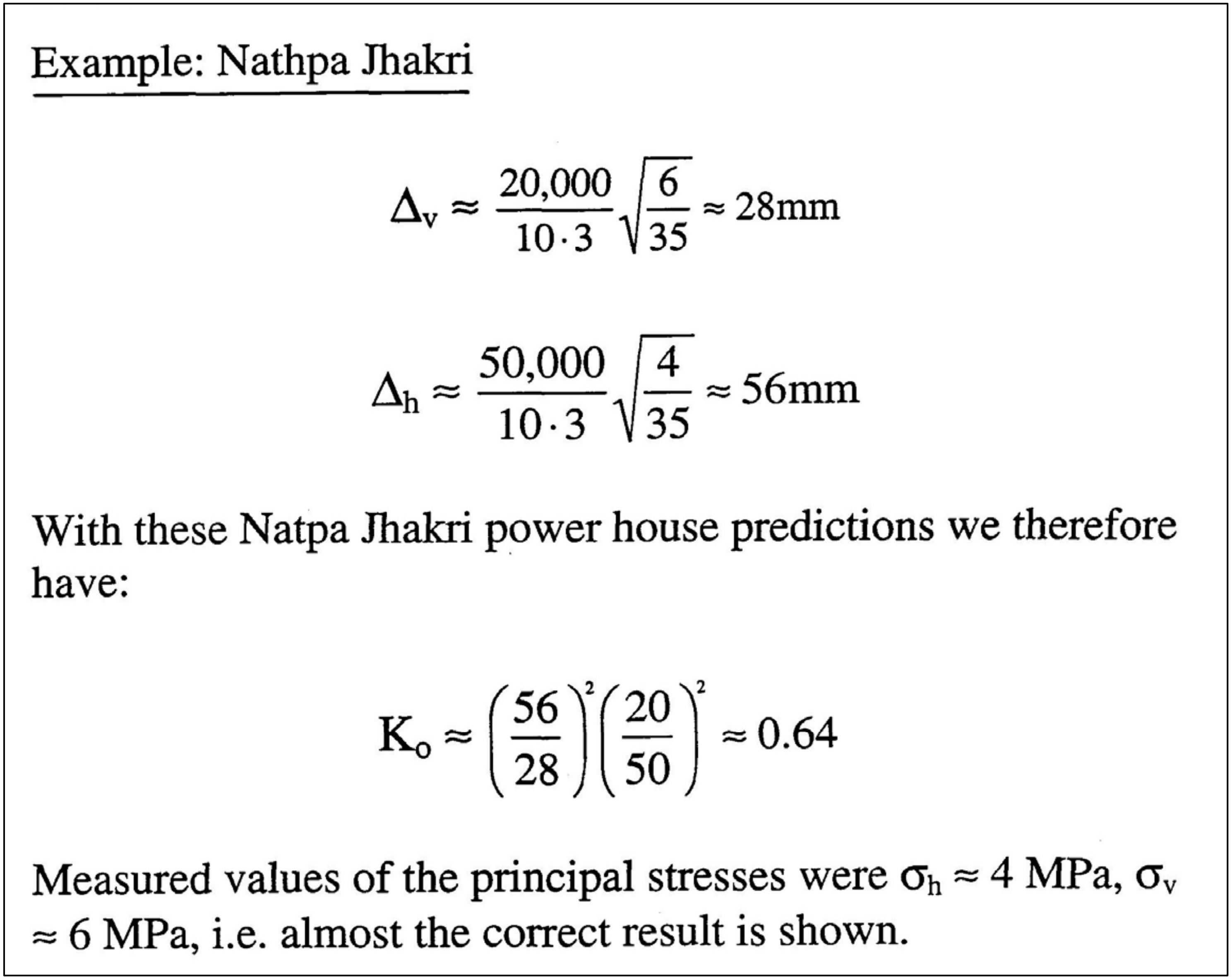
STRESS/STRENGTH DIRECTLY, NOT JUST AS IN SRF

$$\boxed{\Delta_{\mathrm{v}} = \frac{\mathrm{SPAN}}{100\,\mathrm{Q}}\sqrt{\frac{\sigma_{\mathrm{v}}}{\sigma_{\mathrm{c}}}}}$$

$$\boxed{\Delta_{\mathrm{h}} = \frac{\mathrm{HEIGHT}}{100\,\mathrm{Q}}\sqrt{\frac{\sigma_{\mathrm{h}}}{\sigma_{\mathrm{c}}}}}$$

$$\boxed{k_o = \left(\frac{SPAN}{HEIGHT}\right)^2\left(\frac{\Delta_h}{\Delta_v}\right)^2}$$

(Units are as follows : SPAN, HEIGHT, Δ_v and Δ_h are each in millimetres, while rock stresses and rock strengths need consistent units such as MPa).



Example: Nathpa Jhakri

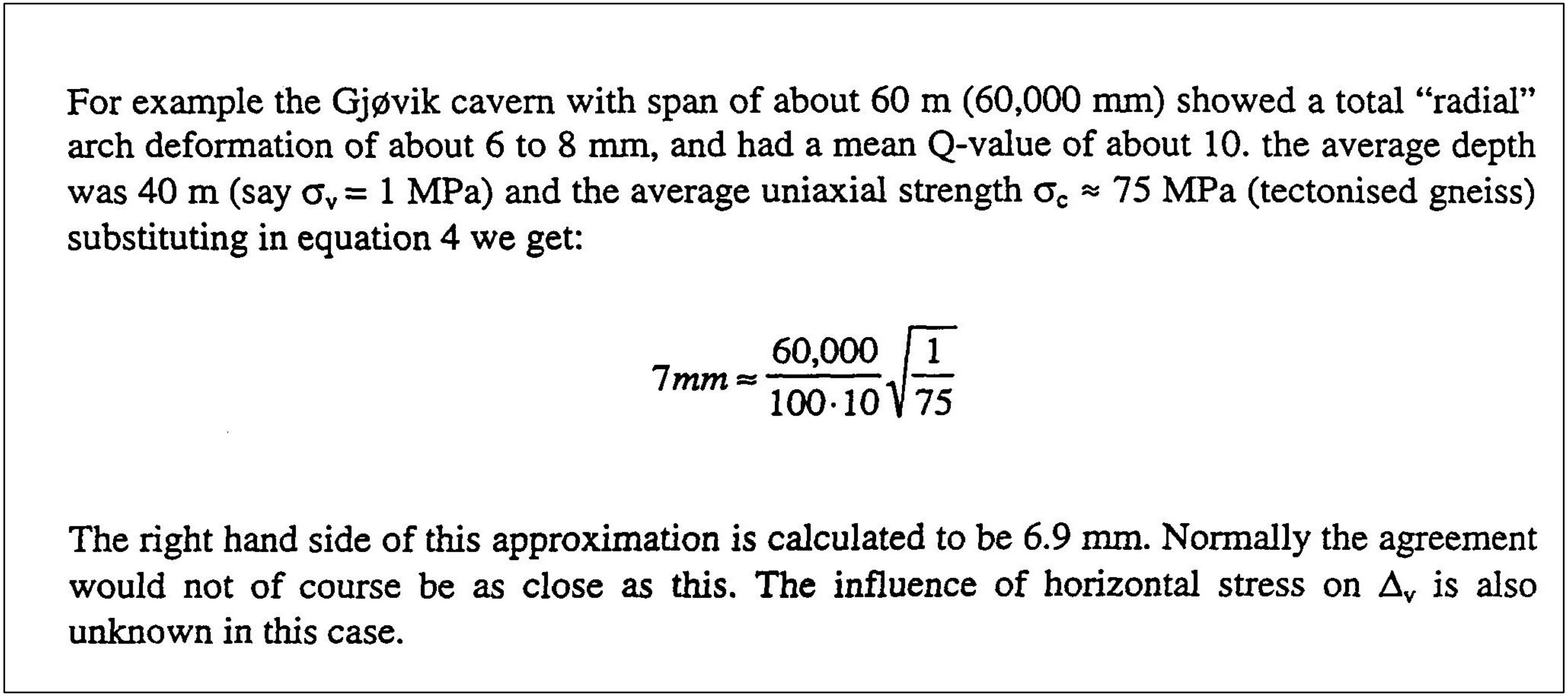
$$\Delta_v \approx \frac{20{,}000}{10 \cdot 3}\sqrt{\frac{6}{35}} \approx 28\text{mm}$$

$$\Delta_h \approx \frac{50{,}000}{10 \cdot 3}\sqrt{\frac{4}{35}} \approx 56\text{mm}$$

With these Natpa Jhakri power house predictions we therefore have:

$$K_o \approx \left(\frac{56}{28}\right)^2 \left(\frac{20}{50}\right)^2 \approx 0.64$$

Measured values of the principal stresses were $\sigma_h \approx 4$ MPa, $\sigma_v \approx 6$ MPa, i.e. almost the correct result is shown.



For example the Gjøvik cavern with span of about 60 m (60,000 mm) showed a total "radial" arch deformation of about 6 to 8 mm, and had a mean Q-value of about 10. the average depth was 40 m (say $\sigma_v = 1$ MPa) and the average uniaxial strength $\sigma_c \approx 75$ MPa (tectonised gneiss) substituting in equation 4 we get:

$$7mm \approx \frac{60{,}000}{100 \cdot 10}\sqrt{\frac{1}{75}}$$

The right hand side of this approximation is calculated to be 6.9 mm. Normally the agreement would not of course be as close as this. The influence of horizontal stress on Δ_v is also unknown in this case.

EXAMPLE OF DEFORMATION ESTIMATION IN FAULTED ROCK

- **Pinglin Tunnel: heavily jointed, slickensided and sometimes clay-bearing quartzites, acted on by exceptionally high joint-water pressures. An initial Q-value, prior to eventual drainage is about :**

$$Q = \frac{15}{9} \times \frac{0.5}{4} \times \frac{0.05}{1} = 0.01$$

- **The above equation implies a potential deformation of about 1 meter.**

- **The reality is actually repeatedly stuck TBM, and sometimes badly deformed steel sets, or occasional piping failures at the face as the water tries to drain through probe holes.**

- **A key to 'improved' Q-value and reduced deformations, would be drainage if achievable, and effective high pressure pre-grouting. These two potential measures can be beneficial to one or to several of the six Q-parameters.**