International Progress Report

IPR-04-07

Äspö Hard Rock Laboratory

Äspö Pillar Stability Experiment

Q-logging of the TASQ tunnel at Äspö

For rock quality assessment and for development of preliminary model parameters

Nick Barton

Nick Barton & Associates

August 2003

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

Äspö Hard Rock Laboratory

Report no.	No.
IPR-04-07	F86K
Author	Date
Nick Barton	2003-08-20
Checked by	Date
Christer Andersson	2004-11-24
Approved	Date
Christer Svemar	2004-11-26

Äspö Hard Rock Laboratory

Äspö Pillar Stability Experiment

Q-logging of the TASQ tunnel at Äspö

For rock quality assessment and for development of preliminary model parameters

Nick Barton

Nick Barton & Associates

August 2003

Keywords: TASQ, KA3376B01, KA3386A01, KF0069A01, Sonic velocity, Young´s modulus, Convergence

Abstract

Statistical logging of individual Q-parameters has been performed along 55m of the APSE tunnel (ch. 24 to 80m) and for the full length of the KA 3376 B01 core, which runs in the left wall of the tunnel. The overall picture is of increased jointing towards the end of the tunnel and towards the end of the borehole. The best values of Q_{mean} and $Q_{most\ frequent}$ and relative block size RQD/J_n were registered in the chainage 45 to 53m. Since the target area, with completed invert, is from about ch. 60 to 75m, the Q_{mean} and $Q_{most\ frequent}$ averages of 20 and 40 from this 15m of tunnel have been used to make preliminary estimates of seismic velocity (5.8 to 6.0 km/s) and E_{mass} (59 to 66 GPa). Estimates have also been made of tunnel convergence, which corresponds quite well to measured convergences. Rock mass strengths and cohesive and frictional strengths have also been empirically estimated, based on the Q-logging.

Sammanfattning

Statistisk Q-loggning har genomförts mellan sektionerna 24 och 80 meter i APSE-tunneln (TASQ) samt utefter kärnborrhålet KA3376B01:s fulla längd. Kärnborrhålet är beläget strax utanför tunnelns vänstra vägg. Den generella trenden som observerats är en ökad sprickighet mot slutet av både tunneln och kärnborrhålet. De högsta värdena för Q_{mean} , $Q_{most\ frequend}$ och blockstorleken RQD/J_n fanns mellan sektionerna 45 och 53 meter. Eftersom experimentets målområde finns mellan sektionerna 60 till 75 meter har medelvärdena 20 respektive 40 på Q_{mean} och $Q_{most\ frequent}$ använts för att göra bedömningar av den seismiska hastigheten (5,8 och 6,0 km/s) samt elasticitetsmodulen för bergmassan (59 och 66 GPa) i detta 15 meter långa område. Bedömningar har även gjorts på tunnelkonvergensen vilken stämmer ganska bra mot faktisk mätta konvergenser. Q-loggningen har även använts för att göra empiriska bedömningar av bergmassans hållfasthet, kohesions samt friktionsegenskaper.

Contents

1 Introduction

This report contains details of the Q-logging performed in the inner 55m of the APSE Tunnel, and of the adjacent borehole KA3376 B01, located in the left-hand wall, parallel to the tunnel. Mention is also made of the overall results of Q-logging of the SSW oriented hole KA3386A01 drilled from TASA. This was reported, together with that of a NNE oriented hole (KF0069A01) in Appendix E. The objective of this report is the derivation of an understanding of the range of rock quality from which representative input data can be estimated. This is done with respect to the 450m depth and the assumed anisotropic stress field. Since rock quality varies along the tunnel there will be potential ranges of e.g. rock mass deformation modulus, which could potentially be used in larger scale continuum modelling of the boundary conditions for the pillar loading experiment (which at present has not been finally located).

2 Logging philosophy and method

The anisotropic principal stresses in TASQ, which can be assumed to be about 30, 15 and 10 MPa, cause an even stronger anisotropy of tangential stresses when the tunnel is excavated. When Q-logging, the maxima of σ_θ in the arch and invert, and the minima of σ_θ in the walls have been accounted for. The pillar loading experiment has a local scale of roughly 1 to 3m, and this has been the focus for Q-parameter logging.

There are up to five joint set orientations that can be identified along the length of the TASQ tunnel, but in most locations there are only one or two joints sets present locally on the 1 to 3m scale that is the subject of logging (and of planned pillar loading). There are also parts of the tunnel with virtually no joints per se (non, or less than 50 cm continuity), where all half-rounds are continuous, even along the walls (where stresses are less optimal due to low minimum tangential stresses).

Since all these local variations of jointing are of importance in locating the experiment, and in selection of (local) rock mass deformation moduli, the statistical areal variation of rock mass quality parameters is considered the fairest way to capture the variability of the medium. Appendix A and B show how the variability was captured by multiple-position (and therefore multiple-opinion) logging of each of the six Q-system parameters.

Logging was performed of ch. 24 to 59m (the position of the tunnel face on 26 June 2003) and of ch. 59 to 67m (face at 67m on 30 June 2003). On these occasions only the upper portion (about 4 m) of the walls could be logged, together with the arch. As will be noted in Appendix A (scans of the original logging sheets), ten opinions of ratings of each of the six Q-parameters are given for ***each*** of the following: left wall, arch, right wall, making thirty observations (× 6) for each 5m of tunnel. Since seven 5m long panels were logged on this occasion, there were 30×6×7 = 1270 observed values of Q-parameters recorded on this occasion.

An opportunity to log the latest 8m (59 to 67 m) while the tunnel face was being loaded is also recorded in Appendix A. However, as access was limited by the presence of the jumbo and many personnel (see Figure 1), this logging served as only a check of part of the subsequent logging of chainage 60 to 80m, when the tunnel was more accessible.

This final logging is recorded in Appendix B. On this occasion the invert had been completed over this 60 to 80m chainage, and the Q-parameter logging therefore consisted of ten opinions of both the right and left ***lower walls and invert*** (where visible). There are therefore 20×6×5 = 600 observed values of Q-parameters recorded on this occasion.

To complete reference to the logging phase of this work, we can also refer to Appendix C, where the Q-parameter logging of core from KA3376B01 is recorded. This hole is located a couple of metres (approx.) into the left wall of the tunnel and is also 80m long, but with the collar originating about 10 metres ‘before’ the tunnel chainage of 0.0m. Hence the borehole collar originates at tunnel chainage 10m. For this core, in view of its limited ‘weighting’ in the overall quality assessment, five opinions of each Q-parameter were given for each core box containing 5m of core, with fewer assessments when less than 5m of core was stored.

***Figure 1**. Preparations for blasting with the face at 67m. Note tangential stress effects in arch, and lack of half-rounds in right wall.*

3 SRF estimation and stress effects

Q-system logging instructions and tables of ratings (which are reproduced for reference in Appendix D) show the following details concerning SRF.

'component rock, rock stress problems'	**SRF**	**σ_c/σ_1**	**σ_θ/σ_c**
K High stress, very tight structure. (Usually favourable to stability, may be unfavourable for wall stability)	**0.5-2**	**10-5**	**0.3-0.4**

Footnotes below the tables, which were expanded in Barton (2002a), contain the following suggestion for distinguishing 'classification' (as in tunnel support estimation exercises) from 'characterization' (without excavation-induced stress changes):

'For general characterization of rock masses distant from excavation influences, the use of SRF = 5, 2.5, 1.0 and 0.5 is recommended as depth increases from say 0-5, 5-25, 25-250 to > 250m. This will help to adjust Q for some of the effective stress effects, in combination with appropriate characterization values of J_w.'

When logging the core from KA 3376 B01, the SRF value of 0.5 has been used as in ***characterization*** of a site deeper than 250m, where also σ_c/σ_1 is in the typical range (185→215 MPa)/(25→35 MPa) or between 5 and 10, as above.

In the case of the tunnel, the early logging included the use of SRF = 2.0 for the two walls, and SRF = 0.5 for the arch and invert. Since the invert is the focus of attention, Q-value calculations later excluded the value of SRF = 2.0 suitable for ***classification*** of the walls, and an overall value for SRF = 0.5 was used.

Since σ_1 may be in the range 25 to 35 MPa, and σ_3 about 10 MPa in the APSE area of Äspö, the theoretical elastic solution for the maximum tangential stress [$\sigma_\theta = 3\ (\sigma_1 - \sigma_3)$] is perhaps in the range 65 to 95 MPa, which is roughly 0.3 to 0.4 of the uniaxial strength range for the diorite and granite. This also satisfies the use of SRF = 0.5, following the Q-system notes listed above.

The fact that the elastic solution suggests low (5 MPa) or even negative values of σ_θ (minimum) is perhaps reflected in the typical logging experience of more frequent half-pipes visible in the arch (and invert where visible) and the more frequent lack of half-pipes (and increased water inflows) in the walls. Figure 2 illustrates typical differences between the appearances of the walls and arch, ***where any jointing in the walls has a stronger tendency to reduce the number of half-pipes in the walls, than it has in the arch (or invert).***

Contrasting areas of the walls with a) some loss of half-pipes and b) not loss of half-pipes, are shown in Figure 3 (ch. 59 to 67m) and in Figure 4 (ch. 47 to 53m). Inevitably, the impression is given of improved rock mass quality where, in this case, set 1 and set 2 joints (see later sketch of orientations) are less prominent regarding continuity, frequency and degree of mineral coating.

***Figure 2**. Contrasting quality due to jointing and tangential stress effect: few half-rounds visible on left wall (38 to 46m approx.), excellent arch (45-49m approx.).*

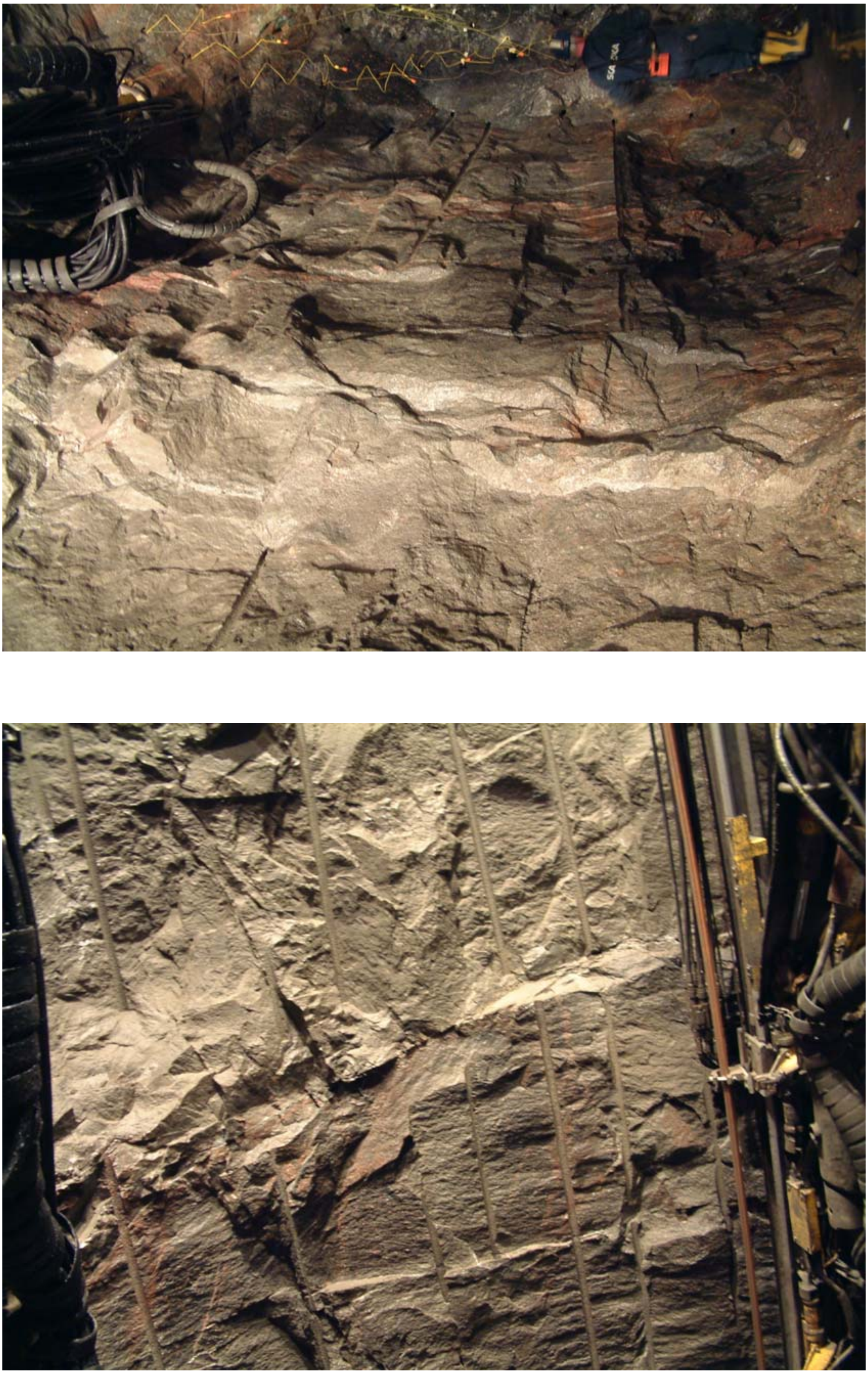


Figure 3. *Section 59-67m, with missing half-pipes on left and right walls due partly to jointing, and also to stress.*

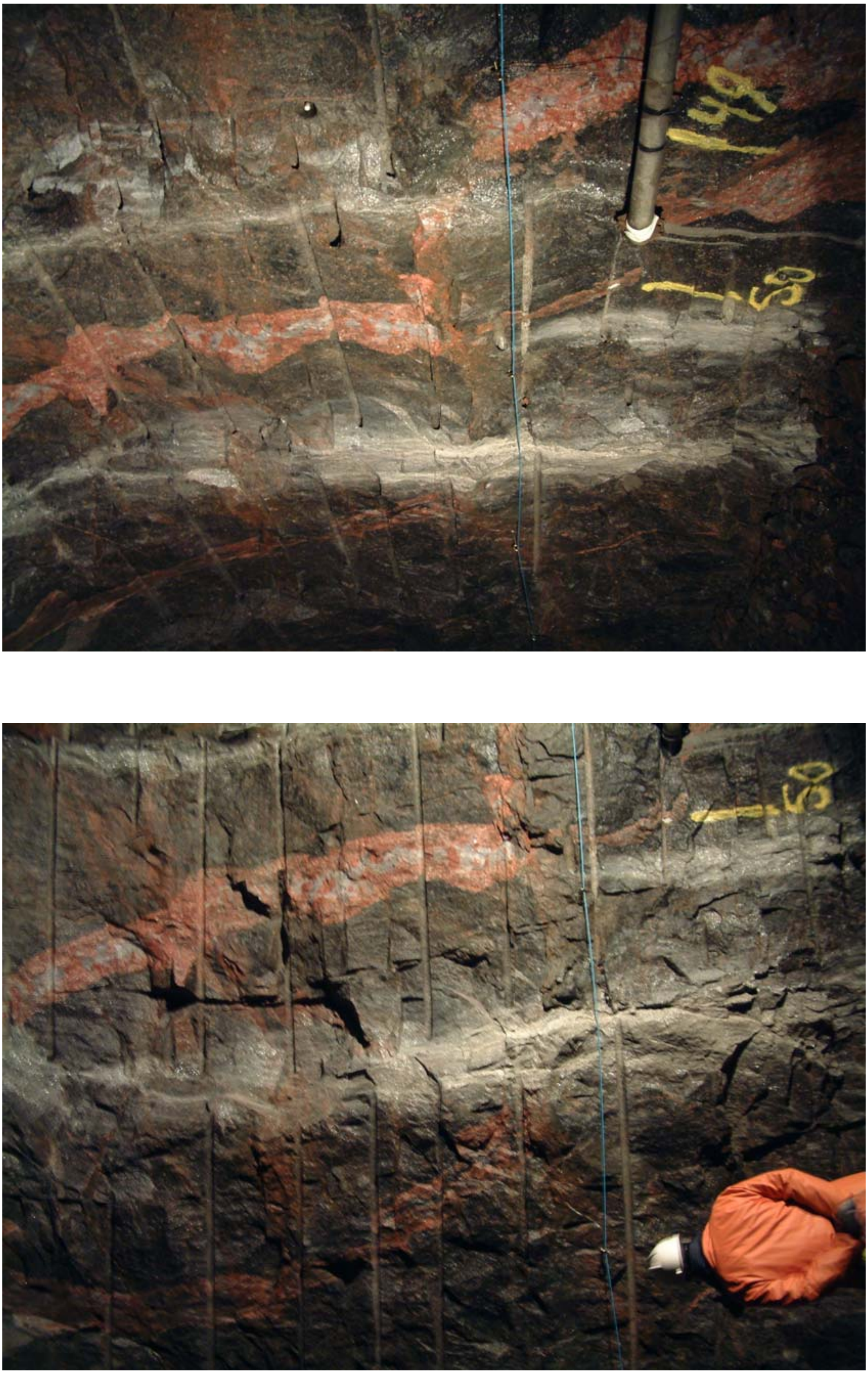


***Figure 4**. Excellent quality and numerous half-rounds in walls (both) and arch are evident between ch. 47 to 53m, probably due to reduced jointing.*

4 Water inflow, pre-grouting and J_w

A 'complicating' factor in the tunnel logging was a) the degree of potential water leakage, b) its reduction to less inflow due to pre-injection, and c) the fact that joints sometimes appeared to have mineral coatings, but were in fact containing thin grout infillings.

Illustrations of where it was easy to see the difference are given in Figure 5. The two component filling of calcite (?) and a millimetre or two of grout in σ_1 parallel (set 1) joints is easy to see, and evidence of grout take on two joint sets is also evident.

A lot of water continued to flow into the tunnel despite the pre-grouting, perhaps due to insufficient grouting pressures. There were therefore numerous recordings of $J_w = 0.66$ ('medium inflow, or pressure') and a lesser number of $J_w = 1.0$ (dry or minor inflow). Without the pre-grouting, which largely solved a 300 litres/minute grout-hole inflow, it would undoubtedly have been correct to use a more serious category of $J_w = 0.5$ in several places along the tunnel.

The 5m long invert 'panels' in the final 20m of the tunnel (ch. 60 to 80m) require frequent pump action. Figure 6 suggests that this inflow may be coming in the lower walls and invert more than from in the upper walls and arch, from which only frequent drips are coming. Since the invert is the experimental area, the majority logging result of $J_w = 0.66$, and J_w (mean) = 0.79 in the chainage 60 to 80m seems justified. Overall, the logged 24 to 80m chainage showed J_w (most frequent) = 1.0, and J_w (mean) = 0.83.

An observation of relevance to coupled behaviour was the wetness of the face area when at 59m (with the two sub-parallel injected joints (set 1 and set 2), followed by much drier conditions at the same chainage when the tunnel was advanced beyond this location. This is perhaps due to the removal of some of shear stress components, acting at (around) the face, but not behind the face.

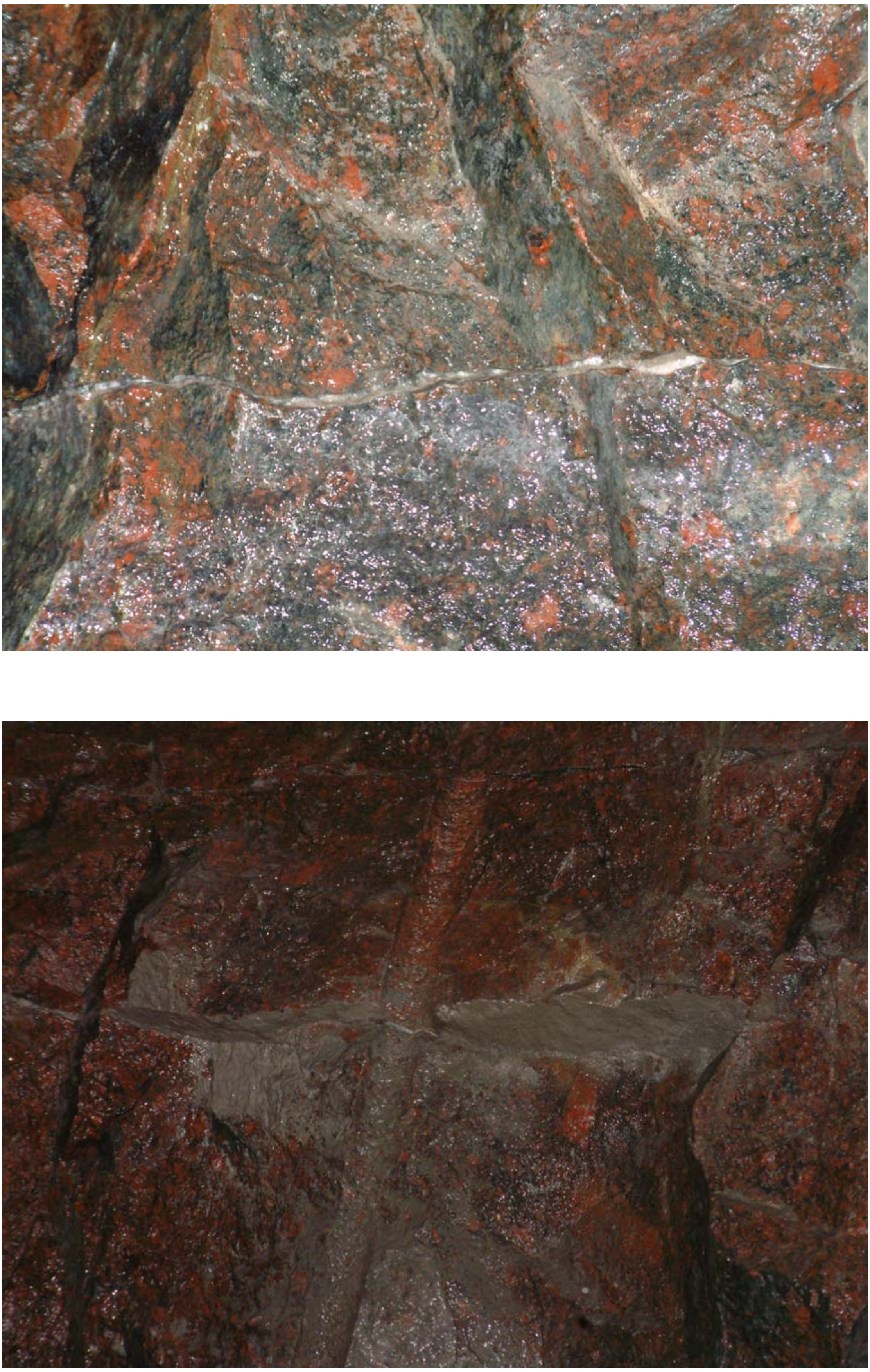


Figure 5. *Evidence of grout penetration (sometimes on two sets) and joint deformation due to pre-grouting pressures.*

Figure 6. *General view from about ch. 75 to 60m. Note accumulation of water in invert and from lower walls, where $J_w = 0.66$ was the most frequent character logged.*

5 Core logging result(s)

In Appendix E the results of ***characterization*** logging of two boreholes drilled in potential experimental areas for APSE is reported. In view of the southerly final location of the TASQ tunnel, it is appropriate to record only the result for KA3386A01, which was drilled to a length of 65m in a SSW direction, directly opposite direction to the TASQ-tunnel from TASA.

KA3386A01

$$Q_{mean} = \frac{97.5}{3.9} \times \frac{2.0}{2.4} \times \frac{0.9}{0.5} = 37.3$$

$$Q_{most\ frequent} = \frac{100}{3} \times \frac{2}{3} \times \frac{1}{0.5} = 44.4$$

In the present, final phase of logging, which was performed independently from these earlier results, the 80.2m long KA33760B1 hole drilled in the left wall of the future TASQ tunnel gave the logging results that are assembled in Appendix C. As can be noted, there are five recordings of Q-parameters for each box of 5m core, and less when fewer metres were found in a core box. Although there was a certain disturbance in the logging quality (and sequence) due to the stress measurement over-coring, the overall result serves as a reasonable source of comparison with the subsequent tunnel logging.

Due to sequencing of visits, there was not the desired 'separation' of core logging and tunnel logging. Part of the tunnel (arch and upper walls, ch. 24 to 59m) was logged immediately prior to the core logging, the remainder (ch. 59 to 67m) and subsequently ch 60 to 80m (lower walls and invert) were logged later, the latter one month later.

Figure 7 shows the appearance of a typical good quality core box and examples of mineral or clay coatings on several of the joints. There appeared to be three sets. The overall Q-parameter histograms for the 80.2m of core are shown in Excel format in Figure 8. The following overall statistics for the hole are evident:

KA3376B01 **0 to 80.2m**

$$Q_{mean} = \frac{94}{3.2} \times \frac{2.1}{2.4} \times \frac{0.79}{0.5} = 40.8$$

$$Q_{most\ frequent} = \frac{100}{2} \times \frac{2}{3} \times \frac{0.66}{0.5} = 44.0$$

In view of the tunnel logging sequencing (24 to 59m logged first, 60 to 80m logged one month later), the core logging results were also separated into two portions (see Figures 9 and 10). Although not strictly comparable, chainage against chainage, the core logging result showed the following reduction in quality when comparing the first 60m with the last 20m:

KA3376B01 **0 to 59.4 m**

$$Q_{mean} = \frac{94}{3.0} \times \frac{2.2}{2.3} \times \frac{0.81}{0.5} = 48.4$$

$$Q_{most\ frequent} = \frac{100}{2} \times \frac{2}{3} \times \frac{0.83}{0.5} = 55.3$$

59.4 to 80.2 m

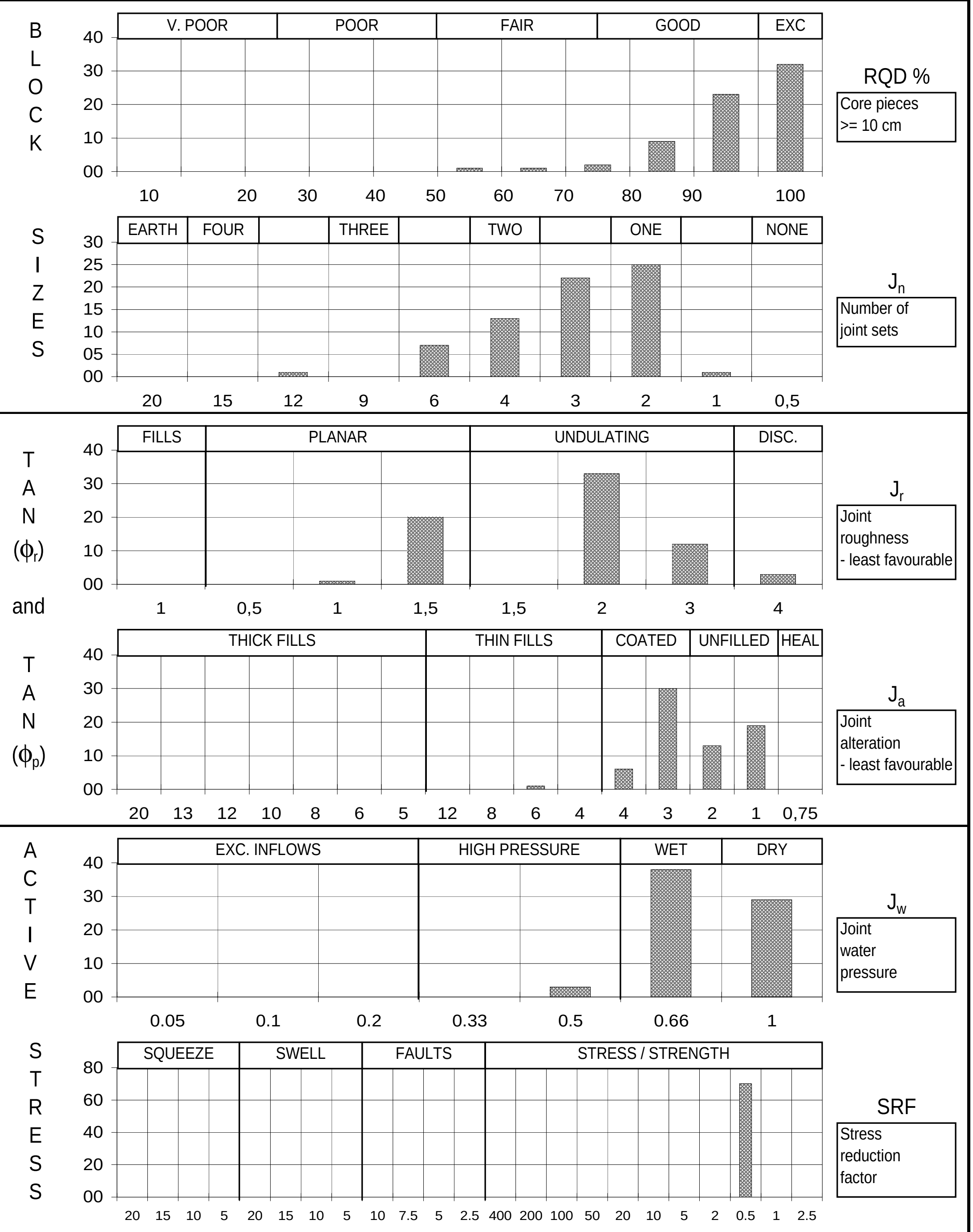
$$Q_{mean} = \frac{90}{3.7} \times \frac{1.8}{2.7} \times \frac{0.73}{0.5} = 22.3$$

$$Q_{most\ frequent} = \frac{95}{3.5} \times \frac{2}{3} \times \frac{0.66}{0.5} = 23.9$$

Unfortunately, there proved to be a certain correspondence in the subsequent tunnel logging result. Since the first 50m or so of the tunnel was not considered suitable due to the nearby (but diminishing) influence of the TBM tunnel and due to some anisotropic banding, one was left with the potential for somewhat more jointing (RQD/J_n) in the core is reduced from 31 to 24) and there may apparently be less favourable joint properties (J_r/J_a is reduced from 0.96 to 0.67) in the inner 20m or the hole.

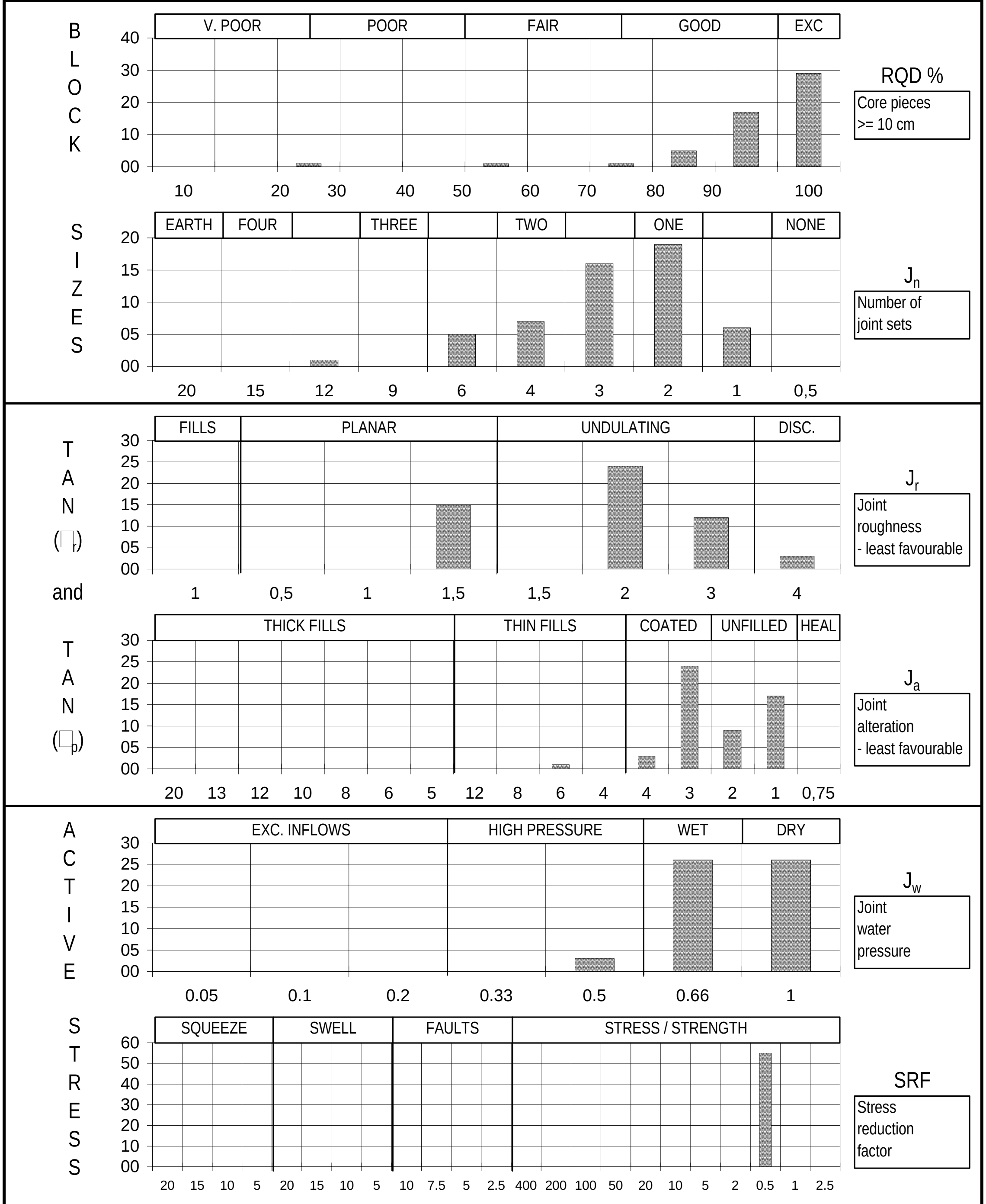
Figure 7. *Typical appearance of KA3376B01 core, and details of three joint sets with* J_a *= 3 to 4.*

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	6.0	*	1.5	/	4.0	*	0.66	/	0.5	=	**7.013**
Q (typical max)=	100	/	1.0	*	4.0	/	1.0	*	1.00	/	0.5	=	**800.0**
Q (mean value)=	94	/	3.2	*	2.1	/	2.4	*	0.79	/	0.5	=	**40.77**
Q (most frequent)=	100	/	2.0	*	2.0	/	3.0	*	0.66	/	0.5	=	**44.00**



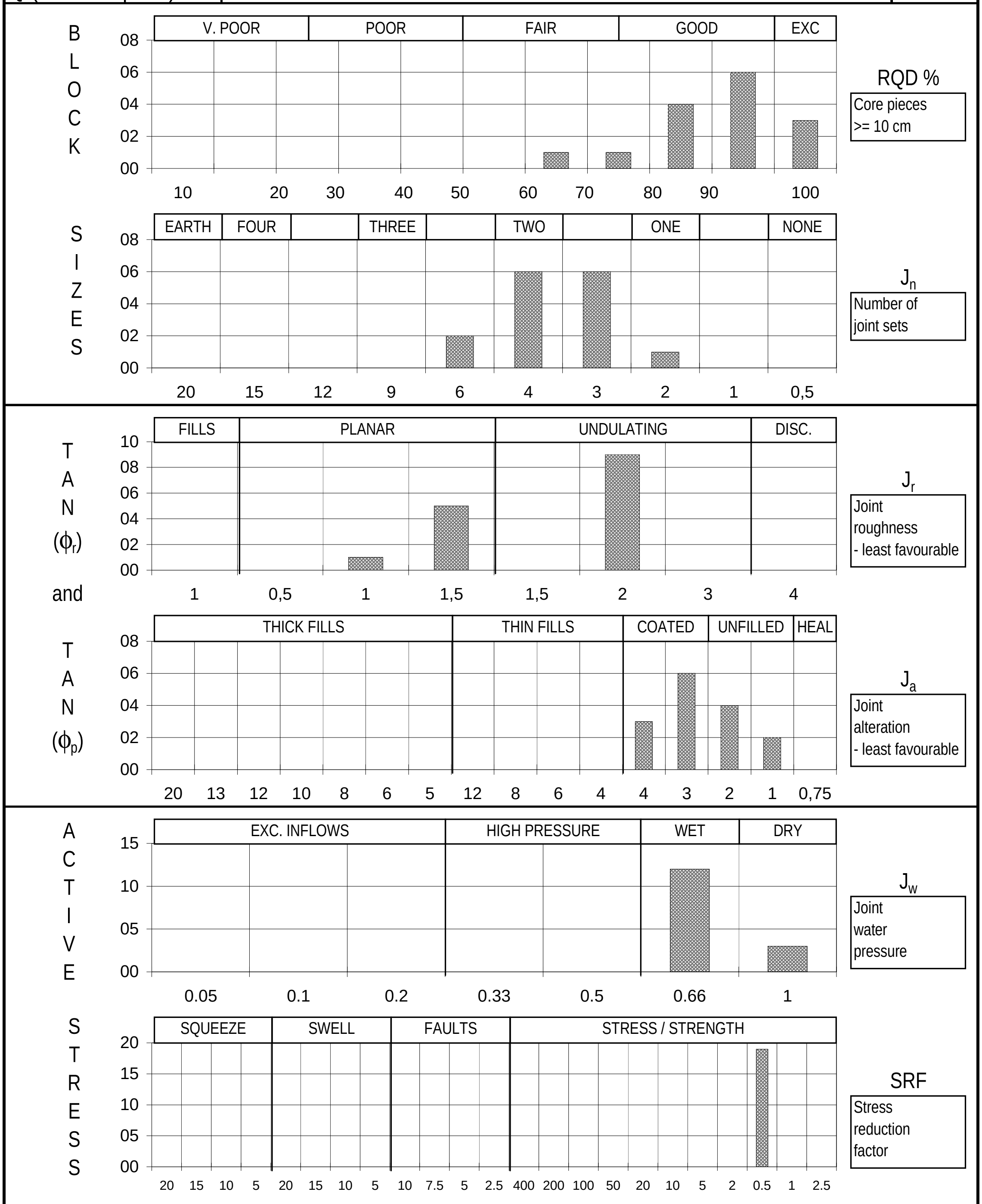
	Rev.	Report No.	Figure No.
SKB APSE BOREHOLE KA 3376 B01		NB&A 2	8
Overall Q-statistics for the whole of borehole KA 3376	Borehole No. : KA 3376 0B1	Drawn by nrb	Date 20/08/03
which is drilled in the left wall of the tunnel.	Depth zone (m) 0.0-80.2	Checked nrb	
Note SRF = 0.5 assumption for relevance to tunnel invert.	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	6.0	*	1.5	/	4.0	*	0.50	/	0.5	=	**5.313**
Q (typical max)=	100	/	1.0	*	4.0	/	1.0	*	1.00	/	0.5	=	**800.0**
Q (mean value)=	94	/	3.0	*	2.2	/	2.3	*	0.81	/	0.5	=	**48.42**
Q (most frequent)=	100	/	2.0	*	2.0	/	3.0	*	0.83	/	0.5	=	**55.33**



SKB APSE BOREHOLE KA 3376 B01	Rev.	Report No. NB&A 2	Figure No. 9
Q-statistics for the first 60m approx of KA 3376 B01,	Borehole No. : KA 3376 B01	Drawn by nrb	Date 20/08/03
which is drilled in the left wall of the tunnel.	Depth zone (m) ch. 0.0-59.4	Checked nrb	
Note SRF = 0.5 assumption for relevance to tunnel invert.	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	**Q**
Q (typical min)=	85	/	6.0	*	1.5	/	4.0	*	0.66	/	0.5	=	**7.013**
Q (typical max)=	100	/	3.0	*	2.0	/	1.0	*	1.00	/	0.5	=	**133.3**
Q (mean value)=	90	/	3.7	*	1.8	/	2.7	*	0.73	/	0.5	=	**23.25**
Q (most frequent)=	95	/	3.5	*	2.0	/	3.0	*	0.66	/	0.5	=	**23.89**



SKB APSE TUNNEL ÅSPØ	Rev.	Report No. NB&A 2	Figure No. 10
Q-statistics for the deepest 20m of KA 3376 B01, from 59.4 to 80.2m, which is drilled in the left wall of the tunnel. Note SRF = 0.5 assumption for relevance to tunnel invert.	Borehole No. : KA 3376 B01	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 59.4-80.2	Checked nrb	
	Logg 1.0	Approved	

6 Tunnel logging results (24 to 59m)

Appendix A gives the raw data for the preliminary tunnel logging of the arch and upper walls (ch. 24 to 59m). The logging philosophy and some details concerning SRF and J_w were described earlier, in Chapters 2, 3 and 4.

The Excel results are presented here in the same format as for the core logging, i.e. the overall result (24 to 80m), the first depth interval logged (24 to 59m) and then the last depth interval (60 to 80m). Figure 11 shows the following result:

TASQ tunnel

(ch. 24 to 80m)

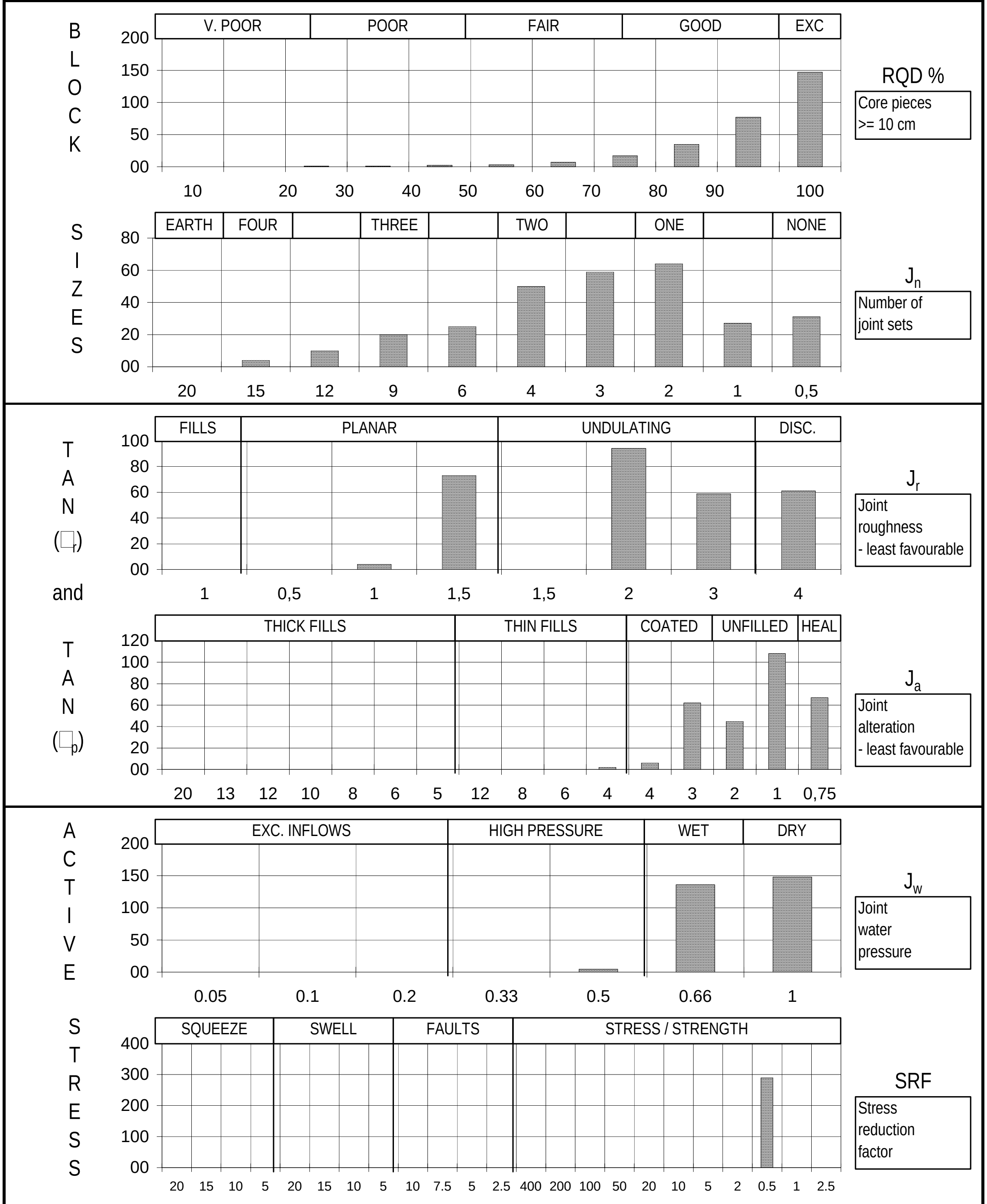
$$Q_{mean} = \frac{93}{3.6} \times \frac{2.5}{1.6} \times \frac{0.83}{0.5} = 65.6$$

$$Q_{most\ frequent} = \frac{100}{2} \times \frac{2}{1} \times \frac{1}{0.5} = 200$$

Here we already see one of the 'disadvantages' of careful tunnel blasting on Q-logging, namely that it is not easy to see mineral coatings. Core logging J_a values tend then to be more correct.

While RQD = 100 and J_n = 2 (one set) dominate as a most frequent (locally) observed result (on the 1 to 3 m experimental scale), there is a significant tail of reduced RQD and increased number of joints sets, which brings the RQD/J_n ratio (relative block size) down from 50 (most frequent) to 26.

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	12.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**4.125**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.3**
Q (mean value)=	93	/	3.6	*	2.5	/	1.6	*	0.83	/	0.5	=	**65.64**
Q (most frequent)=	100	/	2.0	*	2.0	/	1.0	*	1.00	/	0.5	=	**200.00**



SKB APSE TUNNEL ÅSPØ	Rev.	Report No. NB&A 2	Figure No. 11
Overall Q-parameter statistics for the eleven, 5m long sections logged from 24 to 80m. Note SRF = 0.5 assumption relevant to tunnel invert.	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 24-80	Checked nrb	
	Logg 1.0	Approved	

7 Tunnel logging results (60 to 80 m)

Appendix B gives the raw data for the subsequent tunnel logging of the four panels in which the lower walls and invert were available for logging (ch. 60 to 80m). In practice the invert itself (the central 2m) were not observable due to the presence of the drilling machine in the only panel with fully cleaned invert. However, only the central 2m (approx.) was missed, as the lower walls were easily observed and were clean.

The general appearance of the last 15m (approx.) of the tunnel with invert was shown in Figure 6, while Figure 12 gives four detailed views of lower wall conditions from 75 to 70m, and from 65 to 60m.

Concerning frequency of half rounds in the walls and upper invert (lower wall) area, it is clear that the 75 to 70m panel is significantly superior to the quality of the 65 to 60m panel.

Figure 14 shows the Excel Q-parameter histograms for ch. 60 to 80m. The two different chainages are compared and contrasted in Chapter 8.

***Figure 12**. Condition in lower walls, ch. 75-70m and 65-60m.*

8 Variation of quality along the tunnel

The different Q-parameter results for the chainage 24 to 59m (logging of upper walls and arch) compared to the chainage 60 to 80m (logging mid- to lower walls and invert) are given in Excel format in Figures 13 and 14. The reduced quality, due especially to an increased number of joint sets, is clearly visible when comparing the two sheets side-by-side. The following mean and most frequent results, serve only to emphasise these differences.

TASQ tunnel **(upper walls and arch, 10+10+10 observations)**

(ch. 24 to 59m)

$$Q_{mean} = \frac{94}{2.5} \times \frac{2.6}{1.5} \times \frac{0.85}{0.5} = 110.8$$

$$Q_{most\ frequent} = \frac{100}{2} \times \frac{2}{1} \times \frac{1}{0.5} = 200$$

TASQ tunnel **(mid- and lower walls, part of invert, 10+10 observations)**

(ch. 60 to 80m)

$$Q_{mean} = \frac{91}{6.7} \times \frac{2.2}{1.9} \times \frac{0.79}{0.5} = 25.1$$

$$Q_{most\ frequent} = \frac{100}{6.5} \times \frac{2}{1} \times \frac{0.66}{0.5} = 40.6$$

Concerning Q_{mean} values, we see the following comparison of core and tunnel logging. The borehole sections are adjusted to the tunnel chainage for easier comparison (the borehole collar begins at tunnel section 10). Please not that in appendix C is the uncorrelated borehole section given (true borehole depth).

KA3376B01	**14 to 49.4m**	**Q_{mean} =**	**48.4**
TASQ TUNNEL	**24 to 59m**	**Q_{mean} =**	**110.8**
KA3376B01	**49.4 to 70.2m**	**Q_{mean} =**	**22.3**
TASQ TUNNEL	**60 to 80m**	**Q_{mean} =**	**25.1**

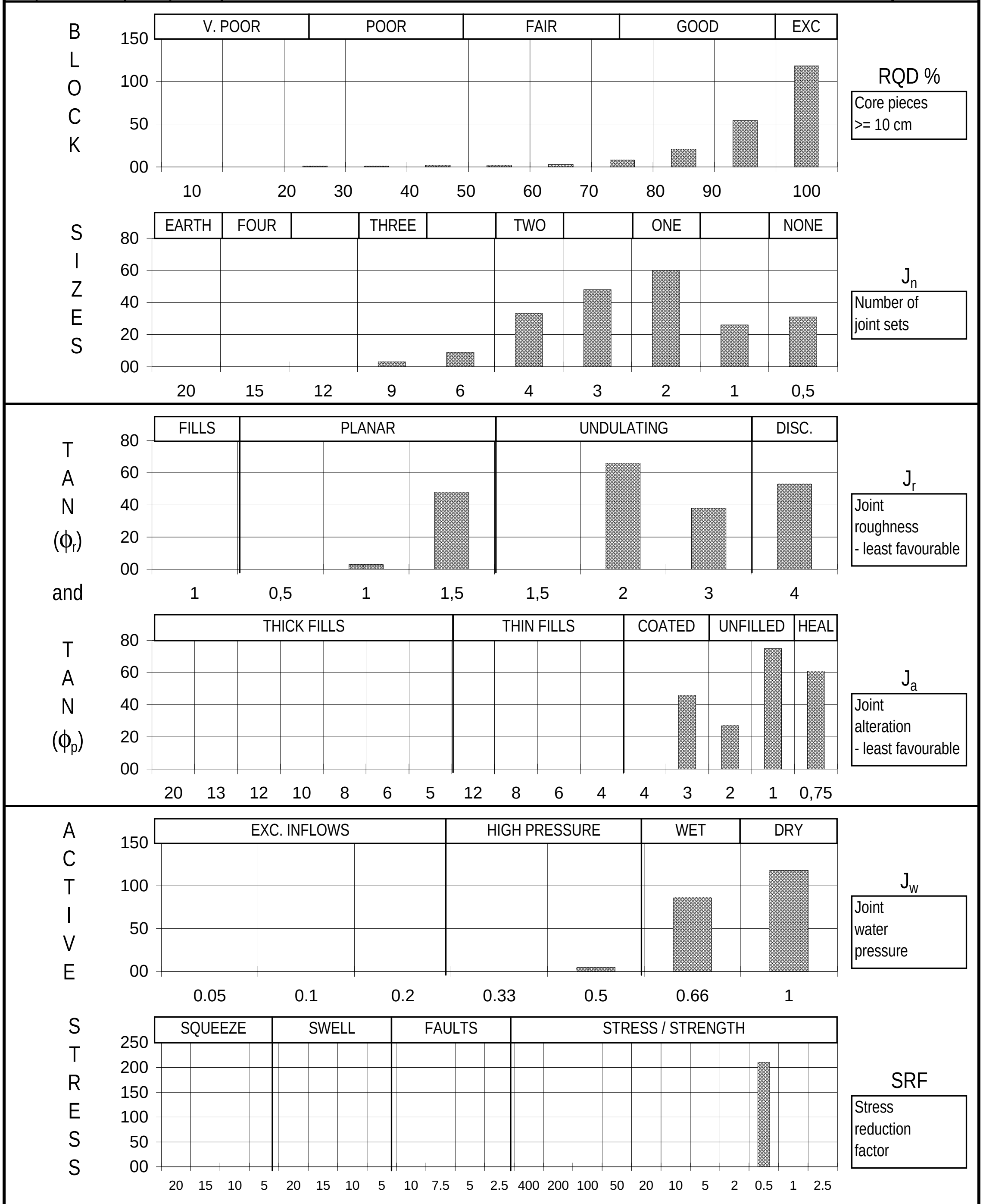
Concerning the inner 20m of both the core and the tunnel, the main differences are the estimation (based on mean values) of a bit more jointing in the 3D tunnel (J_n increases from 3.7 = nearly two joints sets to 6.7 = a bit more than two sets plus random) and less mineral coatings are seen in the tunnel (J_a reduces from 2.7 to 1.9). Mean values of RQD 90 (core) and 91 (tunnel) are very close for this inner 20m, and for the first section of each hole (0 to 59.4 for the core, and 24 to 59m for the tunnel) the RQD values are an identical 94.

The variability of Q-values along the tunnel is significant when comparing these larger samples, but even more pronounced when plotted for each 5m logged, of which there were a total of 11 panels (totalling 1270 + 600 = 1870 Q-parameter observations).

Figure 15 shows the estimated variability of Q_{mean} from chainage 24m to 80m (26.5 to 77.5m taking panel centres). A very good quality region, unfortunately judged unsuitable for invert development, is shown between about 45 and 53m. Photographs of this region were shown in Figure 4.

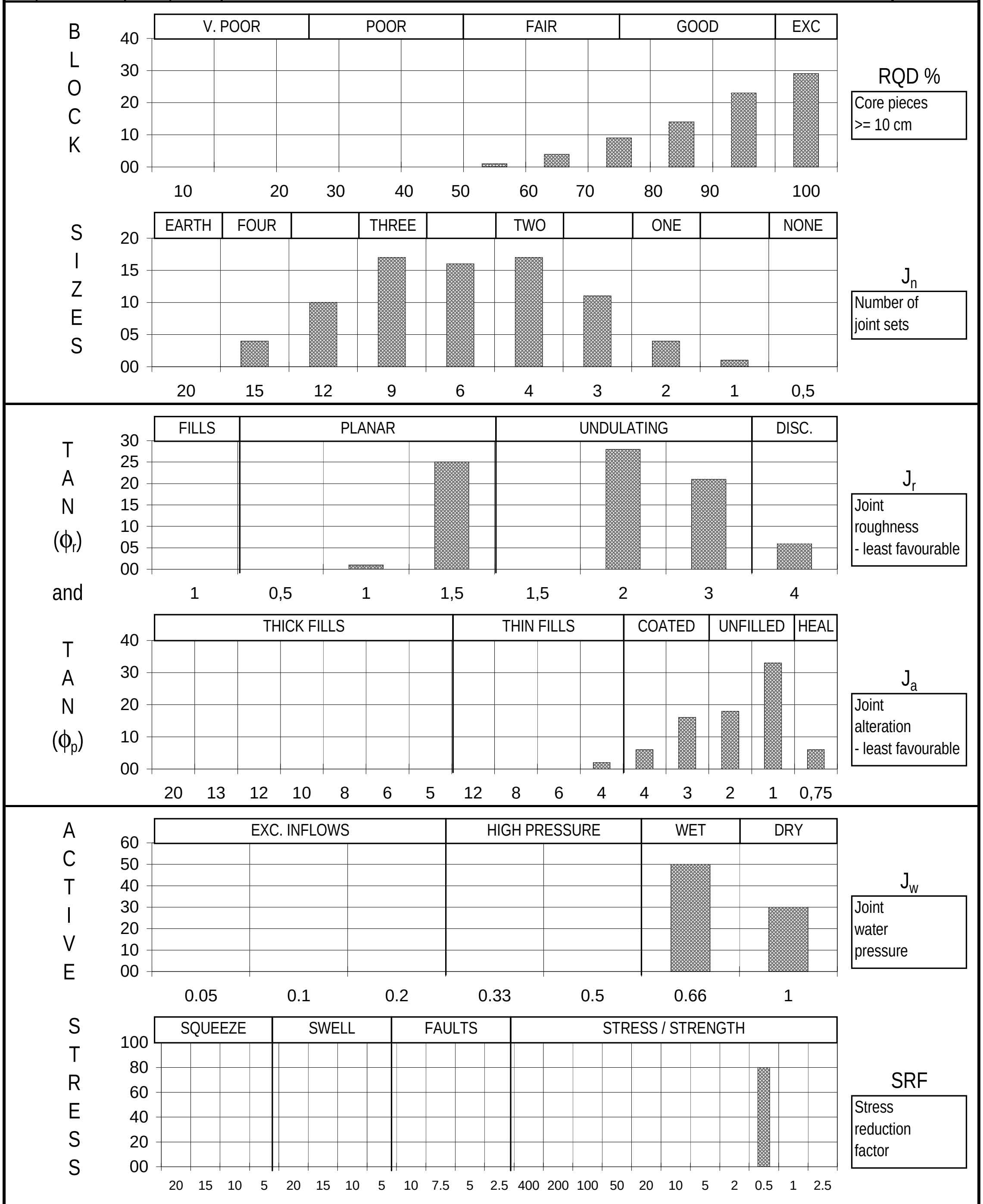
Figure 16 shows the estimated variability of 'relative block size', which is defined as the ratio of RQD/J_n. The two curves show respectively the most frequent observations (blue) and the mean (red). It may be recalled that the RQD/J_n ratios for the core reduced from means of 31 to 24, for 0 to 59.4m and 59.4 to 80.2m respectively. This trend is comparable, but the reduction in RQD/J_n is apparently more marked along the tunnel, than along the core.

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	6.0	*	1.5	/	3.0	*	0.50	/	0.5	=	**8.250**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.0**
Q (mean value)=	94	/	2.5	*	2.6	/	1.5	*	0.85	/	0.5	=	**110.76**
Q (most frequent)=	100	/	2.0	*	2.0	/	1.0	*	1.00	/	0.5	=	**200.00**



SKB APSE TUNNEL ÅSPØ	Rev.	Report No. NB&A 2	Figure No. 13
Q-parameter statistics for seven, 5m long sections logged from 24 to 59m. Note SRF = 0.5 assumption for relevance to tunnel invert.	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 24-59	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	15.0	*	1.5	/	4.0	*	0.66	/	0.5	=	**2.475**
Q (typical max)=	100	/	1.0	*	4.0	/	0.8	*	1.00	/	0.5	=	**1066.7**
Q (mean value)=	91	/	6.7	*	2.2	/	1.9	*	0.79	/	0.5	=	**25.10**
Q (most frequent)=	100	/	6.5	*	2.0	/	1.0	*	0.66	/	0.5	=	**40.62**



SKB APSE TUNNEL ÅSPØ	Rev.	Report No. NB&A 2	Figure No. 14
Q-parameter statistics for the four, 5m long sections logged from ch. 60 to 80m	Borehole No. :	Drawn by nrb	Date 20/08/03
Note SRF = 0.5 assumption for relevance to tunnel invert.	Depth zone (m) ch. 60-80	Checked nrb	
	Logg 1.0	Approved	

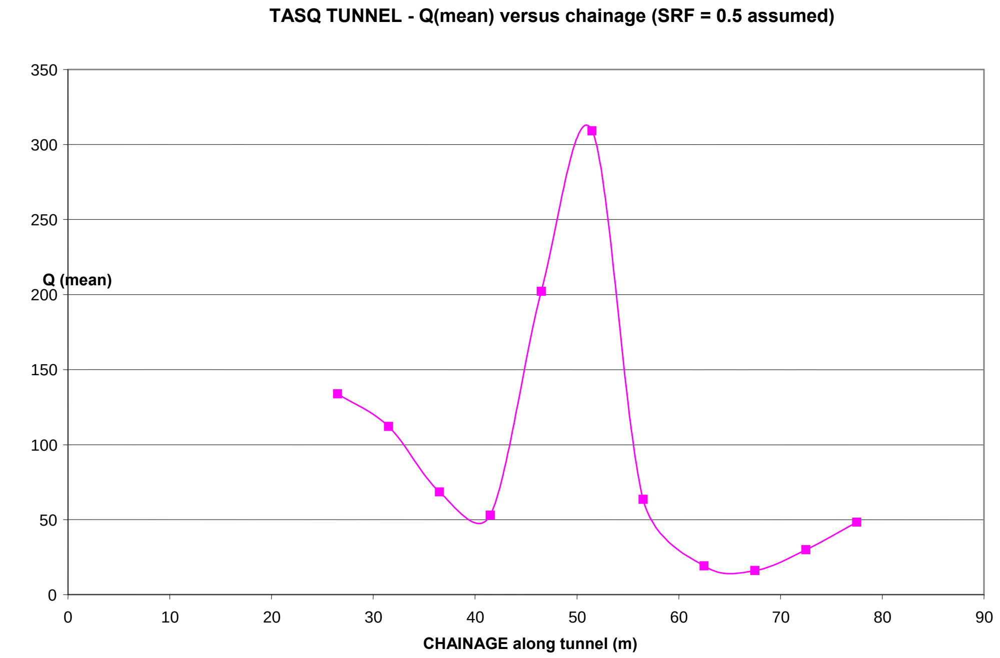


Figure 15. *Variation of Q_{mean} along the TASQ tunnel based on the assumption of SRF = 0.5, which is relevant for general **characterization** and for invert **classification**.*

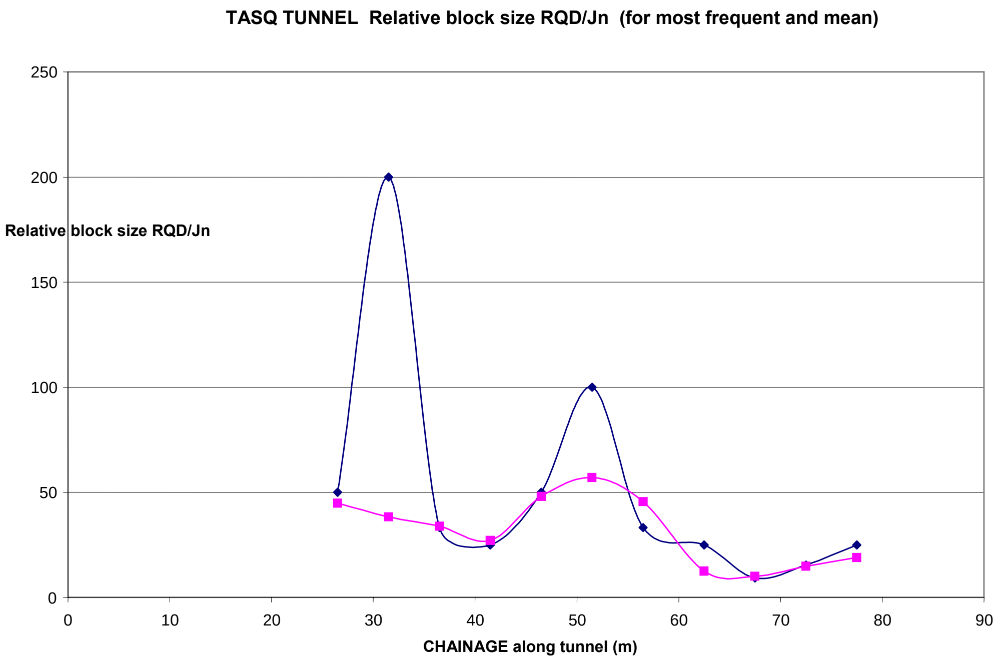


Figure 16. *Variation of 'relative block size' (RQD/J_n) from the most frequent (diamond markers) and mean (square markers) observations.*

9 Panel-by-panel variation

At the time of writing this second report, the event location for the pillar experiment has not been finally chosen, as an unfavourably oriented ‘diagonal and dipping’ mineral coated discontinuity exposed in the invert has delayed the choice of location. (A photograph of this will be shown later when presenting joint property estimates.)

As a possible aid to selecting the final location, but with actual invert observations lacking due to the presence of water, fine tunnel muck, and the drilling machine (Figure 6), the panel-by-panel logging results will be presented here.

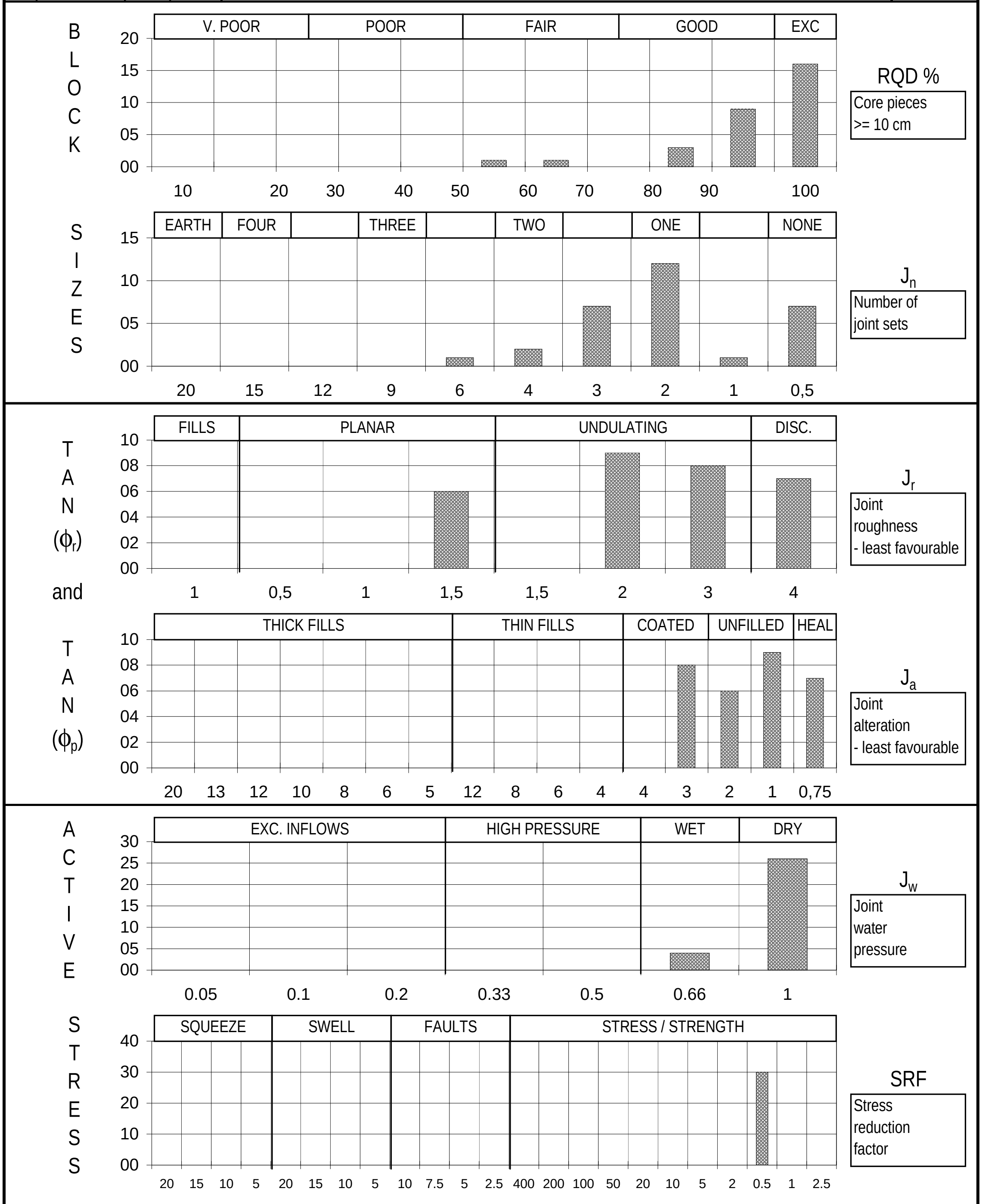
Figures 17 to 27 give the Excel Q-parameter histograms for each 5m panel logged in the tunnel. These are plotted directly from the observations reproduced in Appendix A and B. However, the SRF values (2.0 for the walls, and 0.5 for the arch and invert) have been corrected to 0.5 throughout. Table 1 summarizes key results for each panel, and is the direct source for Figures 15 and 16.

Table 1. Comparison of Q-parameter statistics for eleven 5m long sections of the APSE tunnel.

Section ch. (m)	Q_{mean}	$Q_{most\ frequent}$	RQD / J_n	$Q_{most\ frequent}$ parameters / Q_{mean} parameters *		
24-29	133.8	200	50	100/2.0	× 2/1.0	× 1.0/0.5
			44.8	94/2.1	× 2.6/1.7	× 0.95/0.5
29-34	112.0	2130	200	100/0.5	× 4/0.8	× 1.0/0.5
			38.3	92/2.4	× 2.8/1.7	× 0.9/0.5
34-39	68.4	133	33.3	100/3.0	× 2.0/1.0	× 1.0/0.5
			33.9	95/2.8	× 2.1/1.9	× 0.9/0.5
39-44	53.0	75.0	25	100/4.0	× 1.5/1.0	× 1.0/0.5
			27.1	95/3.5	× 1.8/1.6	× 0.9/0.5
44-49	202.1	352	50	100/2.0	× 4.0/0.8	× 0.66/0.5
			48	96/2.0	× 3.2/1.3	× 0.8/0.5
49-54	309.1	704	100	100/1.0	× 4.0/0.8	× 0.66/0.5
			57	97/1.7	× 3.5/0.9	× 0.7/0.5
54-59	63.5	88.0	33.3	100/3.0	× 2.0/1.0	× 0.66/0.5
			45.5	91/2.9	× 3.1/1.4	× 0.7/0.5
60-65	19.1	66.0	25	100/4.0	× 2.0/1.0	× 0.66/0.5
			12.5	90/7.2	× 2.2/2.0	× 0.7/0.5
65-70	16.1	30.8	9.3	98/10.5	× 2.0/1.0	× 0.8/0.5
			10.1	87/8.6	× 2.2/2.3	× 0.8/0.5
70-75	29.9	30.5	15.4	100/6.5	× 1.5/1.0	× 0.66/0.5
			14.8	92/6.2	× 2.2/1.8	× 0.8/0.5
75-80	48.3	91.3	25	100/4.0	× 2.2/1.0	× 0.8/0.5
			19	95/5.0	× 2.4/1.6	× 0.8/0.5

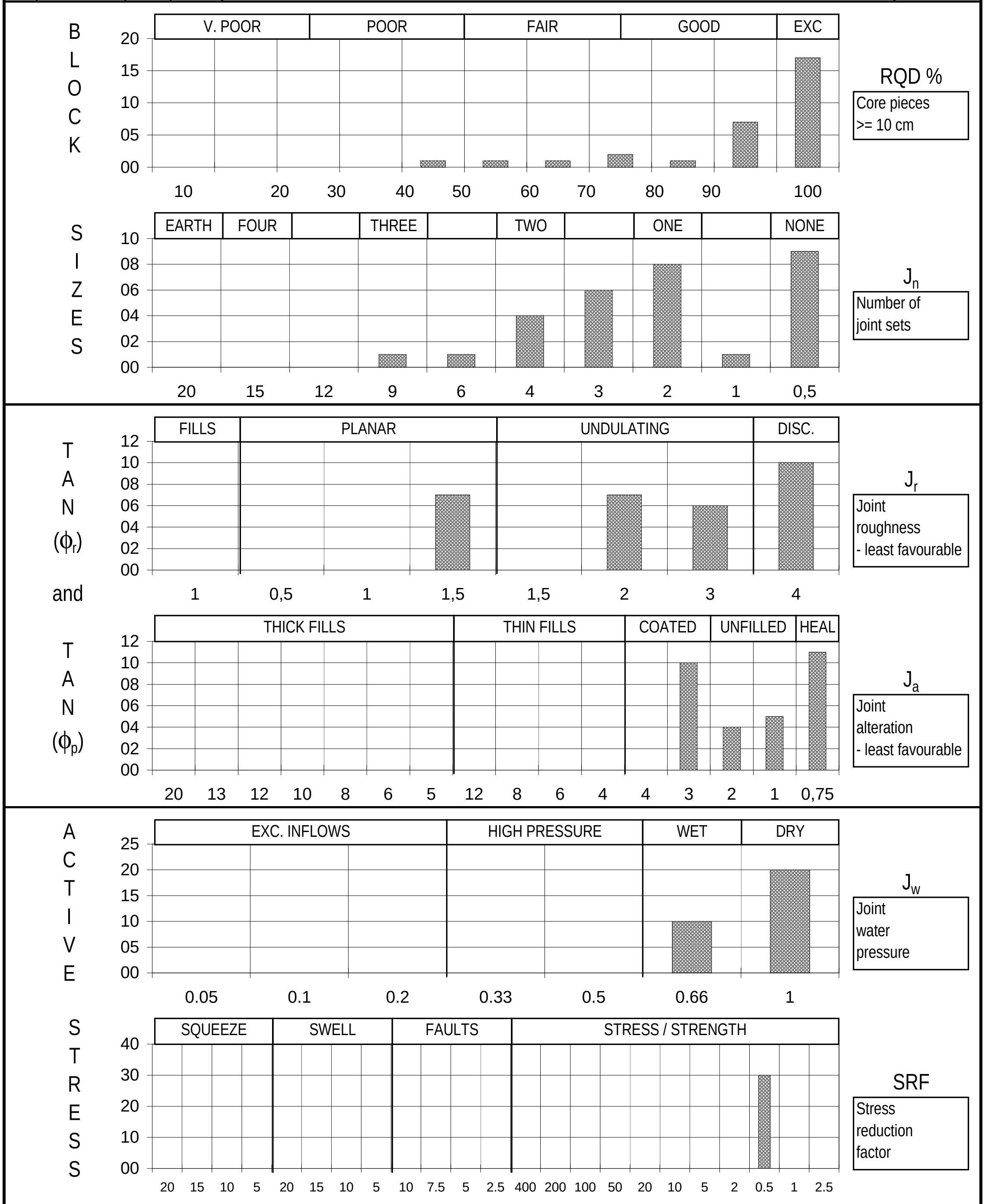
* The chosen value of SRF depends on stress anisotropy, stress/strength ratio, and position (walls or arch/invert). See Chapter 3 for discussion of relevant values.

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	3.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**18.700**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.3**
Q (mean value)=	94	/	2.1	*	2.6	/	1.7	*	0.95	/	0.5	=	**133.78**
Q (most frequent)=	100	/	2.0	*	2.0	/	1.0	*	1.00	/	0.5	=	**200.00**



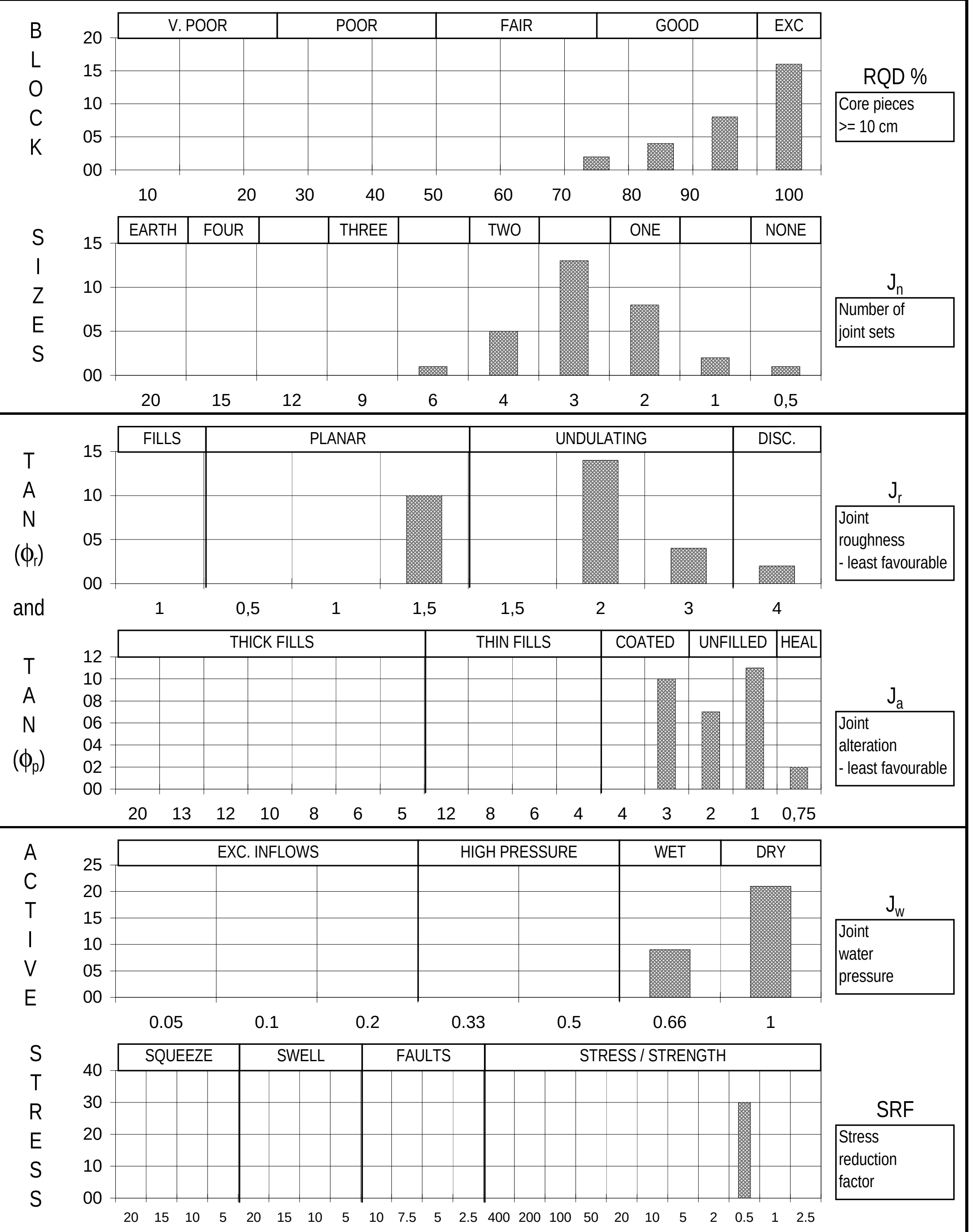
SKB APSE TUNNEL ÅSPØ ch. 24 to 29m	Rev.	Report No. NB&A 2	Figure No. 17
Q-parameters, ch. 24 to 29m	Borehole No. :	Drawn by nrb	Date 20/08/03
Note SRF = 0.5 assumption	Depth zone (m) ch. 29-34	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	95	/	4.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**15.675**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.3**
Q (mean value)=	92	/	2.4	*	2.8	/	1.7	*	0.89	/	0.5	=	**111.96**
Q (most frequent)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.33**



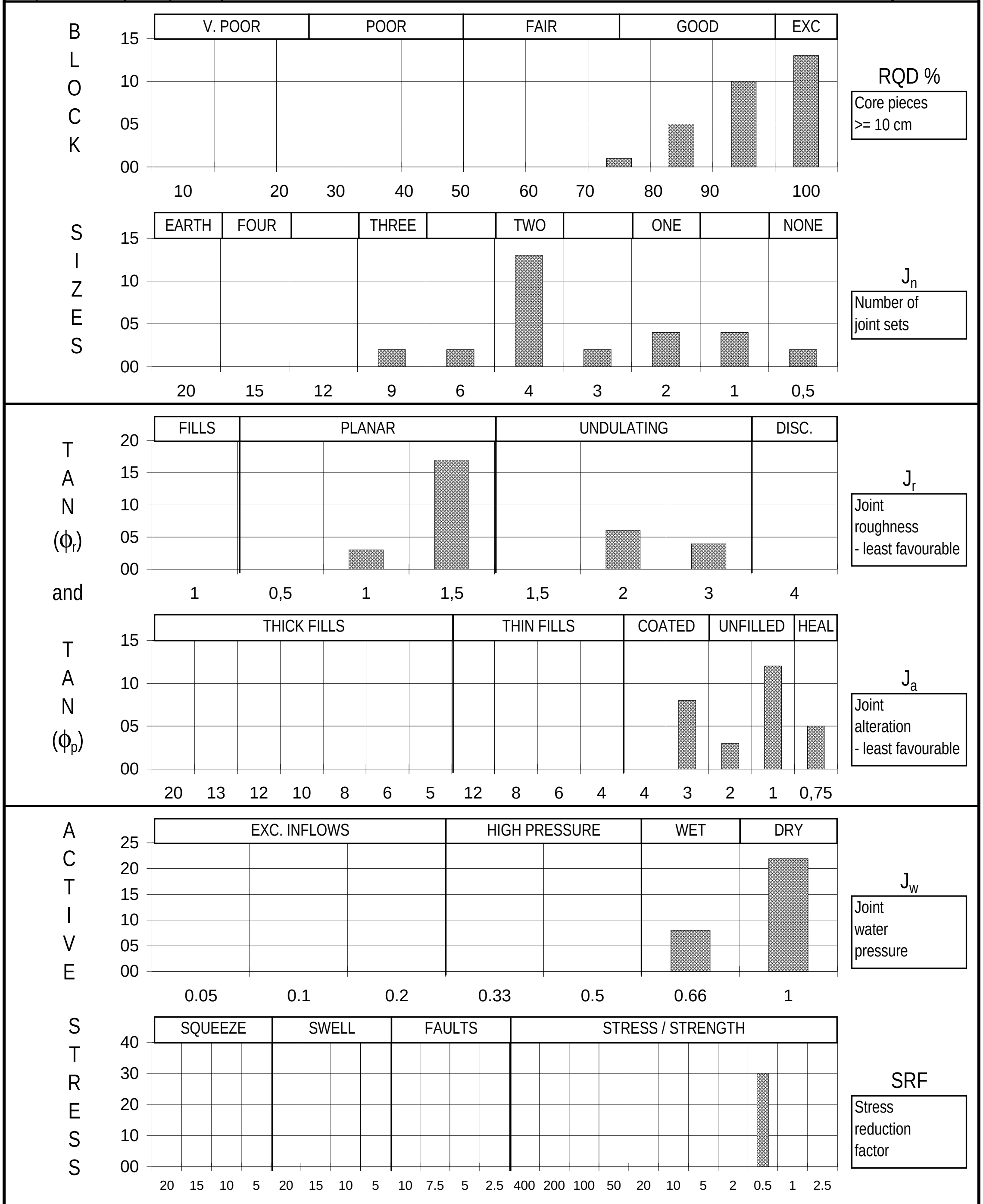
SKB APSE TUNNEL ÅSPØ ch. 29 to 34m	Rev.	Report No. NB&A 2	Figure No. 18
Q-parameters, ch. 29 to 34m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 29-34	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	4.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**14.025**
Q (typical max)=	100	/	2.0	*	4.0	/	1.0	*	1.00	/	0.5	=	**400.0**
Q (mean value)=	95	/	2.8	*	2.1	/	1.9	*	0.90	/	0.5	=	**68.35**
Q (most frequent)=	100	/	3.0	*	2.0	/	1.0	*	1.00	/	0.5	=	**133.33**



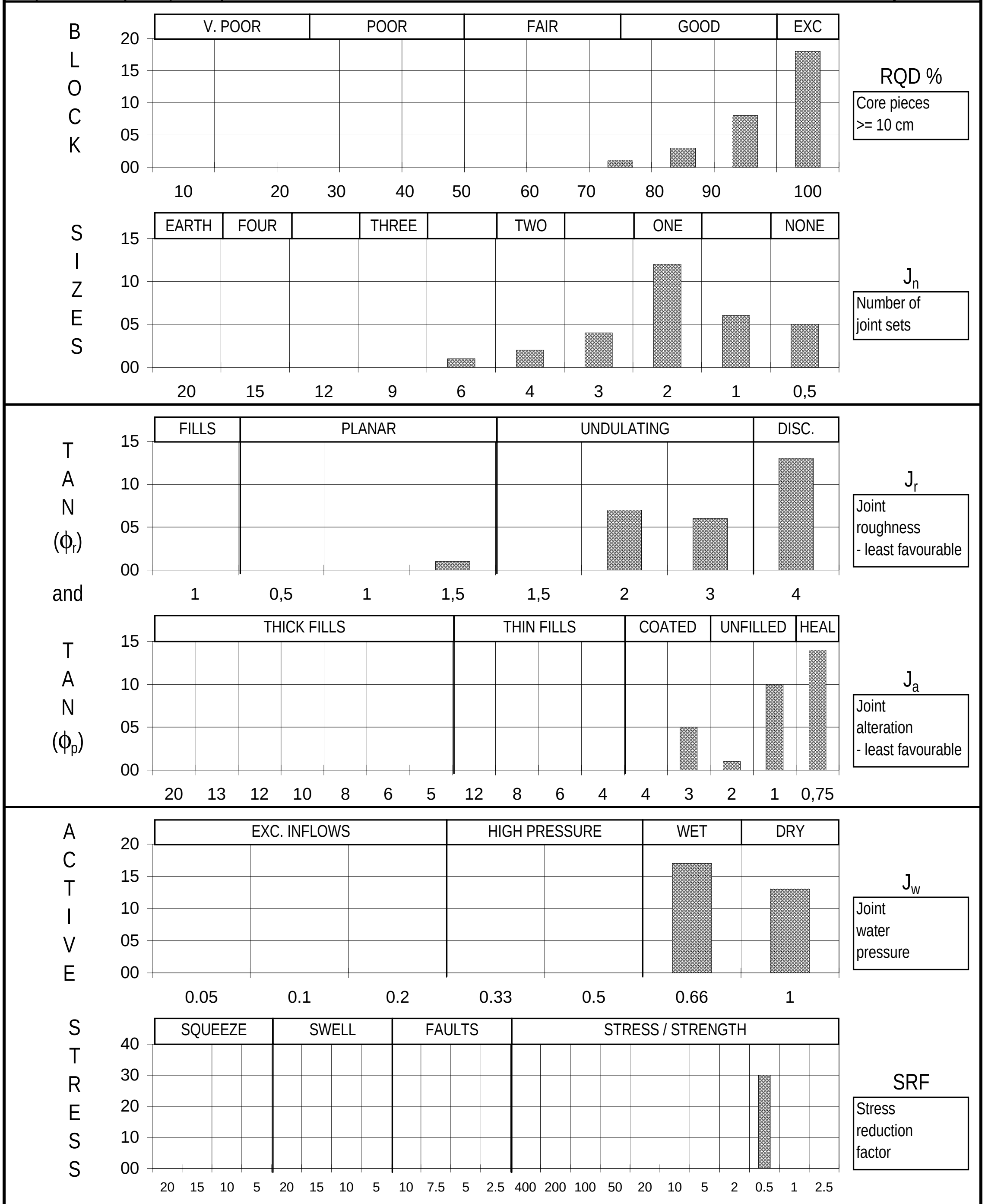
SKB APSE ÅSPØ TUNNEL ch. 34 to 39m	Rev.	Report No. NB&A 2	Figure No. 19
Q-parameters, ch. 34 to 39m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 34-39m	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	4.0	*	1.0	/	3.0	*	0.66	/	0.5	=	**9.350**
Q (typical max)=	100	/	1.0	*	3.0	/	0.8	*	1.00	/	0.5	=	**800.0**
Q (mean value)=	95	/	3.5	*	1.8	/	1.6	*	0.91	/	0.5	=	**53.04**
Q (most frequent)=	100	/	4.0	*	1.5	/	1.0	*	1.00	/	0.5	=	**75.00**



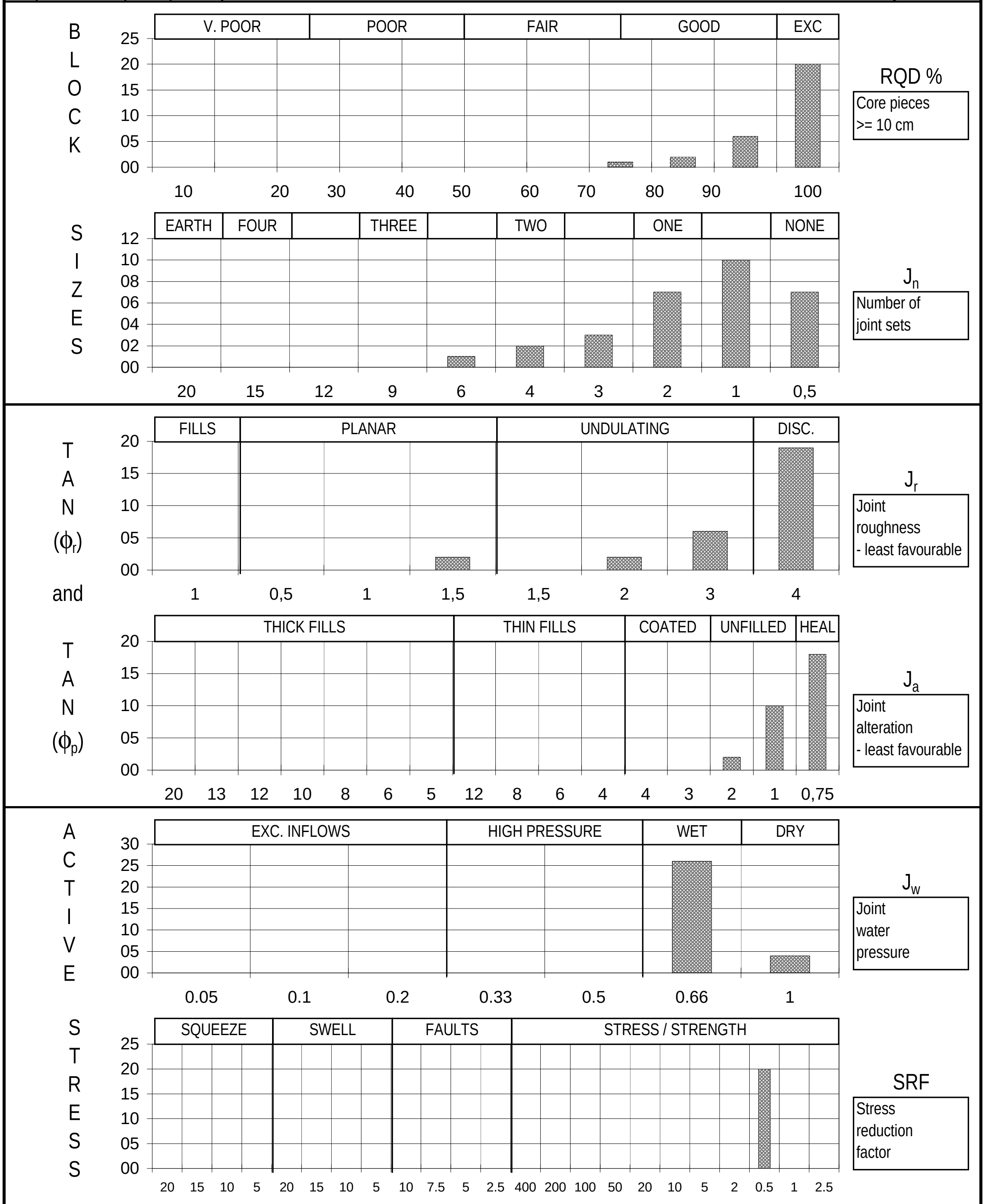
SKB APSE ÅSPØ TUNNEL ch. 39 to 44m	Rev.	Report No. NB&A 2	Figure No. 20
Q-parameters, ch. 39 to 44m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 39-44	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	3.0	*	2.0	/	3.0	*	0.66	/	0.5	=	**24.933**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.3**
Q (mean value)=	96	/	2.0	*	3.2	/	1.3	*	0.81	/	0.5	=	**202.08**
Q (most frequent)=	100	/	2.0	*	4.0	/	0.8	*	0.66	/	0.5	=	**352.00**



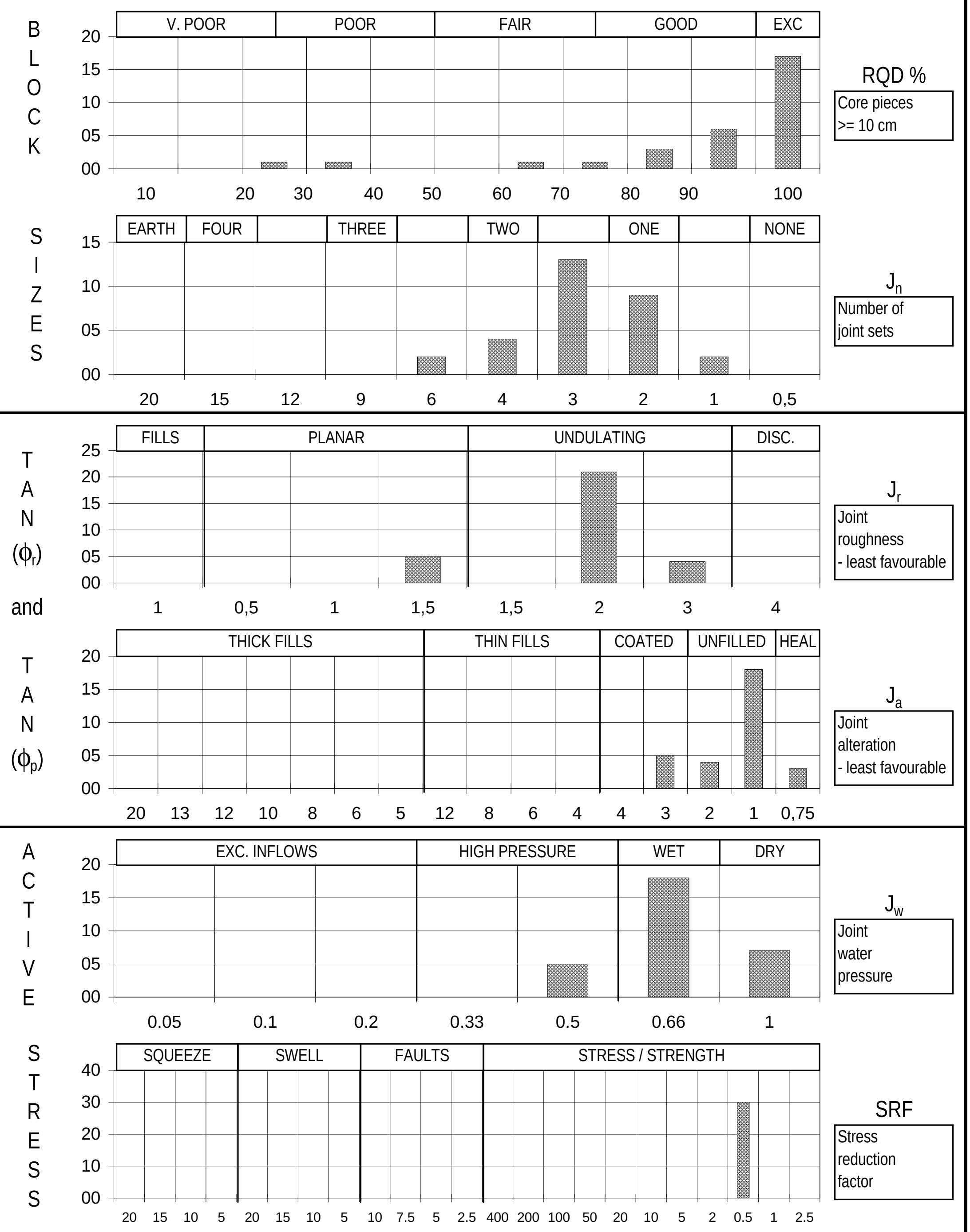
SKB APSE ÅSPØ TUNNEL ch. 44 to 49m	Rev.	Report No. NB&A 2	Figure No. 21
Q-parameters, ch. 44 to 49m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch.44-49m	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	**Q**
Q (typical min)=	95	/	3.0	*	3.0	/	1.0	*	0.66	/	0.5	=	**125.4**
Q (typical max)=	100	/	0.5	*	4.0	/	0.8	*	1.00	/	0.5	=	**2133.3**
Q (mean value)=	97	/	1.7	*	3.5	/	0.9	*	0.71	/	0.5	=	**309.06**
Q (most frequent)=	100	/	1.0	*	4.0	/	0.8	*	0.66	/	0.5	=	**704.00**



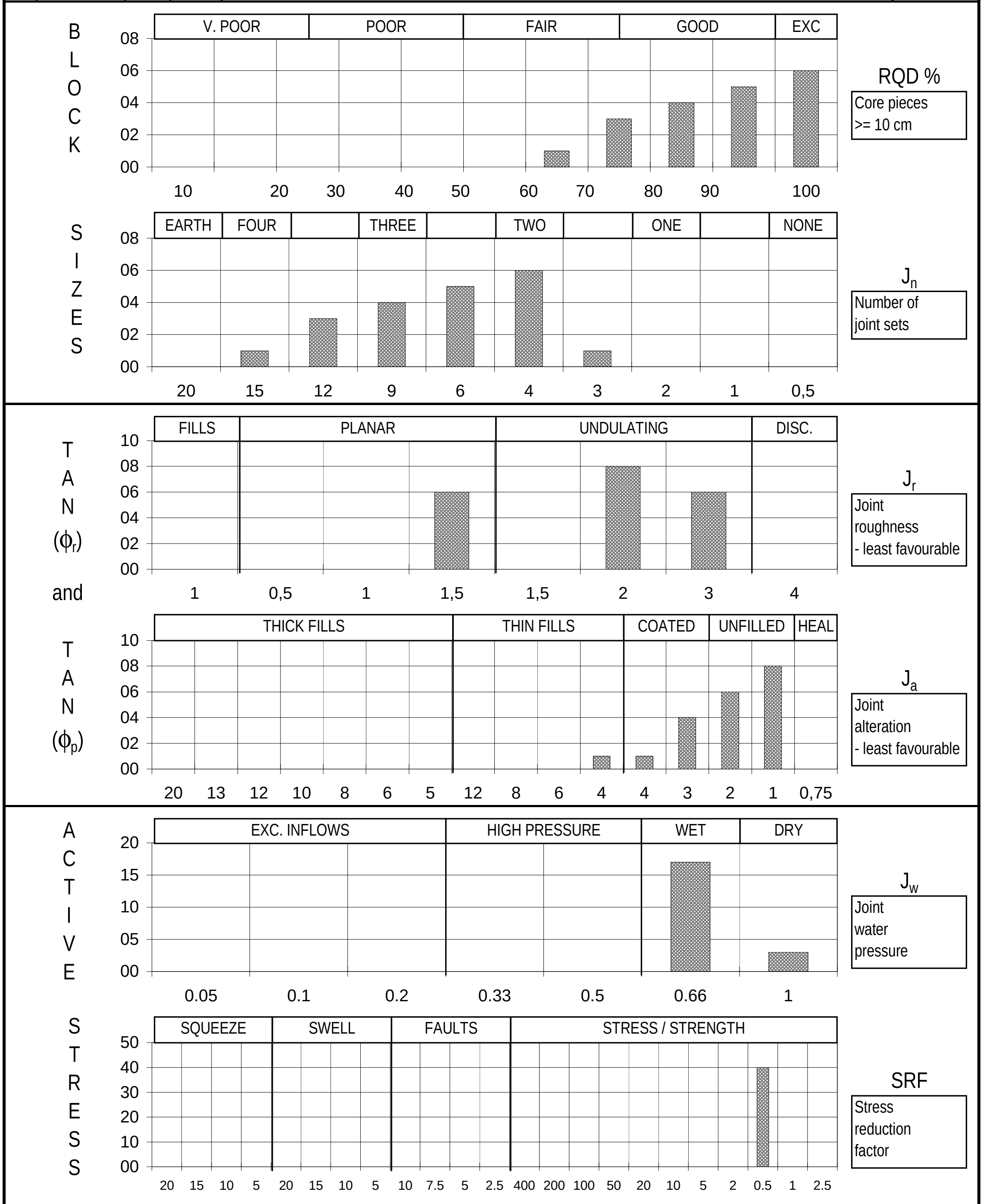
SKB APSE ÅSPØ TUNNEL ch. 49 to 54m	Rev.	Report No. NB&A 2	Figure No. 22
Q-parameters, ch. 49 to 54m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch.49-54	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	85	/	4.0	*	1.5	/	3.0	*	0.50	/	0.5	=	**10.625**
Q (typical max)=	100	/	2.0	*	3.0	/	0.8	*	1.00	/	0.5	=	**400.0**
Q (mean value)=	91	/	2.9	*	2.1	/	1.4	*	0.71	/	0.5	=	**63.48**
Q (most frequent)=	100	/	3.0	*	2.0	/	1.0	*	0.66	/	0.5	=	**88.00**



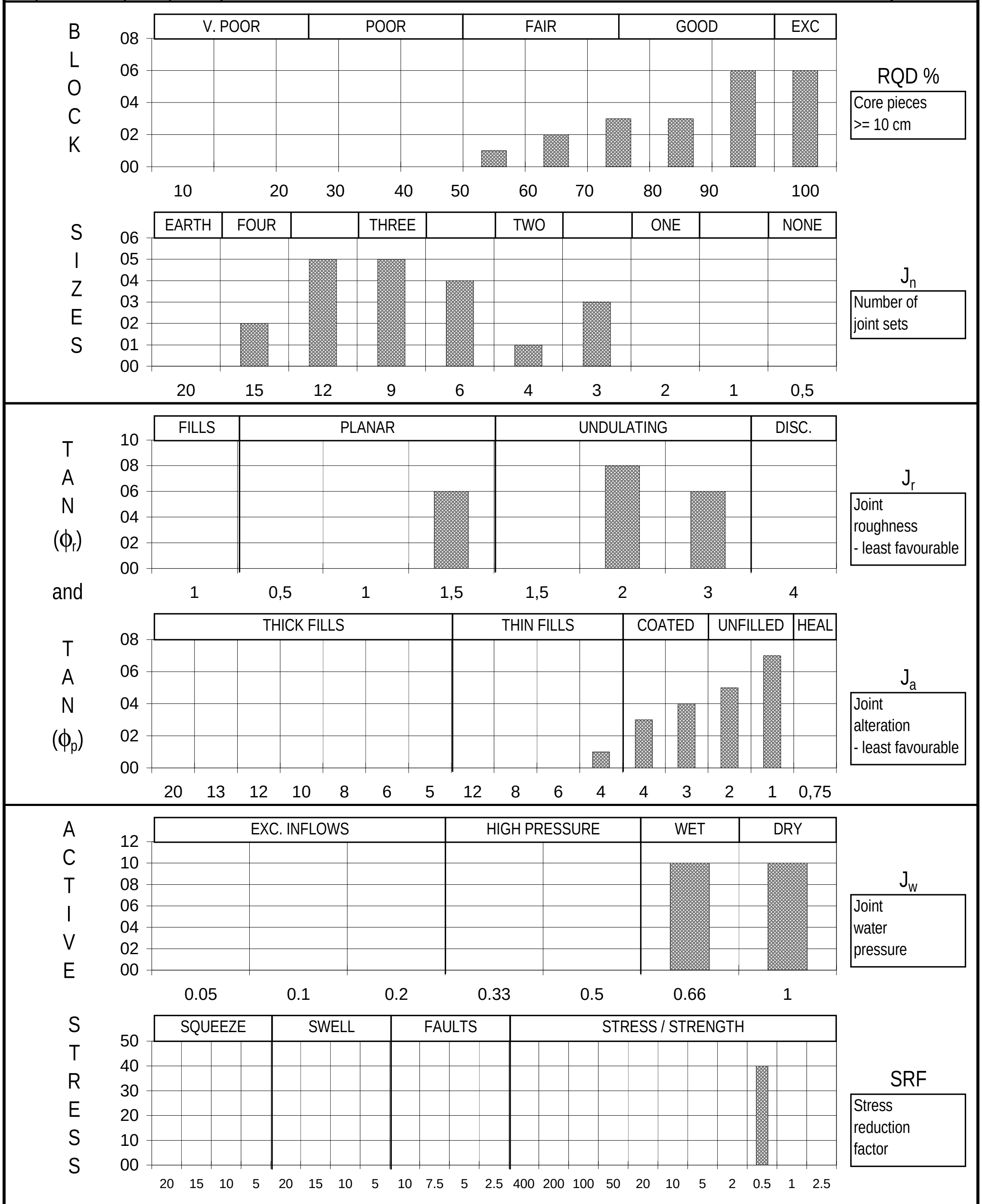
SKB APSE ÅSPØ TUNNEL ch. 54 to 59m	Rev.	Report No. NB&A 2	Figure No. 23
Q-parameters, ch. 54-59m face at 59m, 27/6/03	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch.54-59	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	12.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**4.125**
Q (typical max)=	100	/	4.0	*	3.0	/	1.0	*	1.00	/	0.5	=	**150.0**
Q (mean value)=	90	/	7.2	*	2.2	/	2.0	*	0.71	/	0.5	=	**19.05**
Q (most frequent)=	100	/	4.0	*	2.0	/	1.0	*	0.66	/	0.5	=	**66.00**



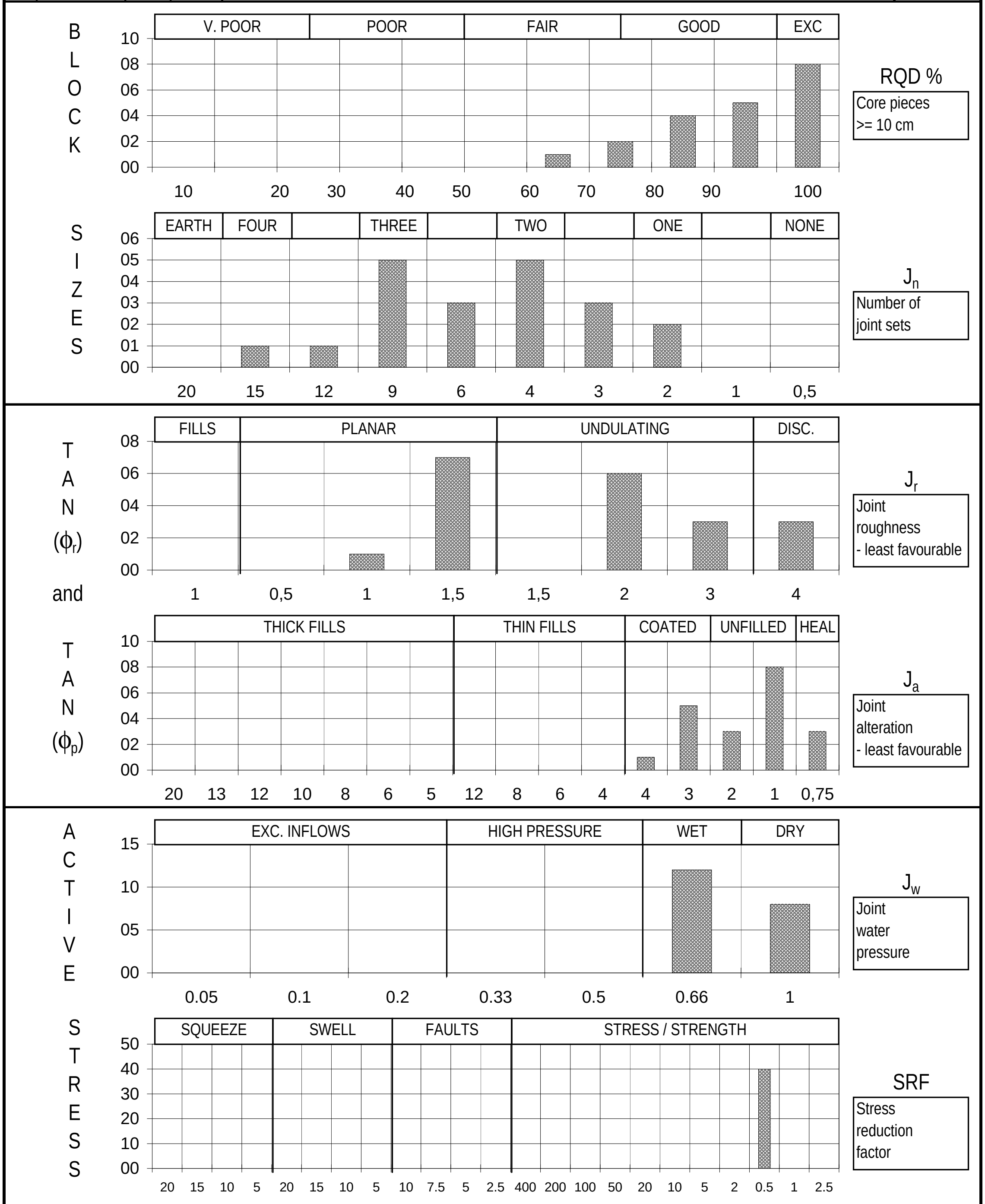
	Rev.	Report No.	Figure No.
SKB APSE ÅSPØ TUNNEL ch. 60 to 65m		NB&A 2	24
Q-parameters, ch. 60 to 65m.	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 60-65	nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	65	/	15.0	*	1.5	/	4.0	*	0.66	/	0.5	=	**2.145**
Q (typical max)=	100	/	3.0	*	3.0	/	1.0	*	1.00	/	0.5	=	**200.0**
Q (mean value)=	87	/	8.6	*	2.2	/	2.3	*	0.83	/	0.5	=	**16.12**
Q (most frequent)=	98	/	10.5	*	2.0	/	1.0	*	0.83	/	0.5	=	**30.83**



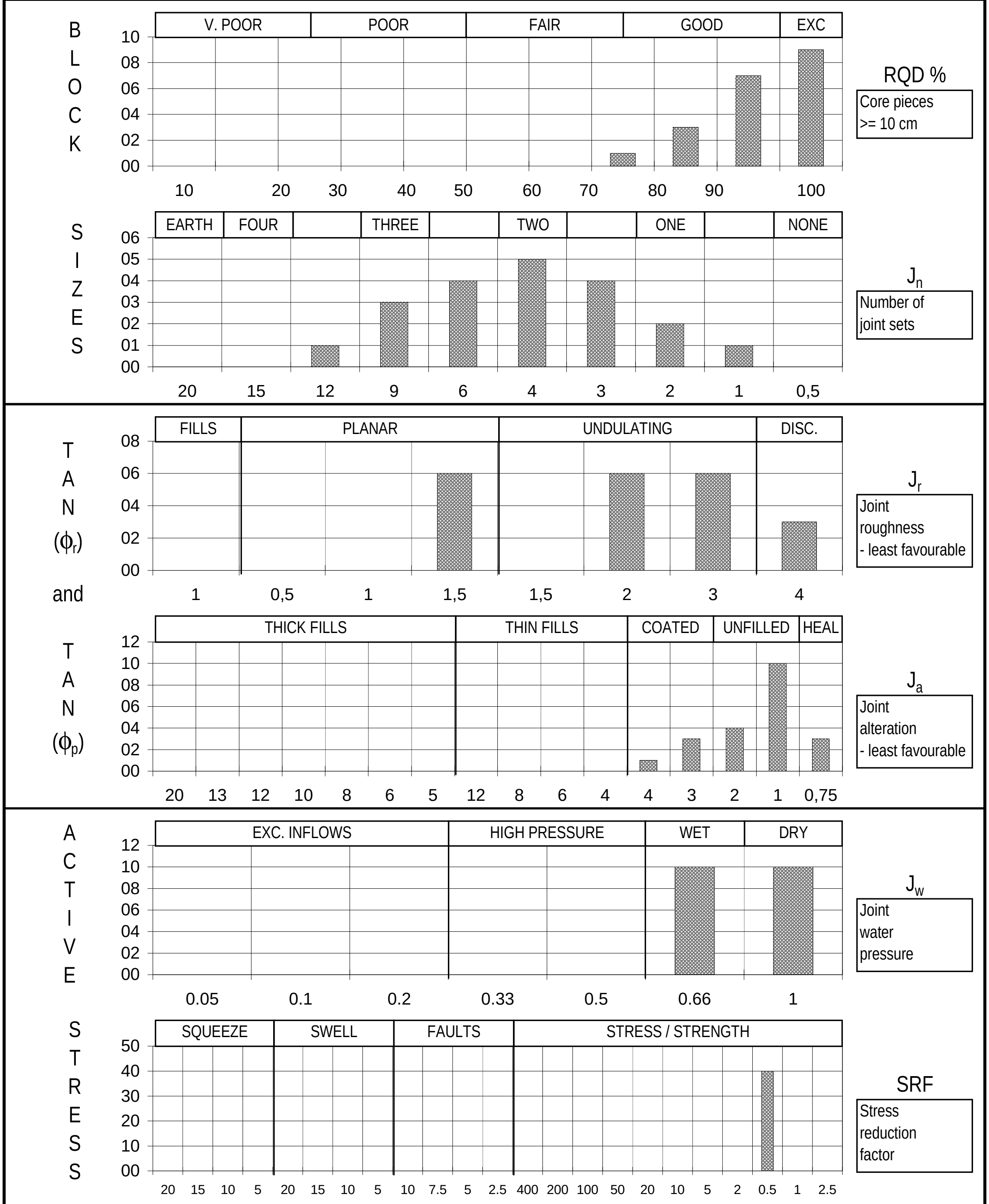
SKB APSE ÅSPØ TUNNEL ch. 65 to 70m	Rev.	Report No. NB&A 2	Figure No. 25
Q-parameters, ch. 65 to 70m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 65-70	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	Q
Q (typical min)=	75	/	9.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**5.500**
Q (typical max)=	100	/	2.0	*	4.0	/	0.8	*	1.00	/	0.5	=	**533.3**
Q (mean value)=	92	/	6.2	*	2.2	/	1.8	*	0.80	/	0.5	=	**29.90**
Q (most frequent)=	100	/	6.5	*	1.5	/	1.0	*	0.66	/	0.5	=	**30.46**



SKB APSE ÅSPØ TUNNEL ch. 70 to 75m	Rev.	Report No. NB&A 2	Figure No. 26
Q-parameters, ch. 70 to 75m	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 70-75	Checked nrb	
	Logg 1.0	Approved	

Q - VALUES:	(RQD	/	Jn)	*	(Jr	/	Ja)	*	(Jw	/	SRF)	=	**Q**
Q (typical min)=	85	/	9.0	*	1.5	/	3.0	*	0.66	/	0.5	=	**6.233**
Q (typical max)=	100	/	2.0	*	4.0	/	0.8	*	1.00	/	0.5	=	**533.3**
Q (mean value)=	95	/	5.0	*	2.4	/	1.6	*	0.83	/	0.5	=	**48.25**
Q (most frequent)=	100	/	4.0	*	2.2	/	1.0	*	0.83	/	0.5	=	**91.30**



	Rev.	Report No.	Figure No.
SKB APSE ÅSPØ TUNNEL ch. 75 to 80m		NB&A 2	27
Q-parameters, ch. 75 to 80	Borehole No. :	Drawn by nrb	Date 20/08/03
	Depth zone (m) ch. 75-80	Checked nrb	
	Logg 1.0	Approved	

10 Joint character and groutability

Since it appears that jointing will be difficult to avoid in the neighbourhood of the pillar loading experiment (unless a move closer to the TBM tunnel at an earlier chainage is allowable, i.e. ch. 45 to 53), it may be important to gain more information on the approximate mechanical properties of the joints. Since jointing in the neighbourhood of the pillar (and in the pillar) may need to be discretely modelled with 3DEC/FRACOD alternatives, this chapter contains some observations of roughness.

It is first necessary to define a joint set numbering system for the APSE tunnel. Since joint logging and reporting is not yet completed, we will use the simple set numbering scheme shown in Figure 28. We will then illustrate the appearance of some of these joints and give their roughness characteristics.

Figure 28 shows typical ± orientations for five different sets; with a sixth (set 4) representing the occasional sub-horizontal joints.

Large-scale examples of set 3a, set 2 and set 1 are seen from right to left in Figure 29. Set 3a, shown here at ch. 39-41m with a partial mineral coating, often has a continuity of several metres. The examples of set 2 and set 1 have been highlighted (and perhaps extended and certainly opened) by the pre-grouting, and were photographed when the tunnel face was at 59m at the end of June 2003. Interestingly, the pre-grouting effect at these joints seemed to have improved when the tunnel was advanced further, as there were very wet conditions close to the face which nearly dried out (or sealed better) when the shear stresses around the face were replaced by a tunnel-parallel σ_2 (and probable Poisson expansion) effect, with further tunnel advance.

Figures 30 and 31 show identified examples of set 1, set 2, set 3a and set 3b, on which roughness amplitude/length measurements were made. These were typically over 250mm (as in Figure 32), 500mm and 1m lengths of profile. The following data were collected, here sorted by joint set.

Table 2. Measurements (and estimates) of a/L amplitude over length for identified joint sets. See Figures 28 and 33.

Joint set	chainage (m)	a/L	J_r	JRC_n
J1	**27**	30/1000	3	13
J1	**49**	25/1000	3	11
J1	**58**	15/1000	1.5-2	7.5
J1	**60**	4/250, 5/500	1.5	7, 8.5
		12/500		10
J2	**27**	8/500	1.5	7
	43	20/1000	2-3	9
	58	30/1000	3	13
	73	5/250, 10/1000	1.5	9, 4.5
J3a	**35**	9/1000	1.5	4
J3b	**62**	4/250, 6/500	1.5	7, 5.5
J3b	**66**	8/250, 15/500	2	5.5, 13
J3b	**66**	5/250, 5/500	2	9, 4.5
J5	**30**	9/500	1.5	8
J5	**81**	4/250, 6/500	1.5	7, 5.5

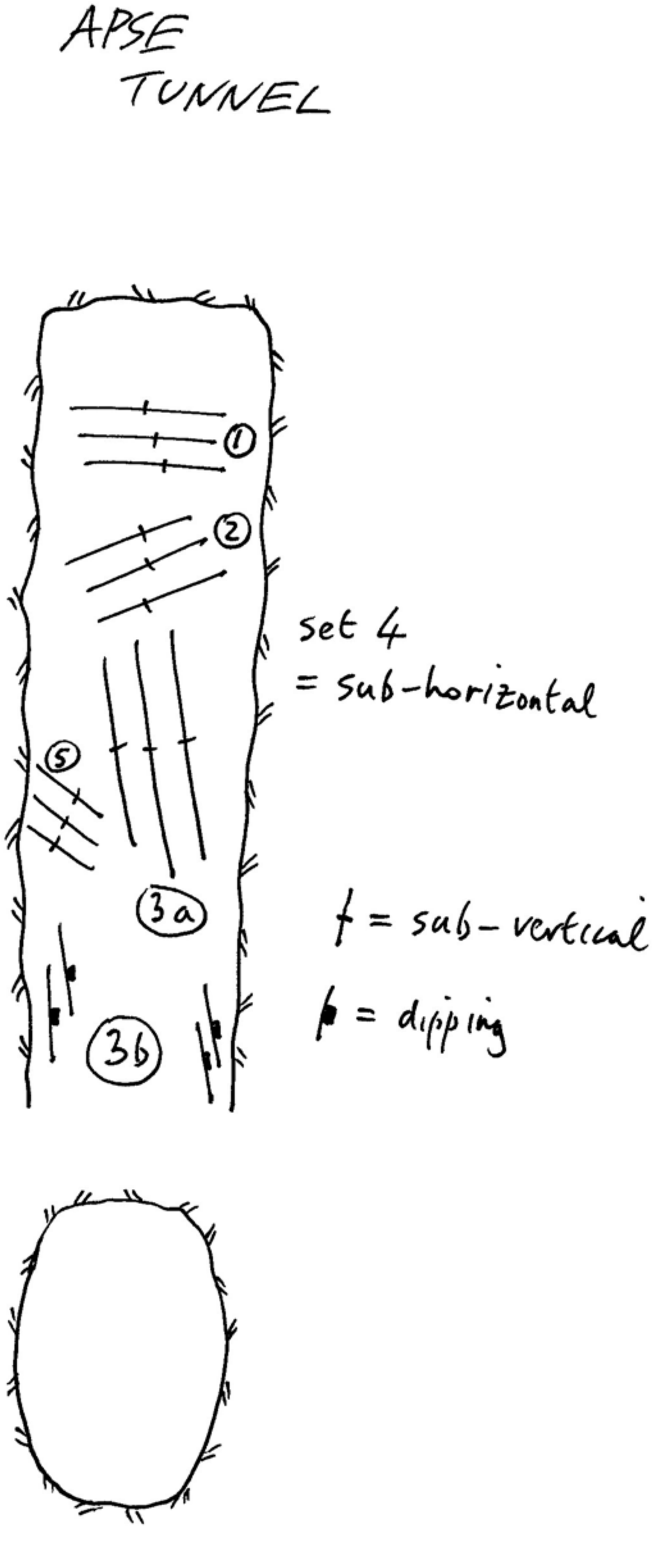


***Figure 28**. A simple joint set numbering system. The tunnel bearing is NO46E in the ÄSPÖ96 co-ordinate system.*

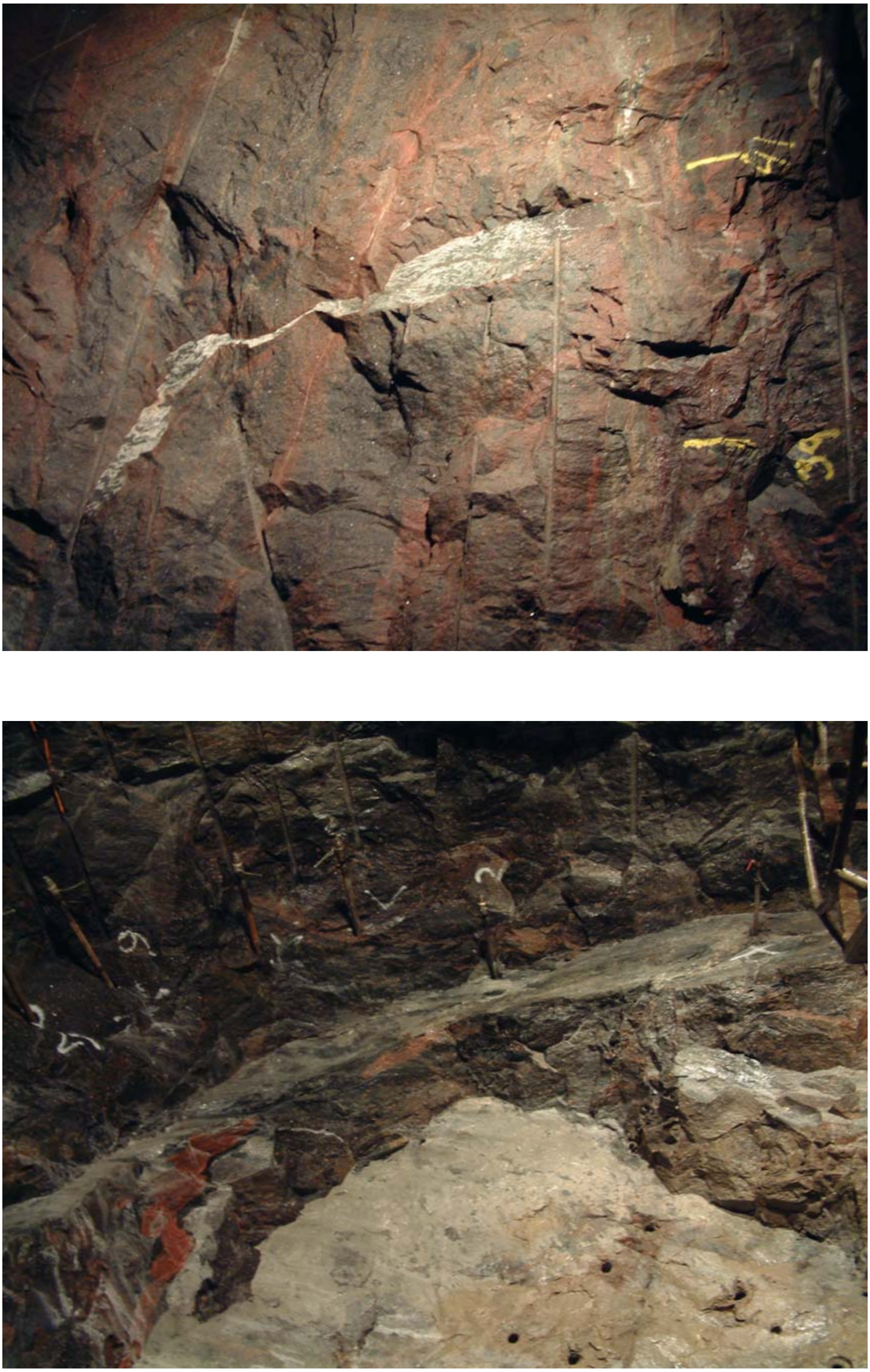


Figure 29. *Larger scale exposures of diagonal (set 3a) sub-perpendicular (set 2) and perpendicular (set 1) joints at ch. 39-41m, and ch. 58-59m respectively.*

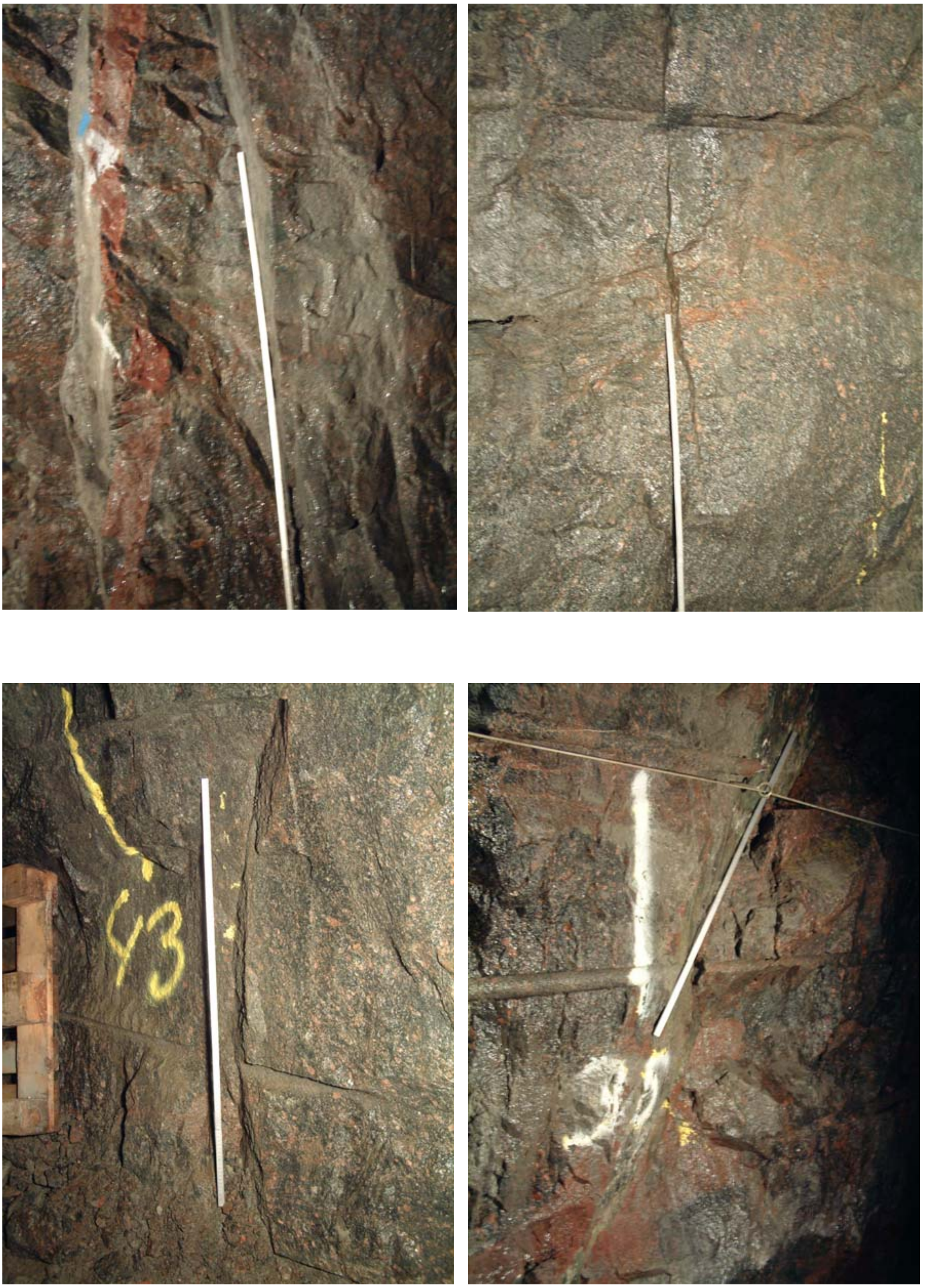


Figure 30. *A selection of joint roughness illustrations: from top left, clockwise: set 2 (58m), set 1 (49m), set 3 (35m) and set 2 (43m).*

***Figure 31**. A selection of joint roughness illustrations: from top left, clockwise: set 2 (73m), set 3b (66m), set 3b (66m) and set 3b (62m).*

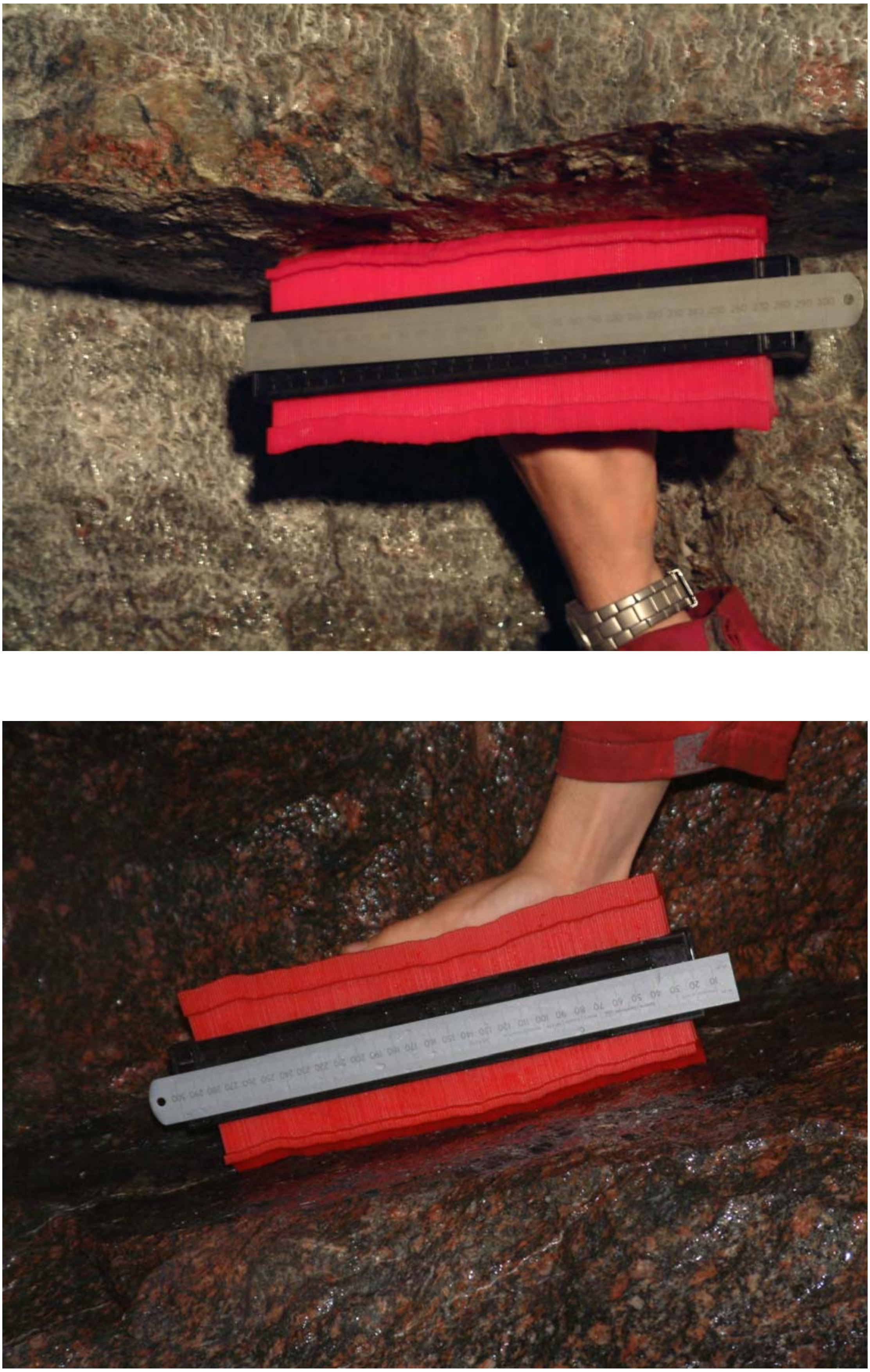


***Figure 32**. Typical roughness traces of set 2 (at 73m) and set 5 (at 81m).*

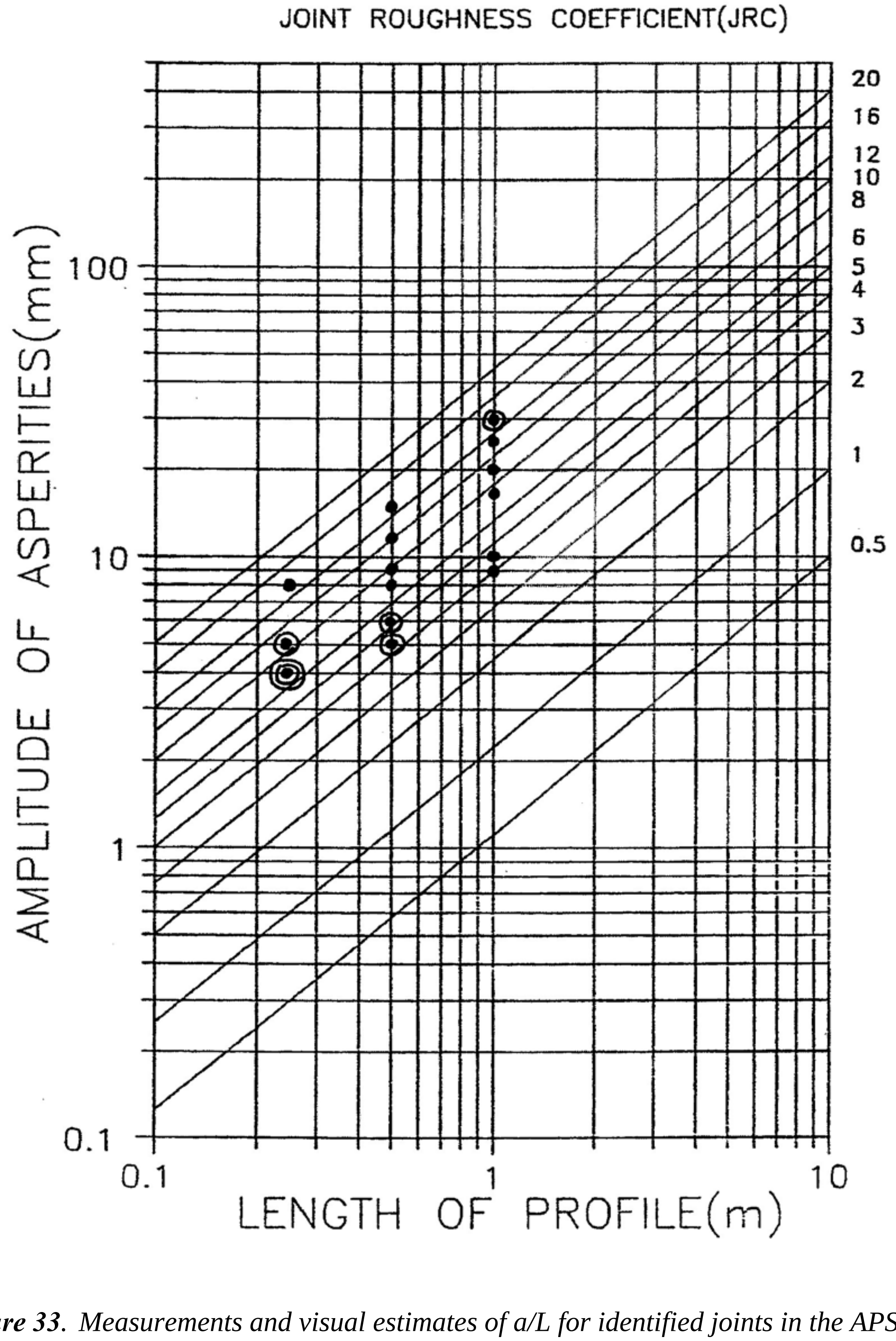


***Figure 33**. Measurements and visual estimates of a/L for identified joints in the APSE tunnel.*

There is considerable variation in joint roughness along the tunnel within each set, and it is therefore tempting to work with global, average values for purposes of illustration. The mean JRC_n value is 8.0 from this limited data set, and the mean J_r value is 2. (The mean length of all the twenty-one profiles considered was about 600mm.)

Taking an alternative approach and constructing envelopes to the data, and extrapolating back to the 0.1m axis in Figure 33, there is also a suggestion of a mean JRC_0 as high as 8, which is also supported by comparison with standard roughness profiles shown in Figure 34. However it is clear from these standard profiles that the typical range of small scale roughness (JRC_0) is from about 3 to 10.

In the next chapter, an approximate impression of the possible distributions of several other joint properties is given in the form of a geotechnical chart for Q, UDEC and BB (Barton-Bandis) joint modelling. We will complete this chapter by providing BB normal closure modelling for a single selection of representative input data. This can be expanded upon if joint modelling (3DEC or FRACOD) proves to be an important component for understanding the pillar load-deformation behaviour.

We will consider the following input data in this demonstration of BB joint modelling:

$JRC_0 = 8$ $JCS_0 = 100$ MPa   ($\sigma_c = 200$ MPa) $\phi_r = 30°$ $L_0 = 0.1$m $L_n = 1.0$m

Figure 35, with inset table of input data and basic calculations for each (consolidating) cycle of loading, shows the way physical aperture (E) and hydraulic aperture (e) may vary with effective stress. The results suggest that for unweathered joints (as modelled) very high pressure grouting would be needed to create a significant aperture increase to assist in grout particle penetration. With the apertures modelled, if the in situ effective stress across a joint was 15 MPa, use of an injection pressure of 10 MPa or higher would be required to significantly deform the joint to assist grout penetration. In the case of calcite filled joints such as illustrated (with grout filling) in Figure 5, a 'softer' behaviour would be indicated, the lower normal stiffness allowing even moderate pressures to widen the joints to large apertures.

According to hydrogeological testing and analysis reported by Fransson (2003), the most conductive features of KA3376B01 are found between 49-50m, and at 57m (four flow anomalies of > 5 l/min). The maximum estimated hydraulic aperture based on actual flow during drilling was ≈ 129 μm, assuming a head of 450m. According to Fransson, the estimated head suggests that local flows of 2 l/min (of which there were relatively fewer) may correspond to hydraulic apertures of 50 μm. It was suggested that grouting would be difficult for joints with apertures less than this. This in fact is where the use of high pressure injection, and the inequality of the physical aperture and hydraulic aperture (e) (Figure 35) play an important role. (See discussion in Barton and Quadros, 2003.)

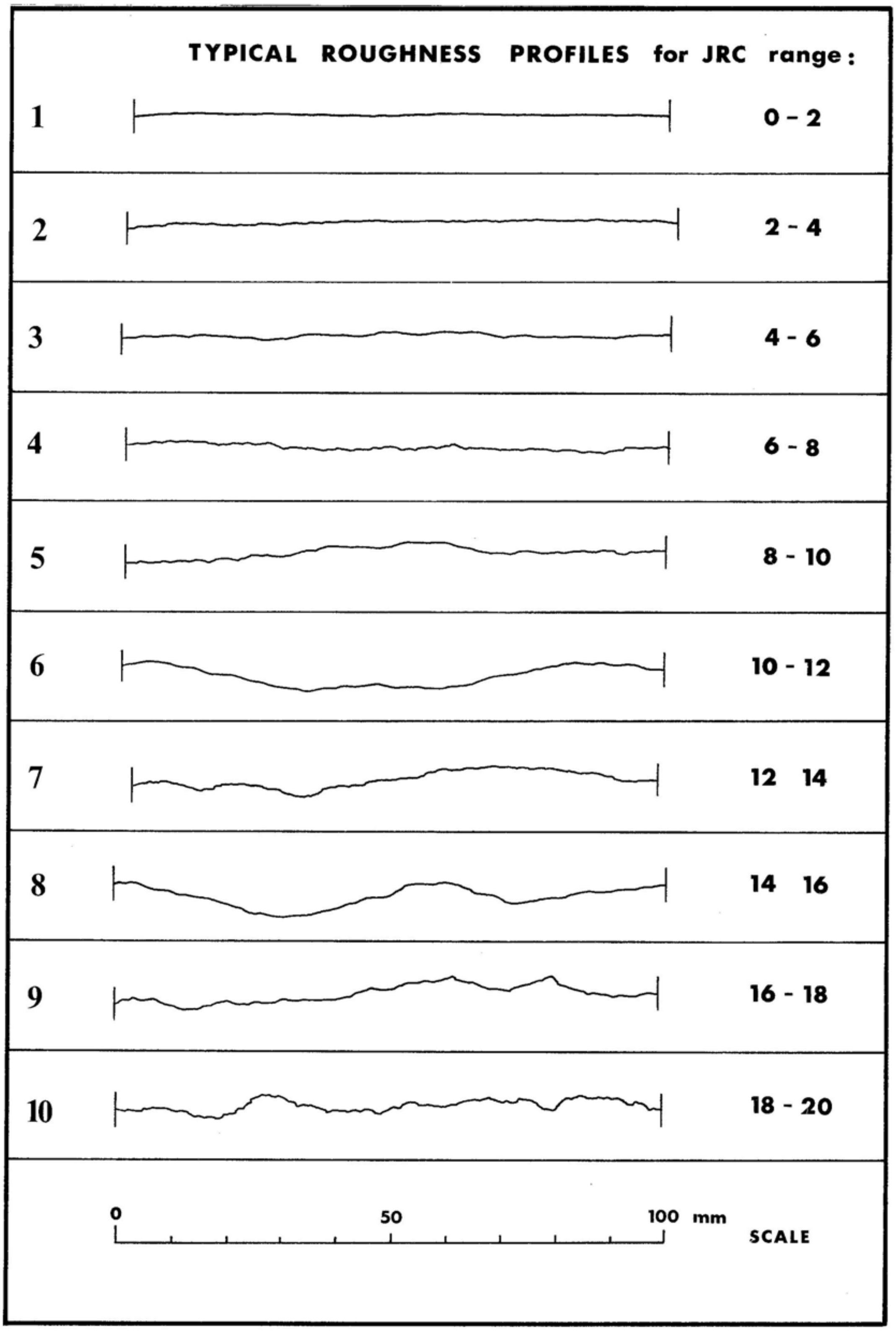


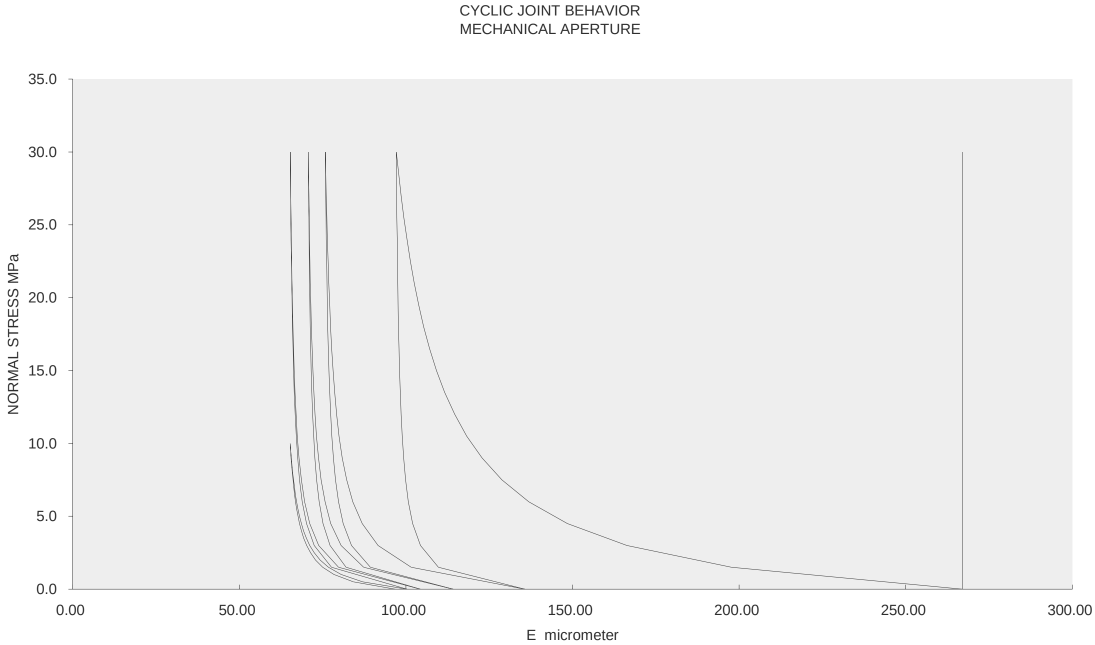
Figure 34. *APSE tunnel is characterized by up to six joint sets in total, whose JRC_0 values generally range from 3 to 10 (from Barton and Choubey, 1977).*

Barton Bandis Joint Model		NORMAL CLOSURE CALCULATION					
INPUT PARAMETERS		SNORM	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4	CYCLE 5
JRC	8	LOAD	30	30	30	30	10 MPa
JCS	100	UNLOAD	0	0	0	0	0 MPa
SIGMAC	200	APERTURE	0.267	0.136	0.114	0.104	0.100 mm
		KNP	2.3E+03	1.3E+04	2.1E+04	2.5E+04	3.3E+03
CALCULATED PARAMETERS							
LOAD		KNI	13.50	19.95	22.42	23.89	24.58 MPa/mm
		VMI	-0.184	-0.062	-0.045	-0.040	-0.038 mm
		AJ	0.074	0.050	0.045	0.042	0.041
		BJ	0.403	0.804	0.993	1.039	1.063
UNLOAD		KNI'	19.95	22.42	23.89	24.58	25.23 MPa/mm
		VIRR	-0.131	-0.022	-0.010	-0.004	-0.004 mm
		DSM	-0.131	-0.153	-0.163	-0.167	-0.170
		SIRR	-0.131	-0.153	-0.163	-0.167	-0.131
		AJ'	0.050	0.045	0.042	0.041	0.040
		BJ'	1.266	1.130	1.211	1.130	1.159
		VMI'	-0.040	-0.039	-0.035	-0.036	-0.034

CONSTANTS

	CYCLE 1	CYCLE 2	CYCLE 3	CYCLE 4
A	-0.2960	-0.1001	-0.1031	-0.1031
B	-0.0056	-0.0073	-0.0074	-0.0074
C	2.2410	1.0082	1.1350	1.1350
D	-0.2450	-0.2300	-0.2510	-0.2510
C1	84.77	43.37	31.38	20.00
C2	0.02	0.01	0.01	0.01
JRC^2.5	181			

DATA	NORMAL STRESS		delta E	E	e	delta e	COND m2	COND c
CYCLE 1	0.0	0.000	0.00	267.00	267.00	0.00	-8.2262	-4.2262
	1.5	-0.069	69.28	197.72	197.72	69.28	-8.4871	-4.4871
	3.0	-0.101	100.65	166.35	152.87	114.13	-8.7105	-4.7105
	4.5	-0.119	118.54	148.46	121.75	145.25	-8.9082	-4.9082
	6.0	-0.130	130.11	136.89	103.53	163.47	-9.0491	-5.0491
	7.5	-0.138	138.19	128.81	91.65	175.35	-9.1549	-5.1549
	9.0	-0.144	144.17	122.83	83.35	183.65	-9.2374	-5.2374
	10.5	-0.149	148.76	118.24	77.23	189.77	-9.3036	-5.3036
	12.0	-0.152	152.41	114.59	72.54	194.46	-9.3580	-5.3580
	13.5	-0.155	155.36	111.64	68.85	198.15	-9.4034	-5.4034
	15.0	-0.158	157.82	109.18	65.86	201.14	-9.4420	-5.4420
	16.5	-0.160	159.88	107.12	63.39	203.61	-9.4751	-5.4751
	18.0	-0.162	161.64	105.36	61.32	205.68	-9.5039	-5.5039
	19.5	-0.163	163.16	103.84	59.56	207.44	-9.5292	-5.5292
	21.0	-0.164	164.49	102.51	58.05	208.95	-9.5515	-5.5515
	22.5	-0.166	165.66	101.34	56.74	210.26	-9.5714	-5.5714



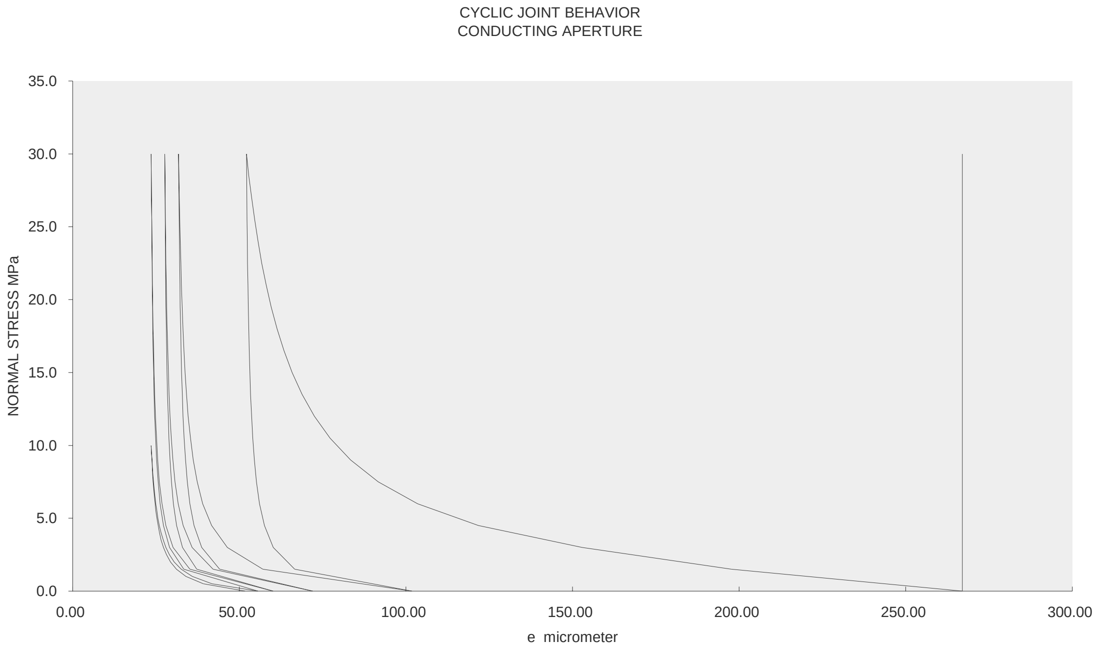


***Figure 35**. Example of BB normal closure modelling.*

11 General geotechnical log

Figure 36 gives a general geotechnical log of the TASQ tunnel. The left (Q-side) of the figure represents the rigorous logging results shown earlier for almost the whole tunnel (24 to 80m) in Figure 11. The remainder of the distributions (middle and right-hand columns in Figure 36) represent estimates only, of such parameters as Fm^{-1}, S(m), JRC_0, JCS_0, K(m/s), σ_c (MPa), σ_1 (MPa), V_p (km/s), L (m), a/L (0.1 and 1.0m). An explanation of these parameters in relation to earlier core logging at TASQ is given in Appendix E.

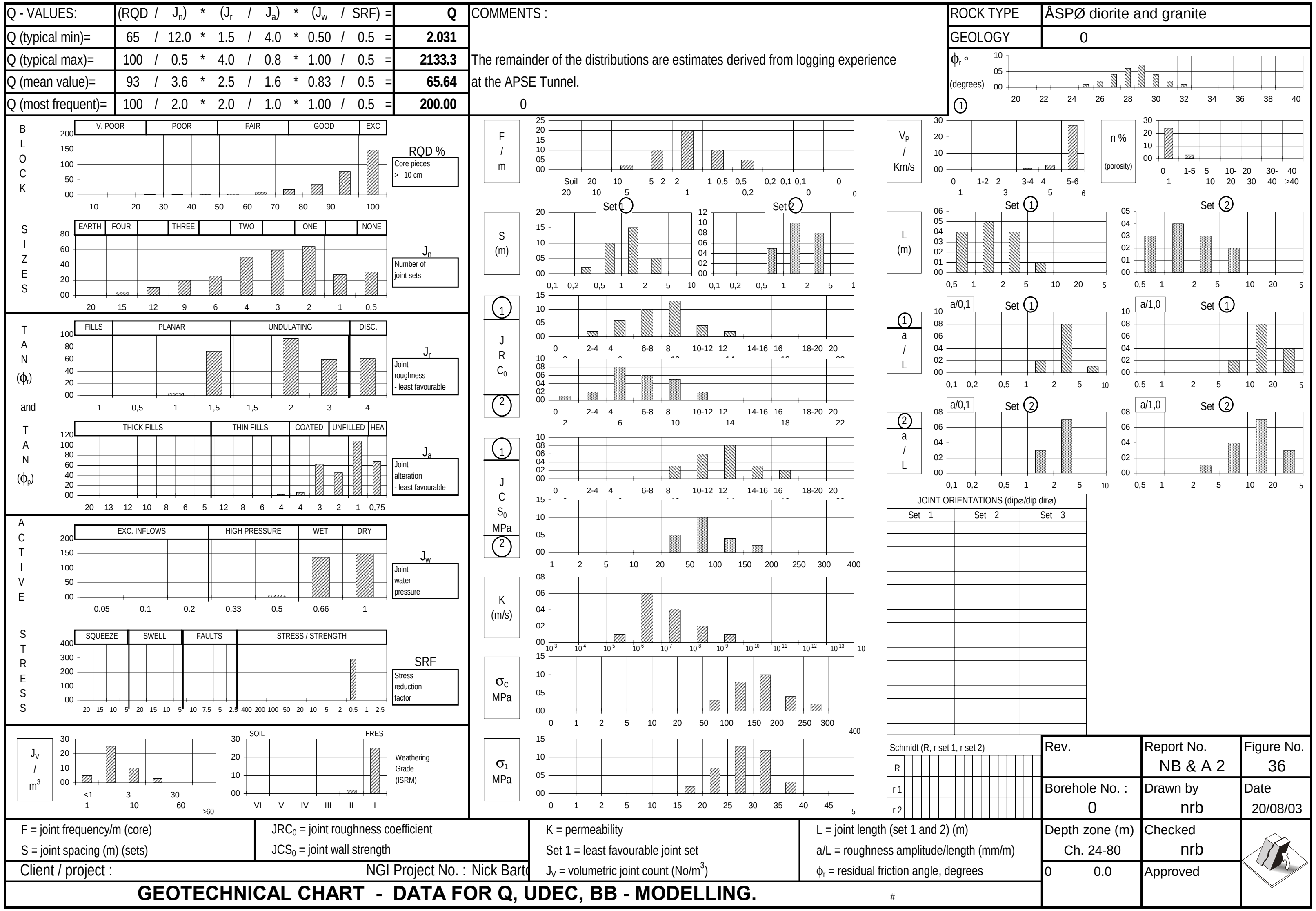


Figure 36. Geotechnical log of APSE tunnel. Only the Q-parameter histograms have been collected in a rigorous manner.

12 Some Q-parameter correlations for modelling

With the exact experimental site as yet undecided, but likely to be where the invert has already been developed (ch. 60-80m), we have only to refer to the end of Table 1 to see the likely range of Q-values. If we exclude the panel closest to the face of the tunnel (ch. 75-80m), the Q_{mean} and $Q_{most\ frequent}$ values are respectively 19.1, 16.1, 29.9 and 66.0, 30.8, 30.5, which for convenience can be averaged to about 20 and 40 respectively.

For correlation with engineering parameters, the term Q_c is used following Barton, 2002a:

$$Q_c = Q \times \frac{\sigma_c}{100} \tag{1}$$

If we make the present assumption from the compilation by Staube et al., 2003, that the granite and diorite have representative mean values of about 182 and 214 MPa, it is clear that an acceptable approximation will be to set $Q_c \approx 2 \times Q$ or to 40 and 80 respectively for the $Q_{c\ (mean)}$ and $Q_{c\ (most\ frequent)}$.

12.1 Estimation of V_p

The following empirical equation can be used for near-surface correlation between V_p and Q_c.

$$V_p \approx 3.5 + \log Q_c \tag{2}$$

Barton (2002a) has shown that stress effects are important components of both V_p and deformation modulus E_m (see later) and suggested the following approximation for 500m depth (or equivalent stress):

$$V_p \approx 5 + 0.5 \log Q_c \tag{3}$$

We can therefore predict the following:

Table 3. Possible ranges of V_p in the APSE experimental area.

Quality	V_p (surface)	V_p (500m)
$Q_{c\ (mean)}$ 40	5.1 km/s	5.8 km/s
$Q_{c\ (most\ frequent)}$ 80	5.4 km/s	6.0 km/s

It may be noted from Figure 37c that the '1000m line', which is closer to the σ_1 estimates at TASQ (25 to 35 MPa approx.) suggests V_p values as high as 6.1 and 6.2 km/s. As pointed out in Appendix E, values of the above order (5.8 to 6.2 km/s) are very similar to those derived by Cosma et al., 2001, when performing cross-hole seismic tomography in the ZEDEX experiment, 200m up the TBM ramp from TASQ.

12.2 Estimation of E_{mass}

The foregoing emphasis on V_p and its treatment as the first predicted parameter is deliberate as most other parameters needed by modellers have not been directly measured at Äspö.

The importance of V_p is that links to the ***static*** modulus of deformation Emass have been suggested (Barton, 2002a). In the following we will first examine the 'conventional' near-surface correlation between Q_c and E_{mass}:

$$E_{mass} \approx 10\, Q_c^{1/3} \tag{4}$$

As discussed in Barton, 2002a, with general correlation between V_p and E_{mass} assumed, it can be estimated that the 500m depth (or equivalent stress) value of E_{mass} is as follows, form the geometry of Figure 37c:

$$E_{mass} \approx 10^{(4.5+0.5 \log Q_c)/3} \tag{5}$$

We can therefore predict the following:

Table 4. Possible ranges of E_{mass} in the APSE experimental area.

Quality	E_{mass} (surface)	E_{mass} (500m)
$Q_{c\ (mean)} = 40$	34.2 GPa	58.5 GPa
$Q_{c\ (most\ frequent)} = 80$	43.1 GPa	65.6 GPa

A direct linkage between E_{mass} and V_p can be derived from equations 2 and 4, and from equations 3 and 5. It is as follows:

$$E_{mass} \approx 10^{(V_p - 0.5)/3} \tag{6}$$

Using Figure 37c, where it is easiest to use the linear scale (of V_p) rather than the non-linear scale (of E_{mass} or M), the earlier estimates of V_p = 6.1 and 6.2 km/s for the '1000m depth line' (nearly equivalent to σ_1) convert to E_{mass} estimates of 73.6 GPa and 79.4 GPa respectively from the $Q_{c\ (mean)}$ and $Q_{c\ (most\ frequent)}$ estimates of 'mean' qualities between ch. 60 and 75m.

The above values of E_{mass} (58.5, 65.6, 73.6 and 79.4) from the '500m' ($\sigma_{2,3}$) and '1000m' (σ_1) depth lines compare with average laboratory triaxial E-moduli of about 74 to 65 GPa on samples from the vertical and horizontal holes used for Doorstopper gauge (DDGS) stress measurements (Christiansson & Janson, 2002), and average E-moduli of 70 and 60 GPa from uniaxial tests on cores from the same vertical and horizontal holes. The above authors gave the following overall mean values and ranges from their investigations:

Vertical hole	E-modulus = 72.5 ± 21 GPa
Horizontal hole	E-modulus = 56.2 ± 26 GPa

At this stage a 'modeller's compromise' stressed E_{mass} value of 65 GPa can be tentatively recommended for the undisturbed rock mass, roughly relevant to the magnitudes of σ_2 and σ_3 confinement. It is a matter of conjecture whether one would be justified in using values of even 75 to 80 GPa for loading directions equivalent to σ_1.

12.3 Estimation and deformation

The Q-system has been linked for many years to estimates of tunnel or cavern deformation (or ***convergence*** which may be twice as large). A central trend of measured data is:

$$\Delta \text{ (mm)} \approx \frac{\text{SPAN (m)}}{\text{Q}} \tag{7}$$

But there is a wide scatter and 'refined' equations have been suggested (Barton, 2002a) taking into account the likely influence of the competence factor or ratio of stress to strength. We therefore estimate:

$$\Delta_v \approx \frac{\text{SPAN}}{100\text{ Q}}\sqrt{\frac{\sigma_v}{\sigma_c}} \tag{8}$$

$$\Delta_h \approx \frac{\text{HEIGHT}}{100\text{ Q}}\sqrt{\frac{\sigma_h}{\sigma_c}} \tag{9}$$

We will assume the following for simplicity: SPAN = 5000mm, and HEIGHT = 7500mm, Q_{mean} = 20 and $Q_{most\ frequent}$ = 40, $\sigma_v \approx$ 10 MPa, σ_h (here σ_H) $\approx$ 30 MPa, $\sigma_{c\ (mean)}$ = 200 MPa. From equations 8 and 9 we obtain the following estimates:

Table 5. APSE tunnel deformation estimates.

Quality	**σ_v = 10 MPa**	**σ_H = 30 MPa**
Q_{mean} = 20	Δ_v = 0.6mm	Δ_H = 1.5mm
$Q_{most\ frequent}$ = 40	Δ_v = 0.3mm	Δ_H = 0.7mm

* Decimal places have been rounded to avoid implication of precision.

In each of the above cases one would be justified in doubling the values of 'Δ' to obtain convergence, as measured by a ***tape extensometer***, which of course is already too late to record the total deformation since access is required. However this, or near-tunnel-face MPBX installations must necessarily be the source of the numerous convergence and deformation measurements reviewed in Barton, 2002a.

Interestingly, the excellent convergence measurements performed at numerous sections along the TASQ tunnel and elastic continuum modelling using E = 55 GPa appear to be supporting both each other and the magnitudes of deformation predicted by empirical means. Figure 38 reproduces one example of the above, as presented by Christer Andersson in the July 2003 APSE meeting. (Bolt numbers '3-4' represent diametral measurement at mid-wall height, while '5-6' is higher up across the arch itself, as in the elastic model).

Clearly, equations 8 and 9 will predict other values of deformations Δ_v and Δ_h, as the Q-value varies in other sections of the tunnel. Using the overall Q_{mean} = 66 from all the logging performed (ch. 24 to 80m from Figure 11), the predictions given in Table 5 will reduce by factors 20/66 and 40/66 respectively, giving mean horizontal convergence predictions of about 0.85mm.

12.4 Estimation of 'rock mass strength'

In the recent Barton, 2002a publication on classification and characterization techniques in the Q-system, and the possibility for correlation with various parameters useful for modelling and design studies, it was suggested that the 'crushing strength' of the rock mass could be estimated using a formula derived for TBM penetration rate prediction (Barton, 2000):

$$\mathrm{SIGMA}_{cm} \approx 5\,\gamma\,Q_c^{1/3} \quad \mathrm{MPa} \tag{10}$$

This was made orientation-sensitive by recommending the use of RQD_o, the RQD oriented in the loading (or tunnelling) direction, and the use of the J_r/J_a ratio most appropriate to the loaded direction (i.e. its weakening or strengthening effect). The estimate of 'crushing strength' was given a further 'anisotropy correction' by allowing the user to evaluate (and compare) the ratio of σ_c and I_{50}. The equation involving I_{50} was:

$$\mathrm{SIGMA}_{tm} \approx 5\,\gamma\,Q_t^{1/3} \quad \mathrm{MPa} \tag{11}$$

where Q_t is defined as $Q \times I_{50}/4$ (in contrast to Q_c which is defined as $Q \times \sigma_c/100$). The I_{50} value, or point load strength using 50mm diameter samples, may be 1/25 times the value of σ_c when rock is isotropic (but can be as little as 1/75 times the value of σ_c when strongly anisotropic schistose, foliated rock is present).

Considering just the first of these equations for the moderately homogeneous diorite and fine-grained granite intrusions, we may utilise an approximate mean density (γ) of 2.7 t/m^3 and $Q_{c\,(mean)}$ and $Q_{c\,(most\ frequent)}$ values of 40 and 80 (as before) to obtain the following estimates from equation 10:

Table 6. TASQ tunnel estimates of $SIGMA_{cm}$.

Quality	$SIGMA_{cm}$
$Q_{c\ (mean)} = 40$	46 MPa
$Q_{c\ (most\ frequent)} = 80$	58 MPa

Although not presented as a 'confining stress correction' in Barton, 2002a, the matching of TBM cutter force (F) with $SIGMA_{cm}$ or $SIGMA_{tm}$ in the Q_{TBM} method of prognosis (Barton, 2000) also included a tunnel depth (or biaxial-stress-at-the-tunnel-face) correction of [× (σθ/5)], where the biaxial stress at the face (σθ) was assumed to be about 5 MPa at 100m depth, making tunnelling more difficult at greater depths than this.

At 450m depth we could crudely adjust the above to 'confined strengths' of about 450/100 × 46 = 207 MPa and 450/100 × 58 = 261 MPa.

Confined 3DEC models reported by Staub et al., 2002, showed ultimate strengths of about 180 to 240 MPa in the recent Äspö studies. The effect of confining stress on crushing strength is obviously complicated in the case of rock masses, and the resulting strength will be particularly sensitive to boundary conditions. Clearly a tunnel wall, or an overstressed web between two large diameter boreholes is not under the same biaxial (semi-triaxial) boundary conditions as the rock under a TBM's cutter on an otherwise biaxially (semi-triaxially) stressed tunnel face.

12.5 Estimating cohesive and frictional components CC and FC

In the recent development of Q-value correlations, it was discovered that the Q-value numerically resembled the product of ***cohesion*** and the ***friction coefficient***, and perhaps could be expressed in units MPa. It was also suggested that since the Q-parameter ratings had been derived from the need for given amounts of shotcrete and rock bolts, there would likely be uncertainty in the assumed values of ***cohesion*** and ***friction coefficient*** in the case of the most massive rock that did not need such rock support (as basically at Äspö).

Barton (2002a) presented the above '***cohesion***' and '***friction coefficient***' as tentative components CC and FC, the 'cohesive and frictional components':

$$CC = \frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100} \tag{12}$$

$$CC = \tan^{-1}\left(\frac{J_r}{J_a} \times J_w\right) \tag{13}$$

To apply these equations for CC and FC to the 'average' rock between ch. 60 and 75m, we can refer to the Table 1 compilation of Q-parameters, which were taken from Figures 17 to 27. Mean values of the relevant Q-parameters from ch. 60 to 75m are given in the following Table 7.

Table 7. Mean Q-parameter values for ch. 60 to 75m.

Source	RQD	J_n	J_r	J_a	J_w	SRF
From Q_{mean}	87, 92, 95	8.6, 6.2, 5.0	2.2, 2.2, 2.4	2.3, 1.8, 1.6	0.7, 0.8, 0.8	0.5, 0.5, 0.5
From $Q_{most\ frequent}$	100, 98, 100,	10.5, 6.5, 4.0	2.0, 1.5, 2.2	1.0, 1.0, 1.0	0.66, 0.8, 0.66	0.5, 0.5, 0.5
averages	91	6.6	2.3	1.9	0.8	0.5
averages	99	7.0	1.9	1.0	0.7	0.5

From this data we can estimate CC and FC as follows (assuming again σ_c = 200 MPa):

From Q_{mean}

$$CC = \frac{91}{6.6} \times \frac{1}{0.5} \times \frac{200}{100} = 55 \text{ (MPa)}$$

$$FC = \tan^{-1}\left(\frac{2.3}{1.9} \times 0.8\right) = 44 \text{ degrees}$$

From $Q_{most\ frequent}$

$$CC = \frac{99}{7.0} \times \frac{1}{0.5} \times \frac{200}{100} = 57 \text{ (MPa)}$$

$$FC = \tan^{-1}\left(\frac{1.9}{1.0} \times 0.7\right) = 53 \text{ degrees}$$

It may be observed that in the walls of the APSE tunnel, where we originally used SRF = 2.0 for the purpose of ***classification*** (and in view of the unfavourable, low tangential stresses) the above CC estimates would simply become about 14 MPa in both cases (when rounding decimal places).

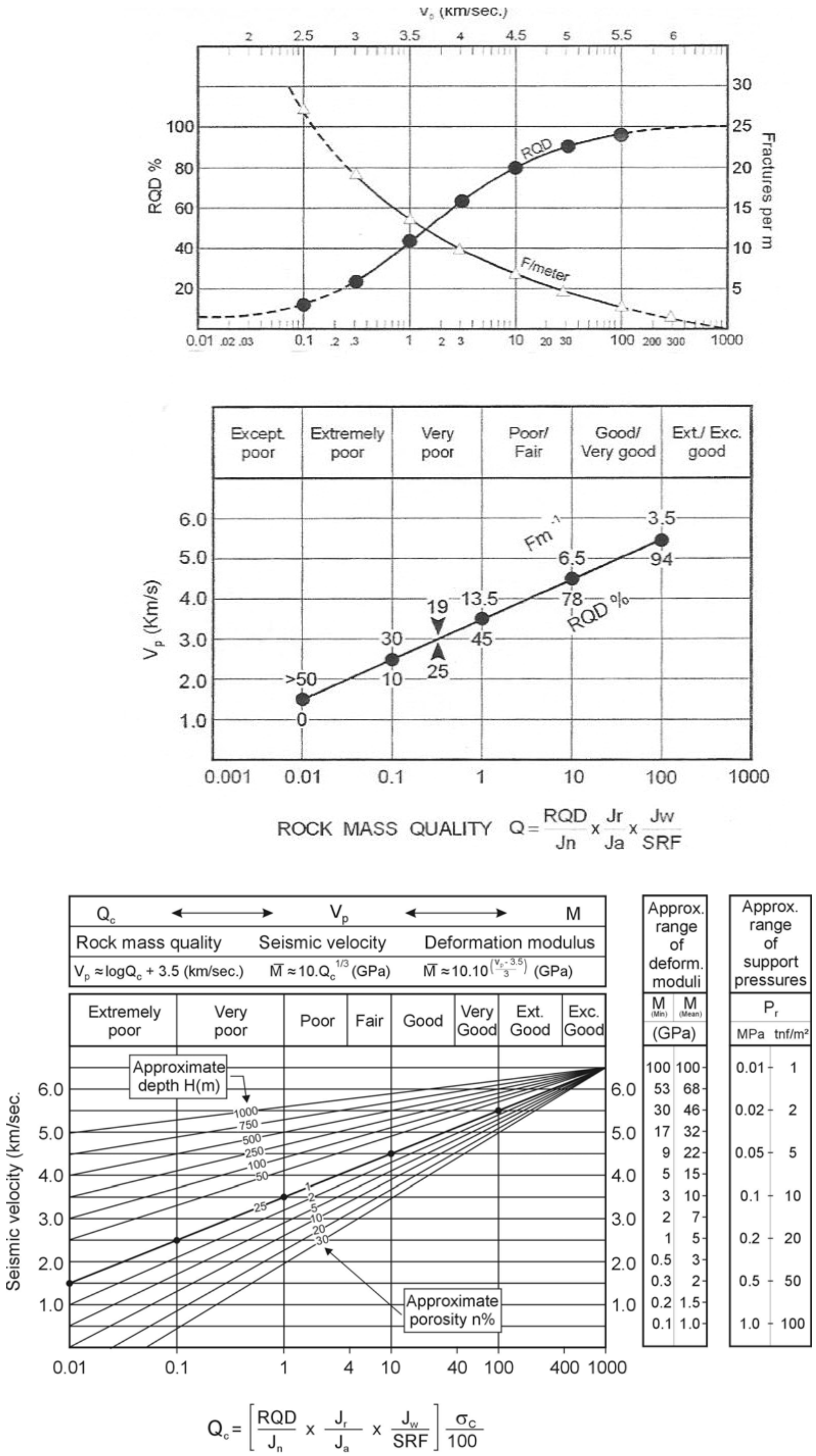


***Figure 37**. Inter-relationships between RQD, F m-1 and Vp (from Sjøgren et al., 1979, and subsequent generalisation between Q_c, V_p and E_{mass} with correction for depth or stress (+ve) and porosity (-ve). Barton, 1995, 2002a.*

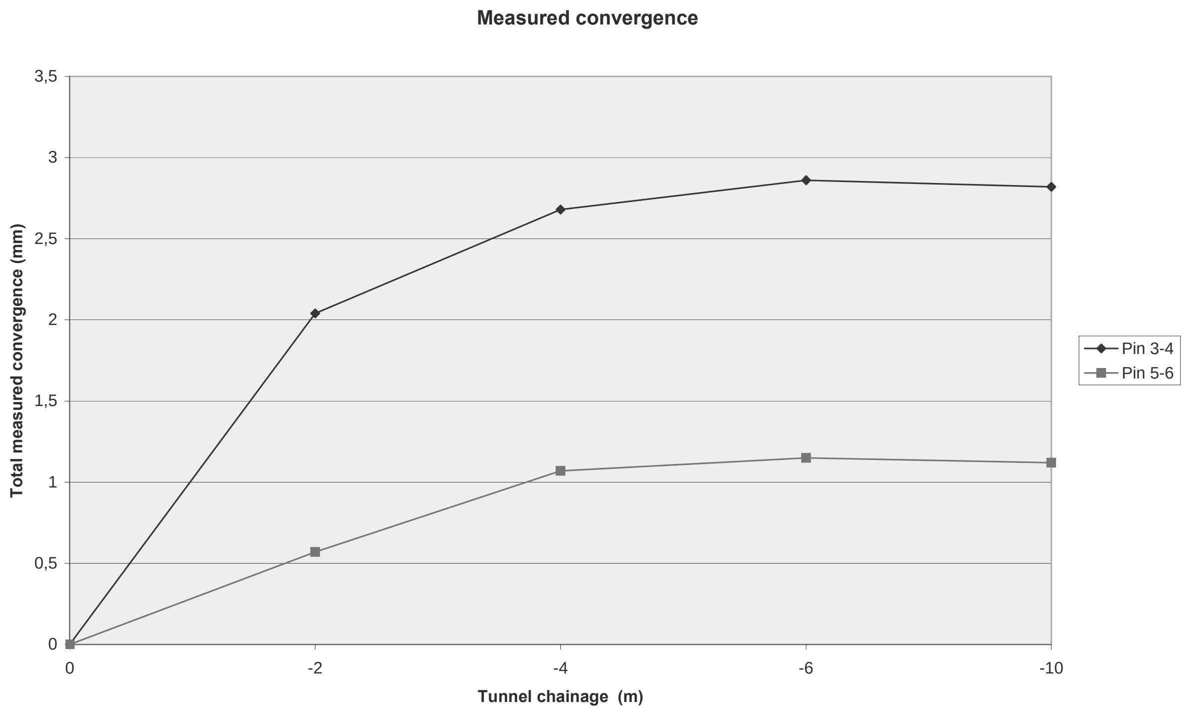


Figure 38. *Results of measured convergence at section 49 in the TASQ tunnel (Andersson,2003. Staub, 2004).*

13 Conclusions

1. The Q-logging performed in the TASQ Tunnel has taken the form of Q-parameter histogram logging of each 5m of the tunnel. In the first phase in June 2003, the arch and upper walls from ch. 24 to 59m was logged using thirty opinions of each Q-parameter per 5m, 10 for the arch and 10 each for the walls. The best quality was registered between ch. 45 and 53m, where almost all half-rounds were visible and where there was limited jointing.

2. The second phase of logging in July 2003 was of the walls and invert (where visible) of ch. 60 to 80m, and twenty opinions of each Q-parameter per 5m were given, 10 for each side of the tunnel. The best quality was registered between ch. 75 and 80m, but this quality was lower than between ch. 45 and 53m. A disadvantage and potential source of error was the insufficiently cleaned and water-collecting state of the invert, which needed frequent pumping.

3. Q-histogram logging of the core from KA3376B01, which runs inside the left wall of the tunnel, also confirmed the increased amount of jointing and lower Q-values in the inner 20m of the hole compared to the outer 60m. The core depths and tunnel chainages do not however correspond, due to the different collar and portal chainages, but the tendency of more jointing and lower Q-values is clear.

4. A total of six specific joint sets were identified in the 55m of tunnel that was logged. Roughness-profiled examples representing five of the sets are given, together with J_r and JRC_n roughness estimates. The most typical J_r value from this and all other logging was 2, and JRC_n was typically 8 for an average profile length of 600mm.

5. Since the earlier chainages in the tunnel have not been targeted for invert development, perhaps due to the proximity of the TBM tunnel, the assumption was made that the pillar development will be within the 60 to 75m chainage. Here the average Q_{mean} is 20 and the average $Q_{most\ frequent}$ is 40, in round figures. With σ_c approximating 200 MPa in round figures, we can therefore use Q_c values of 40 and 80 for a preliminary estimate of rock mass parameters.

6. Stressed (500m depth) estimates of V_p and E_{mass} based on Q_c correlations were therefore ranging from 5.8 to 6.0 km/s and 59 to 66 GPa respectively. A more stressed (1000m depth) model, ***perhaps*** equivalent to σ_1 stress levels (rather than σ_2, σ_3 levels) suggested V_p ranges of 6.1 to 6.2 km/s, and E_{mass} ranges of 74 to 79 GPa. There is necessarily little empirical data from these stress levels in relation to E_{mass}, but more from V_p. One is therefore relying on direct V_p–E_{mass} correlation based on Barton, 2002a.

7. Empirical relationships for wall and arch/invert deformation, using the assumptions of σ_v = 10 MPa and σ_H = 30 MPa, and σ_c = 200 MPa, suggest average closures of 3.0mm and 1.4mm horizontally and vertically in the chainage 60 to 75m. The higher overall Qmean for the 'whole' tunnel (24 to 80m) of 66 would reduce the prediction of horizontal convergence to about 0.9mm. There appears to be reasonable correspondence to measured convergences and to elastic continuum modelling prediction, using Emass = 55 GPa.

14 References

Andersson, C. 2003. Seminar communication.

Barton, N. & Choubey, V. 1977. The shear strength of rock joints in theory and practice. Rock Mechanics 1/2:1-54. Vienna: Springer. Also NGI-Publ. 119, 1978.

Barton, N., Løset, F., Smallwood, A., Vik, G., Rawlings, C., Chryssanthakis, P., Hansteen, H. & Ireland, T. 1992. Geotechnical Core Characterization for the UK Radioactive Waste Repository Design. 1992 Proc. of ISRM Symp. EUROCK, Chester, UK.

Barton, N. 1995. The Influence of Joint Properties in Modelling Jointed Rock Masses. Keynote Lecture, 8th ISRM Congress, Tokyo, 3; 1023-1032, Balkema, Rotterdam.

Appendix E

Barton, N. 2002a. Some new Q-value correlations to assist in site characterization and tunnel design. Int. J. Rock Mech. & Min. Sci. Vol. 39/2, pp.185-216.

Barton, N. 2002b. Q-logging of two boreholes for the Äspö pillar experiment, for development of preliminary input parameters. SKB, unpublished.

Christiansson,R. and T. Janson 2002. Test with three different stress measurement methods in two orthogonal bore holes. Proc. of North American Rock Mechanics Symposium, NARMS 2002, Toronto.

Cosma, C., Olsson, O., Keskinen, J. & Heikkinen, P. 2001. Seismic characterization of fracturing at the Äspö Hard Rock Laboratory, Sweden, from the kilometre scale to the meter scale. Int. J. Rock Mech.& Min. Sci. 38, (2001), 859-865, Special Issue, Application of Geophysics to Rock Engineering , Pergamon, Elsevier Science Ltd.

Fransson, Å. 2003. Core boreholes KF0066A01, KF0069A01, KA3386 01 and KA 3376 N01: Hydrological characterization and pressure responses during drilling and testing. SKB: IPR-03-06, Swedish Nuclear Fuel and Waste Management Co. Stockholm.

Staub, I., Fredriksson, Q., Outters, N. 2002. Strategy for a descriptive rock mechanics model. Development and testing of the theoretical approach. SKB: R-02-02, Swedish Nuclear Fuel and Waste Management Co. Stockholm.

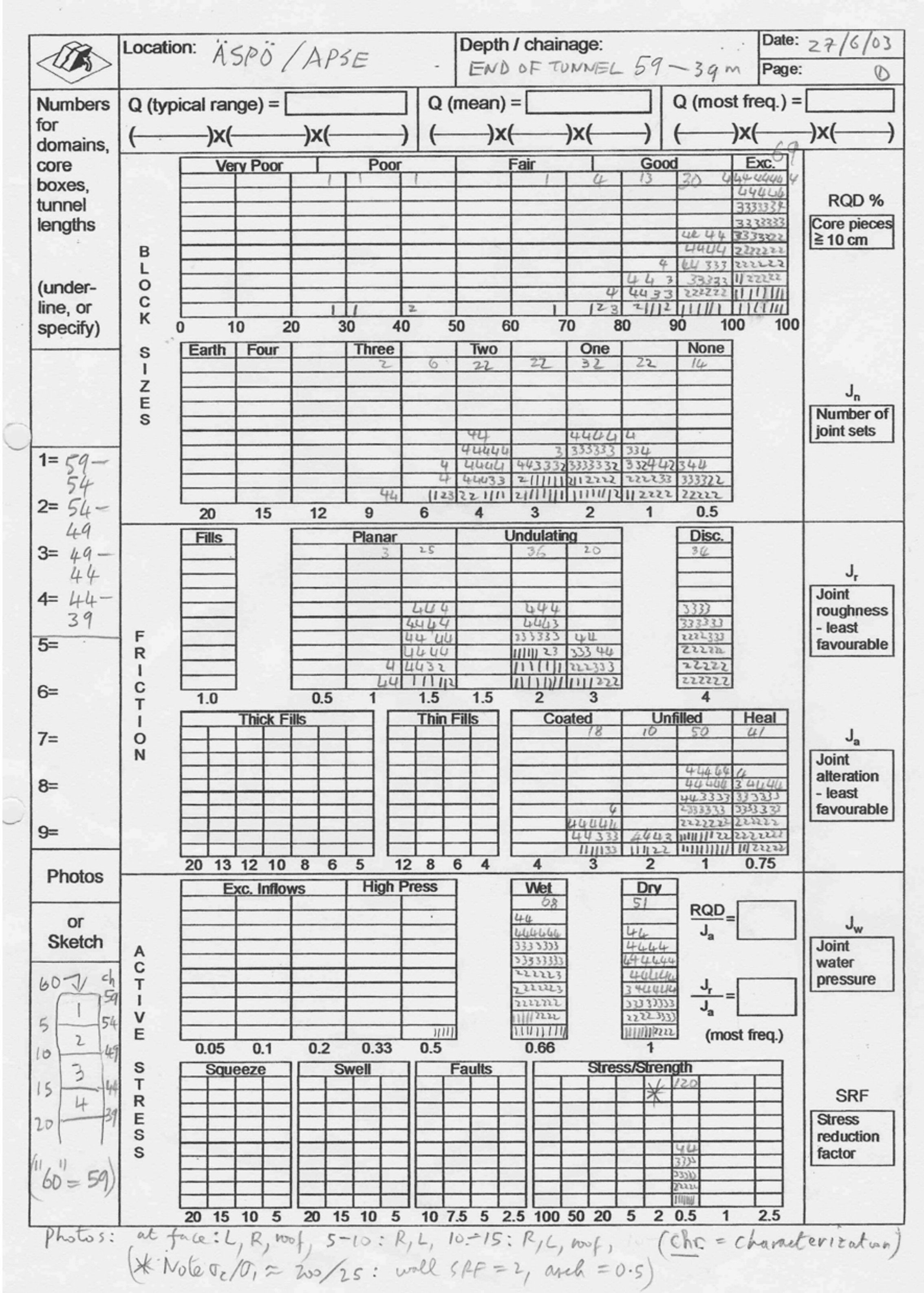
Staub, I., Janson, T. & Fredriksson, A. 2003. Äspö Hard Rock Laboratory – Äspö Pillar Stability Experiment – Geology and properties of the rock mass around the experiment volume. SKB: IPR-03-02, Swedish Nuclear Fuel and Waste Management Co. Stockholm.

Appendix A

APSE tunnel Q-logging

Ch. 24 to 59m

27-28 June 2003



Location: ÄSPÖ / APSE

Depth / chainage: END OF TUNNEL 59 — 39 m

Date: 27/6/03

Page: ①

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

Q (typical range) = (——)x(——)x(——)

Q (mean) = (——)x(——)x(——)

Q (most freq.) = (——)x(——)x(——)

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

1= 59—54

2= 54—49

3= 49—44

4= 44—39

5=

6=

7=

8=

9=

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

Photos

or Sketch

60 ch 59, 5 54, 10 49, 15 44, 20 39 ("60" = 59)

ACTIVE STRESS

Exc. Inflows | High Press | Wet | Dry

0.05 0.1 0.2 0.33 0.5 0.66 1

$\frac{RQD}{J_a}$ =

$\frac{J_r}{J_a}$ =

(most freq.)

J_w

Joint water pressure

Squeeze | Swell | Faults | Stress/Strength

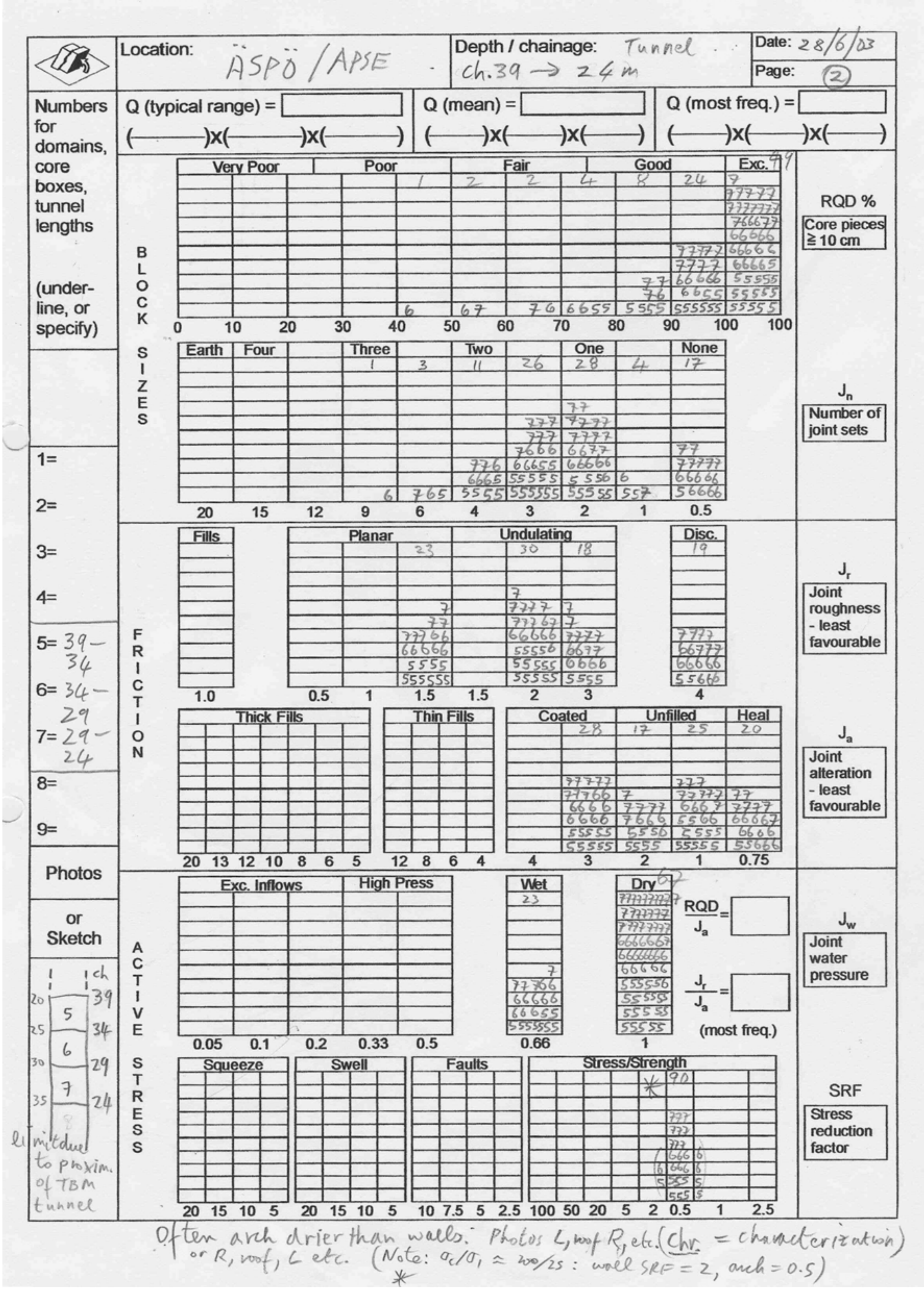
20 15 10 5 20 15 10 5 10 7.5 5 2.5 100 50 20 5 2 0.5 1 2.5

SRF

Stress reduction factor

Photos: at face: L, R, roof, 5–10: R, L, 10–15: R, L, roof, (Chc = characterization)

(* Note $\sigma_c/\sigma_1 \simeq 200/25$: wall SRF = 2, arch = 0.5)



Location: ÄSPÖ / APSE

Depth / chainage: Tunnel ch.39 → 24 m

Date: 28/6/03

Page: 2

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

Q (typical range) = (——)x(——)x(——)

Q (mean) = (——)x(——)x(——)

Q (most freq.) = (——)x(——)x(——)

1=

2=

3=

4=

5= 39–34

6= 34–29

7= 29–24

8=

9=

Photos or Sketch

limit due to proxim. of TBM tunnel

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

$\frac{RQD}{J_a}$ =

$\frac{J_r}{J_a}$ = (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

Often arch drier than walls: Photos L, roof R, etc. (Chr. = characterization) or R, roof, L etc. (Note: $\sigma_c/\sigma_1 \simeq 200/25$: wall SRF = 2, arch = 0.5)

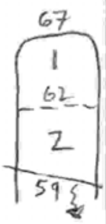
Location: ÄSPÖ / APSE	Depth / chainage: ch 67 – 59 (30/6 face at 67 m)	Date: 30/6/03	Page: 3

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=
2=
3=
4=
5=
6=
7=
8=
9=

Photos or Sketch



BLOCK SIZES

RQD % (Core pieces ≥ 10 cm)

	Very Poor		Poor		Fair			Good		Exc.
Count					3	6	8	17	14	12
Scale	0–10	10–20	20–30	30–40	50–60	60–70	70–80	80–90	90–100	100

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
			4	10	14	17	10	4	2
20	15	12	9	6	4	3	2	1	0.5

FRICTION

J_r (Joint roughness - least favourable)

Fills	Planar			Undulating		Disc.
		4	17	32	7	
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
		3	18	9	28	2
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
		24	36
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			
				23	18	
20 15 10 5	20 15 10 5	10 7.5 5 2.5	100 50 20 5	2	0.5 1	2.5

20 10

Location: ÄSPÖ/APSE	Depth / chainage: TUNNEL ch. 24–59	Date: Page: 4

Q (typical range) = ☐ (——)x(——)x(——)

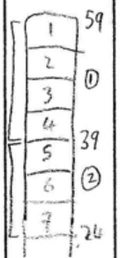
Q (mean) = ☐ (——)x(——)x(——)

Q (most freq.) = ☐ (——)x(——)x(——)

Numbers for domains, core boxes, tunnel lengths (underline, or specify)

1=
2=
3=
4=
5=
6=
7=
8=
9=

Photos or Sketch



BLOCK SIZES

RQD % (Core pieces ≥ 10 cm)

	Very Poor 0–10	Very Poor 10–20	Very Poor 20–30	Poor 30–40	Poor 40–50	Fair 50–60	Fair 60–70	Fair 70–80	Good 80–90	Good 90–100	Exc. 100
1			1	1			1	1	3	6	17
2					1			1	2	6	20
3								1	3	8	18
4								1	5	10	13
5								2	4	8	16
6					1	1	1	2	1	7	17
7						1	1		3	9	16

J_n (Number of joint sets)

	Earth 20	Four 15	12	Three 9	6	Two 4	3	One 2	1	None 0.5
1					2	4	13	9	2	—
2					1	2	3	7	10	7
3					1	2	4	12	6	5
4				2	2	13	2	4	4	2
5					1	5	13	8	2	1
6				1	1	4	6	8	1	9
7					1	2	7	12	1	7

FRICTION

J_r (Joint roughness - least favourable)

	Fills 1.0	Planar 0.5	Planar 1	Planar 1.5	Undulating 1.5	Undulating 2	Undulating 3	Disc. 4
1				5		21	4	—
2				2		2	6	19
3				1		7	6	13
4			3	17		6	4	—
5				10		14	4	2
6				7		7	6	10
7				6		9	8	7

J_a (Joint alteration - least favourable)

	Thick Fills 20	13	12	10	8	6	5	Thin Fills 12	8	6	4	Coated 4	Coated 3	Unfilled 2	Unfilled 1	Heal 0.75
1													5	4	18	3
2													—	2	10	18
3													5	1	10	14
4													8	3	12	5
5													10	7	11	2
6													10	4	5	11
7													8	6	9	7

ACTIVE STRESS

J_w (Joint water pressure)

	Exc. Inflows 0.05	Exc. Inflows 0.1	Exc. Inflows 0.2	High Press 0.33	High Press 0.5	Wet 0.66	Dry 1
1					5	18	7
2						26	4
3						17	13
4						8	22
5						9	21
6						10	20
7						4	26

$\frac{RQD}{J_a} =$ ☐

$\frac{J_r}{J_a} =$ ☐

(most freq.)

SRF (Stress reduction factor)

	Squeeze 20	15	10	5	Swell 20	15	10	5	Faults 10	7.5	5	2.5	Stress/Strength 100	50	20	5	2	0.5	1	2.5
1																	20	10		
2																	20	10		
3																	20	10		
4																	20	10		
5																	20	10		
6																	20	10		
7																	20	10		

*

Note: $\sigma_c/\sigma_1 \approx 200/25$ (220/30?) i.e. < 10

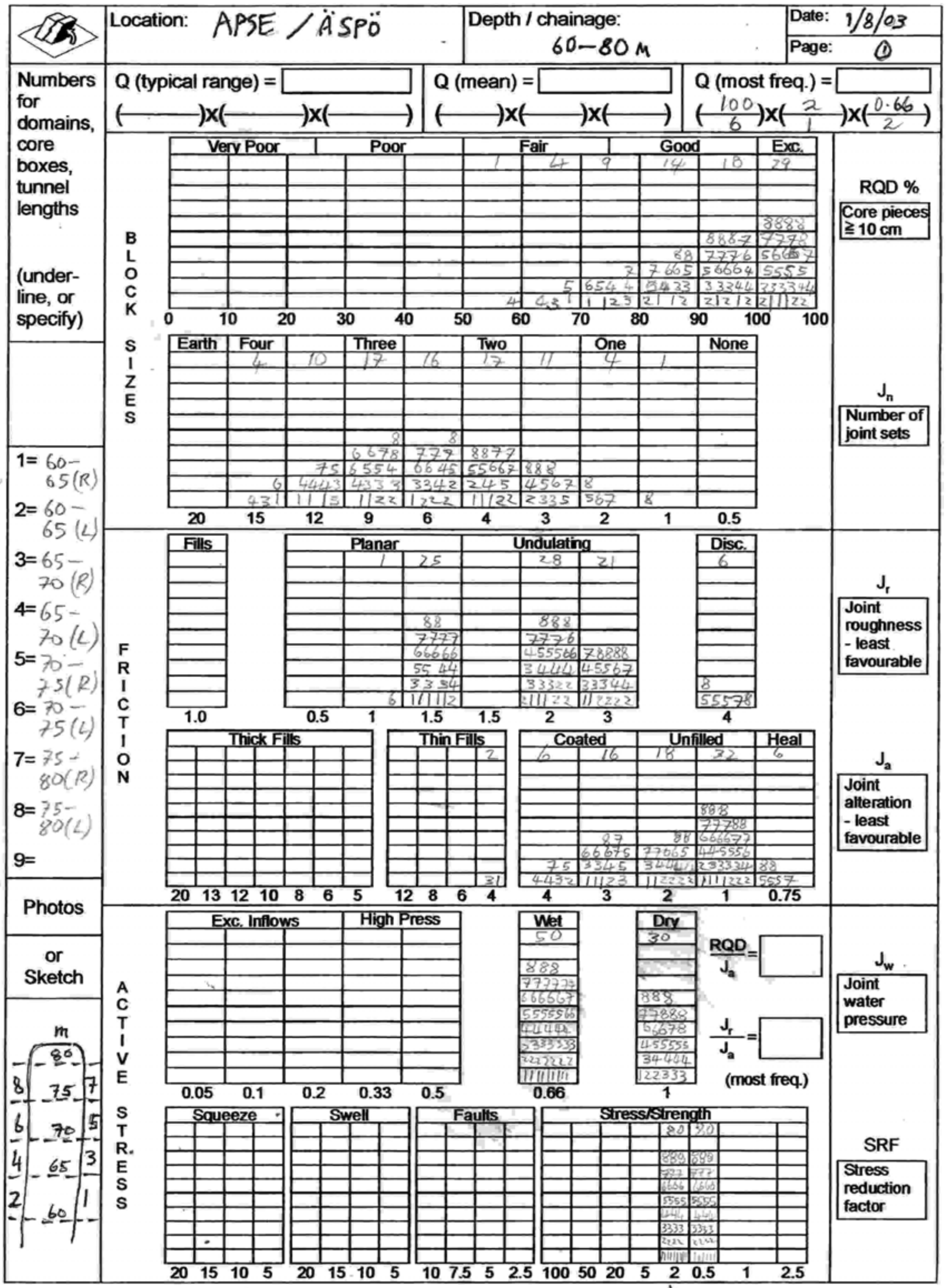
($SRF_{wall} = 2$, $SRF_{arch} = 0.5$)

Appendix B

APSE tunnel Q-logging

Ch. 60 to 80m

1 August 2003



6,4,2 ( ) 1,3,7

65-70 has less half-rounds on both walls.

* unfavourable for walls 20* } SRF
favourable for roof/floor 0.5

Location: APSE / ÄSPÖ -	Depth / chainage: 60 – 90 m Summary (L+R sides)	Date: 5/8/03	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)

BLOCK – RQD % (Core pieces ≥ 10 cm)

	Very Poor 0–10	10–20	20–30	Poor 30–40	40–50	Fair 50–60	60–70	Good 70–80	80–90	Exc. 90–100	100
1+2							1	3	4	5	6
3+4						1	2	3	3	6	6
5+6							1	2	4	5	8
7+8								1	3	7	9
Σ=						1	4	9	14	23	29

SIZES – J_n (Number of joint sets)

	Earth 20	Four 15	12	Three 9	6	Two 4	3	One 2	1	None 0.5
1+2		1	3	4	5	6	1			
3+4		2	5	5	4	1	3			
5+6		1	1	5	3	5	3	2		
7+8			1	3	4	5	4	2	1	
Σ=		4	10	17	16	17	11	4	1	

FRICTION – J_r (Joint roughness - least favourable)

	Fills 1.0	Planar 0.5	Planar 1	Planar 1.5	Undulating 1.5	Undulating 2	Undulating 3	Disc. 4
1+2				6		8	6	
3+4				6		8	6	
5+6			1	7		6	3	3
7+8				6		6	6	3
Σ=			1	25		28	21	6

FRICTION – J_a (Joint alteration - least favourable)

	Thick Fills 20	13	12	10	8	6	5	Thin Fills 12	8	6	4	Coated 4	Coated 3	Unfilled 2	Unfilled 1	Heal 0.75
1+2											1	1	4	6	8	
3+4											1	3	4	5	7	
5+6												1	5	3	8	3
7+8												1	3	4	10	3
Σ=											2	6	16	18	33	6

ACTIVE – J_w (Joint water pressure)

	Exc. Inflows 0.05	0.1	0.2	High Press 0.33	0.5	Wet 0.66	Dry 1
1+2						17	3
3+4						11	9
5+6						12	8
7+8						10	10
Σ=						50	30

$\frac{RQD}{J_a}$ = [ ]

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

STRESS – SRF (Stress reduction factor)

	Squeeze 20	15	10	5	Swell 20	15	10	5	Faults 10	7.5	5	2.5	Stress/Strength 100	50	20	5	2	0.5	1	2.5
1+2																	(20)	20		
3+4																	(20)	20		
5+6																	(20)	20		
7+8																	(20)	20		
Σ=																	(80)	80		

1=

2=

3=

4=

5=

6=

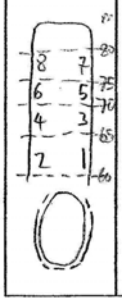
7=

8=

9=

Photos

or Sketch



Appendix C

APSE core logging

KA3376B01 0.0-80.2m

27 June 2003

(KA 3376 B01)

Location: ÄSPÖ / APSE	Depth / chainage: 0 – 45.0 m. KA 3376 (sub-// tunnel)	Date: 27/6/03 Page: ①

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

Q (typical range) = ☐ ( )x( )x( )

Q (mean) = ☐ ( )x( )x( )

Q (most freq.) = ☐ ( )x( )x( )

1= 0.0–2.3

2= 2.3–7.7

3= 7.7–13.0

4= 13.0–18.2

5= 18.2–23.2

6= 23.3–28.9

7= 28.9–34.3

8= 34.3–39.6

9= 39.6–45.0

Photos

or Sketch

BLOCK SIZES

Very Poor | Poor | Fair | Good | Exc.

1 | 5 | 12 | 22

9 | 88 | 532 | 9876 665 4 3442 | 88999 7776 5556 44333 11222

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

RQD % Core pieces ≥ 10 cm

Earth | Four | Three | Two | One | None

2 | 6 | 11 | 19 | 1

9864 | 9866 42 | 989 7654 4332 | 99 7778 65556 3334 11222 | 5

20 15 12 9 6 4 3 2 1 0.5

J_n Number of joint sets

FRICTION

Fills | Planar | Undulating | Disc.

11 | 19 | 9 | 2

99 88665 4322 | 99 7788 6655 4453 3322 | 8 67 445 1123 | 79

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

1 | 1 | 19 | 8 | 12

9 | 4 | 999 8887 7665 5444 3322 | 98 765 231 | 78 45566 12233

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

1 | 22 | 19

4 | 99 88889 77666 44455 22233 | 7899 56677 33455 11223

0.05 0.1 0.2 0.33 0.5 0.66 1

$\frac{RQD}{J_a}$ = ☐

$\frac{J_r}{J_a}$ = ☐ (most freq.)

J_w Joint water pressure

Squeeze | Swell | Faults | Stress/Strength

22 999 888 777 666 555 444 333 2222 11

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

(28.9–34.3, minus 1m of samples)

(KA 3376 B01)

	Location: ÄSPÖ / APSE	Depth / chainage: 45.2 – 80.2 KA 3376 (sub-II tunnel)	Date: 27/6/03 Page: ②

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

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

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

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

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

RQD % — Core pieces ≧ 10 cm

Very Poor | Poor | Fair | Good | Exc.

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

1 2 4 11 9

1 5 62 6555 877 7764 1112 8663 22333

Earth | Four | Three | Two | One | None

J_n — Number of joint sets

20 15 12 9 6 4 3 2 1 0.5

1 3 7 11 6

1 651 776 665 877 6553 1222 48 2333

FRICTION

Fills | Planar | Undulating | Disc.

J_r — Joint roughness - least favourable

1.0 0.5 1 1.5 1.5 2 3 4

1 9 16 3 1

5 666 1112 7 5 88 6777 6554 1223 233 3

Thick Fills | Thin Fills | Coated | Unfilled | Heal

J_a — Joint alteration - least favourable

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

5 11 5 7

61 15 7 778 6663 1122 5762 8 455 2333

ACTIVE STRESS

Exc. Inflows | High Press | Wet | Dry

0.05 0.1 0.2 0.33 0.5 0.66 1

2 11 16 8 77775 666665 1122 10 33485 22333

$\frac{RQD}{J_a}$ =

$\frac{J_r}{J_a}$ = (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

28 88 7777 66666 45555 3333 2222 1111

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:	Depth / chainage:	Date:
ÄSPÖ / APSE	KA 3376 0 – 80.2m (sub // tunnel)	29/6/03
		Page: 3

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

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

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

Numbers for domains, core boxes, tunnel lengths (underline, or specify)

1=
2=
3=
4=
5=
6=
7=
8=
9=

Photos or Sketch

BLOCK SIZES

RQD % — Core pieces ≧ 10 cm

	0–10	10–20	20–30	30–40	40–50	50–60	60–70	70–80	80–90	90–100	100
	Very Poor		Poor			Fair			Good		Exc.
0-45						1			5	12	23
45-80							1	2	4	11	9
Σ						1	1	2	9	23	32

J_n — Number of joint sets

	Earth	Four		Three		Two		One		None
	20	15	12	9	6	4	3	2	1	0.5
0-45					4	6	11	19	1	
45-80			1		3	7	11	6		
Σ			1		7	13	22	25	1	

FRICTION

J_r — Joint roughness - least favourable

	Fills	Planar			Undulating			Disc.
	1.0	0.5	1	1.5	1.5	2	3	4
0-45				11		19	9	2
45-80			1	9		16	3	1
Σ			1	20		33	12	3

J_a — Joint alteration - 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
0-45										1		1	19	8	12	
45-80												5	11	5	7	
Σ										1		6	30	13	19	

ACTIVE

J_w — Joint water pressure

	Exc. Inflows			High Press		Wet	Dry
	0.05	0.1	0.2	0.33	0.5	0.66	1
0-45					1	22	19
45-80					2	16	10
Σ					3	38	29

$\frac{RQD}{J_a}$ =

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

STRESS

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
0-45																		42		
45-80																		28		
Σ																		70		

Appendix D

Q-system rating tables
& logging instructions

(from Barton, 2002)

Q-method of rock classification

Q-logging ratings for RQD, J_n , J_r , J_a , J_w and SRF

(Barton, 2002)

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$$

RQD is the % of competent drill-core sticks > 100 mm in length [1] in a selected domain

J_n = the rating for the number of joint sets (9 for 3 sets, 4 for 2 sets etc.) in the same domain

J_r = the rating for the roughness of the least favourable of these joint sets or filled discontinuities

J_a = the rating for the degree of alteration or clay filling of the least favourable joint set or filled discontinuity

J_w = the rating for the water inflow and pressure effects, which may cause outwash of discontinuity infillings

SRF = the rating for faulting, for strength/stress ratios in hard massive rocks, for squeezing or for swelling

RQD/J_n = relative block size (useful for distinguishing massive, rock-burst-prone rock)

J_r / J_a = relative frictional strength (of the least favourable joint set or filled discontinuity)

J_w /SRF = relative effects of water, faulting, strength/stress ratio, squeezing or swelling (an ‘active stress’ term)

An alternative combination of these three quotients in two groups only, has been found to give fundamental properties for describing the shear strength of rock masses – something close to ***the product of ‘c’ and ‘tan φ’***. By implication Q (and in particular Q_c) have units resembling ***MPa.***

Footnotes below the tables that follow, also give advice for ***site characterization*** ratings for the case of Jw and SRF, which ***must*** **not** be set to 1.0 and 1.0, as some authors have suggested. This destroys the intended multi-purposes of the Q-system, which has an entirely different structure compared to RMR.

1. Rock Quality Designation		RQD (%)
A	Very poor	0-25
B	Poor	25-50
C	Fair	50-75
D	Good	75-90
E	Excellent	90-100

Notes: i) Where RQD is reported or measured as ≤ 10 (including 0), a nominal value of 10 is used to evaluate Q.

ii) RQD intervals of 5, i.e., 100, 95, 90, etc., are sufficiently accurate.

2. Joint set number		J_n
A	Massive, no or few joints	0.5-1
B	One joint set	2
C	One joint set plus random joints	3
D	Two joint sets	4
E	Two joint sets plus random joints	6
F	Three joint sets	9
G	Three joint sets plus random joints	12
H	Four or more joint sets, random, heavily jointed, 'sugar-cube', etc.	15
J	Crushed rock, earth-like	20

Notes: i) For tunnel intersections, use ($3.0 \times Jn$).

ii) For portals use ($2.0 \times Jn$).

3. Joint roughness number		J_r
a) Rock-wall contact, and b) Rock-wall contact before 10 cm shear		
A	Discontinuous joints	4
B	Rough or irregular, undulating	3
C	Smooth, undulating	2
D	Slickensided, undulating	1.5
E	Rough or irregular, planar	1.5
F	Smooth, planar	1.0
G	Slickensided, planar	0.5

Notes: i) Descriptions refer to small-scale features and intermediate scale features, in that order.

b) No rock-wall contact when sheared		
H	Zone containing clay minerals thick enough to prevent rock-wall contact.	1.0
J	Sandy, gravely or crushed zone thick enough to prevent rock-wall contact	1.0

Notes:ii) Add 1.0 if the mean spacing of the relevant joint set is greater than 3m.

iii) Jr = 0.5 can be used for planar, slickensided joints having lineations, provided the lineations are oriented for minimum strength. J_r and J_a classification is applied to the joint set or discontinuity that is least favourable for stability both from the point of view of orientation and shear resistance, τ (where $\tau \approx \sigma n$ tan-1 (J_r / J_a).

4. Joint alteration number		ϕ_r	J_a
a) Rock-wall contact (no mineral fillings, only coatings)			
A	Tightly healed, hard, non-softening, impermeable filling, i.e., quartz or epidote.	--	0.75
B	Unaltered joint walls, surface staining only.	25-35°	1.0
C	Slightly altered joint walls. Non-softening mineral coatings, sandy particles, clay-free disintegrated rock, etc.	25-30°	2.0
D	Silty- or sandy-clay coatings, small clay fraction (non-softening).	20-25°	3.0
E	Softening or low friction clay mineral coatings, i.e., kaolinite or mica. Also chlorite, talc, gypsum, graphite, etc., and small quantities of swelling clays.	8-16°	4.0
b) Rock-wall contact before 10 cm shear (thin mineral fillings).			
F	Sandy particles, clay-free disintegrated rock, etc.	25-30°	4.0
G	Strongly over-consolidated non-softening clay mineral fillings (continuous, but < 5 mm thickness).	16-24°	6.0
H	Medium or low over-consolidation, softening, clay mineral fillings (continuous, but < 5 mm thickness).	12-16°	8.0
J	Swelling-clay fillings, i.e., montmorillonite (continuous, but < 5 mm thickness). Value of J_a depends on per cent of swelling clay-size particles, and access to water, etc.	6-12°	8-12
c) No rock-wall contact when sheared (thick mineral fillings)			
K L M	Zones or bands of disintegrated or crushed rock and clay (see G, H, J for description of clay condition).	6-24°	6, 8, or 8-12
N	Zones or bands of silty- or sandy-clay, small clay fraction (non-softening).	--	5.0
O P R	Thick, continuous zones or bands of clay (see G, H, J for description of clay condition).	6-24°	10, 13, or 13-20

	5. Joint water reduction factor	approx. water	J_w
A	Dry excavations or minor inflow, i.e., < 5 l/min locally.	< 1	1.0
B	Medium inflow or pressure, occasional outwash of joint fillings.	1-2.5	0.66
C	Large inflow or high pressure in competent rock with unfilled joints.	2.5-10	0.5
D	Large inflow or high pressure, considerable outwash of joint fillings.	2.5-10	0.33
E	Exceptionally high inflow or water pressure at blasting, decaying with time.	> 10	0.2-0.1
F	Exceptionally high inflow or water pressure continuing without noticeable decay.	> 10	0.1-0.05

Notes: i) Factors C to F are crude estimates. Increase J_w if drainage measures are installed.

ii) Special problems caused by ice formation are not considered.

*iii) For general **characterization** of rock masses distant from excavation influences, the use of Jw = 1.0, 0.66, 0.5, 0.33 etc. as depth increases from say 0-5m, 5-25m, 25-250m to >250m is recommended, assuming that RQD /Jn is low enough (e.g. 0.5-25) for good hydraulic connectivity. This will help to adjust Q for some of the effective stress and water softening effects, in combination with appropriate **characterization** values of SRF. Correlations with depth- dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.*

6. Stress Reduction Factor		SRF
a) Weakness zones intersecting excavation, which may cause loosening of rock mass when tunnel is excavated		
A	Multiple occurrences of weakness zones containing **clay** or chemically disintegrated rock, very loose surrounding rock (any depth).	10
B	Single weakness zones containing **clay** or chemically disintegrated rock (depth of excavation ≤ 50 m).	5
C	Single weakness zones containing **clay** or chemically disintegrated rock (depth of excavation > 50 m).	2.5
D	Multiple shear zones in competent rock (**clay-free**), loose surrounding rock (any depth).	7.5
E	Single shear zones in competent rock (**clay-free**), (depth of excavation ≤ 50 m).	5.0
F	Single shear zones in competent rock (**clay-free**), (depth of excavation > 50 m).	2.5
G	Loose, open joints, heavily jointed or 'sugar cube', etc. (any depth)	5.0

Notes: i) Reduce these values of SRF by 25-50% if the relevant shear zones only influence but do not intersect the excavation. This will also be relevant for characterization.

b) Competent rock, rock stress problems		σ_c / σ_1	σ_θ / σ_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

Notes: ii) For strongly anisotropic virgin stress field (if measured): When $5 \leq \sigma 1 / \sigma 3 \leq 10$, reduce σc to 0.75 σc. When $\sigma 1 / \sigma 3 > 10$, reduce σc to 0.5 σc, where σc = unconfined compression strength, $\sigma 1$ and $\sigma 3$ are the major and minor principal stresses, and $\sigma\theta$ = maximum tangential stress (estimated from elastic theory).

iii) Few case records available where depth of crown below surface is less than span width. Suggest an SRF increase from 2.5 to 5 for such cases (see H).

iv) Cases L, M, and N are usually most relevant for support design of deep tunnel excavations in hard massive rock masses, with RQD /Jn ratios from about 50 to 200.

v) For general characterization of rock masses distant from excavation influences, the use of SRF = 5, 2.5, 1.0, and 0.5 is recommended as depth increases from say 0-5m, 5-25m, 25-250m to >250m. This will help to adjust Q for some of the effective stress effects, in combination with appropriate characterization values of Jw. Correlations with depth - dependent static deformation modulus and seismic velocity will then follow the practice used when these were developed.

	c) Squeezing rock: plastic flow of incompetent rock under the influence of high rock pressure	σ_θ / σ_c	SRF
O	Mild squeezing rock pressure	1-5	5-10
P	Heavy squeezing rock pressure	> 5	10-20

Notes vi) Cases of squeezing rock may occur for depth H > 350 Q1/3 according to Singh 1993 [34]. Rock mass compression strength can be estimated from SIGMAcm ≈ 5 γQc1/3 (MPa) where γ = rock density in t /m3, and Qc=Qxσc /100, Barton, 2000 [29].

	d) Swelling rock: chemical swelling activity depending on	SRF
R	Mild swelling rock pressure	5-10
S	Heavy swelling rock pressure	10-15

Appendix E

Q-LOGGING OF THE BOREHOLES KA3386A01 AND KF0069A01

FOR THE ÄSPÖ PILLAR EXPERIMENT,

FOR DEVELOPMENT OF

PRELIMINARY INPUT PARAMETERS

by Nick Barton

Contents

1 Introduction

This report contains Q-histogram logs of two boreholes (KF 0069 and KA 3386) that were drilled in opposite directions (NNE, SSW) from TAS F and TAS A respectively. These holes represent two potential locations for the planned Pillar Experiment tunnels at Äspö. The objective of the work was to produce updated (and therefore stress-adjusted) input data for preliminary "class A" prediction modelling. The logging of the two cores (of 70.1 and 65.1 m lengths) was performed on 5 August 2002. A preliminary, combined histogram log of the two cores, and some input data for modellers was delivered on 11 August 2002.

2 Core logging method for Q-determination

The objective of the core logging was to produce some input data for modellers of the planned Pillar Experiment. Consequently, emphasis was placed on the ***characterization*** of the undisturbed rock mass at roughly 450 m depth. (The TAS F and TAS A tunnels are at -450 m).The "high stress tight structure" SRF value was therefore 0.5 (following footnotes in Barton, 2002), as compared to a potential SRF = 2 for classification, as obtained from appropriate σ_1/σ_θ ratios for EDZ related support needs (if any). Both these SRF values have been utilised (where appropriate) in this report, but emphasis has been on the lower, "pre-tunnelling" ***characterization*** value.

Four sheets of Q-histogram logs for KF 0069 and KA 3386/A01, are given in the Appendix. Most of the core boxes contained about 5.5 m of core, and this became the unit length for five Q-value assessments of each full core box.

These histograms, shown in the Appendix, pages A1 to A4, therefore show numbers 11111, 22222, etc. in each Q-parameter category, so that individual lengths of core, and the whole sample, are represented on the same sheets. A full description of the meaning of the different ratings will be found in Barton, 2002, based on the familiar classification scheme of the six parameters.

When the location of the experiment has been chosen, one can return to these logs, e.g. to core boxes 5, 6 and 7 of hole KF 0069, to see the rock mass quality prediction of numbers 55555, 66666 and 77777, for comparison with subsequent tunnel logging.

3 Interpretation of the Q-values

In Figure 1, the accumulated frequencies of observations of the Q-parameters have been assembled for both holes, in the form of numbers of occurrences and rough graphic logs. Hole KF 0069 is represented at the top and KA 3386 at the bottom of each diagram.

The overall sample shows the following trends:

Q (typical range) = 15 to 100

Q (weighted mean) = 40.4

Q (most frequent) = 39

However there are subtle differences between the two holes which cause differences, for example to permeability. These concern mainly some lower RQD and higher J_n observations in hole (core) KA 3386, which cause minor adjustments to weighted mean values, but (reportedly) significant differences to the inflow/local permeability due to greater connectivity when J_n is increased from typically "one set plus random" or "two sets" to occasional "three sets".

KF 0069 $$Q_{\text{weighted mean}} = \frac{98.3}{3.3} \times \frac{1.75}{2.2} \times \frac{0.93}{0.5} = 44.1$$

$$Q_{\text{most frequent}} = \frac{100}{3} \times \frac{1.5}{3} \times \frac{1}{0.5} = 33.3$$

KA 3386 $$Q_{\text{weighted mean}} = \frac{97.5}{3.9} \times \frac{1.99}{2.4} \times \frac{0.90}{0.5} = 37.3$$

$$Q_{\text{most frequent}} = \frac{100}{3} \times \frac{2}{3} \times \frac{1}{0.5} = 44.4$$

The "weighted mean" Q-value differences of 44.1 contra 37.3 are of course more reliable than the "chance" reversal of $J_r = 1.5$ and $J_r = 2.0$ as "most frequent" observations in the above. The two decimal place "accuracy" of J_w was given to distinguish a slight increase in expected water inflow. The best source of this difference, due to the above ***connectivity*** argument, is the respective values of weighted mean J_n = 3.3 and 3.9 for the two cores.

We could speculate that (almost) two sets ($J_n = 3.9$) are very likely to have improved (an unwanted) connectivity and permeability more than (almost) one set plus random ($J_n = 3.3$).

For comparison with the above, the combined sample of KF 0069 and KA 3386 shows the following:

$$Q_{\text{typical range}} = \frac{90-100}{2-4} \times \frac{1.5-2}{2-3} \times \frac{0.66-1}{0.5} = 15-100$$

$$Q_{\text{weighted mean}} = \frac{97.9}{3.6} \times \frac{1.9}{2.3} \times \frac{0.9}{0.5} = 40.4$$

$$Q_{\text{most frequent}} = \frac{100}{3} \times \frac{1.75}{3} \times \frac{1}{0.5} = 39$$

In later parts of the report, we will start with assumed, mean ***characterization*** Q-values of 40 (for the site in general), Q = 44 for the NNE trending KF 0069, and Q = 37 for the SSW trending KA 3386.

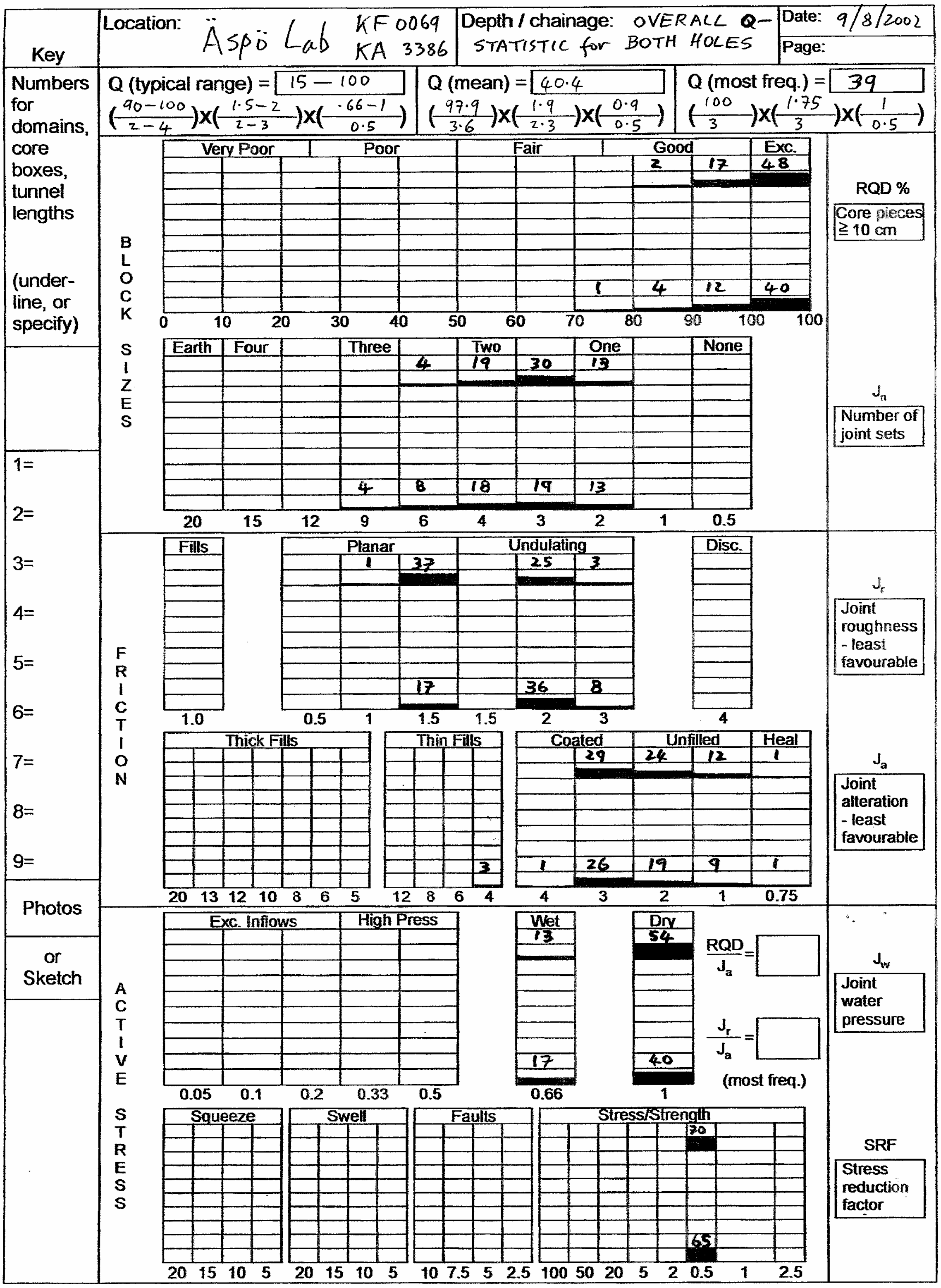


Figure 0-1. *Assembled Q-logging frequencies for KF 0069 and KA 3386 (see page A1 to A4 in Appendix).*

4 General characteristics of the two sites, as estimated from geotechnical core logging

The above Q-value estimates are useful general guides to the rock mass quality, and help to derive some estimates of certain input parameters for modelling.

A more general picture of quality is given here for purposes of estimating the structural input to discontinuum models. We may start with a typical, general picture of the massive appearance of the core (Figure 2). The most frequent jointing (set no. 1 ≈ perpendicular to the core) is supplemented by at least one, and occasionally two obliquely cutting sets. Two of these are seen (with roughness a/L and JRC estimation) in Figures 3 and 4. We will return to this roughness estimation in the next section.

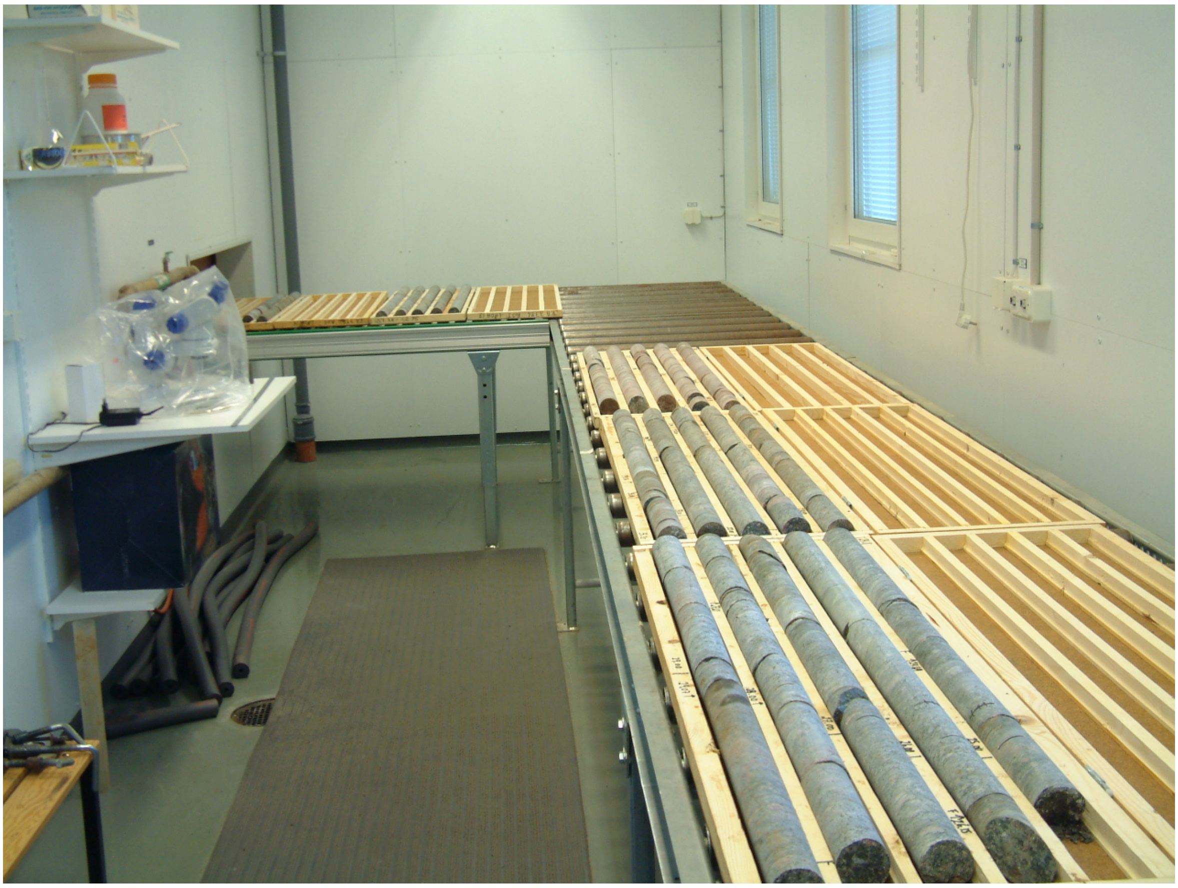


Figure 4-1. *Typical example of massive, sparsely .jointed diorite core.*

Figure 4-2. *Example of a/L and JRC estimation, set 2 (JRC ≈ 4-6).*

Figure 4-3. *Example of a/L and JRC estimation, set 2 (JRC ≈ 6-8).*

Figure 5 shows a compilation of the combined Q-parameter logging for holes KF 0069 and KA 3386 on the left hand side. The other data (mostly estimates at this stage) is organised in the three categories shown in Figure 6. A more comprehensive description of the parameters will be found in Barton et al. 1992. As can be noted, the data is given as a preliminary aid in setting up the principal geometry and joint parameter input (JRC, JCS, ϕ_r) for UDEC-BB modelling.

Since, however, the holes (and planned tunnel axis) have been oriented approximately NNE (in TAS F), or SSW (in TAS A), the designated set 1 joints which approximately parallel σ_H, can represent the "two-dimensional model slices". Principally the secondary set (or random joints) would be represented within such 2D models. The characterization of "set 2" (see Figures 3 and 4) is therefore most relevant for such modelling.

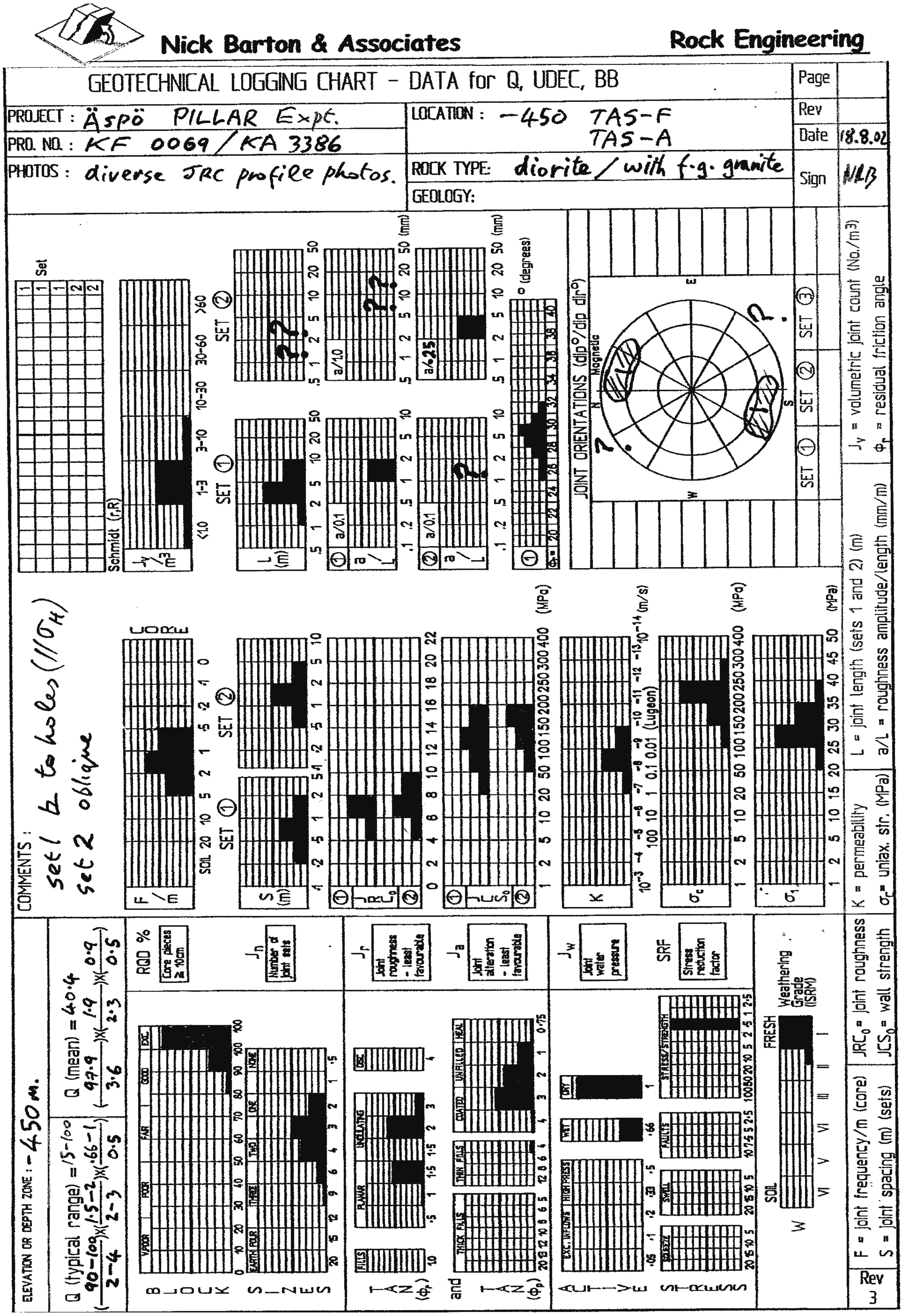


Figure 4-4. Comprehensive geotechnical log, based on holes KF .0069 and KA 3386. These estimates will be updated and improved when the test tunnel is excavated.

4.1 Notes on geotechnical logging estimates

Following the three-part scheme of presentation shown in Figure 6, we can comment on several of the parameters, mentioning shortcomings, estimation methods and future sources of better data.

I – Rock Mass Structure (upper third of Figure 5)

1. RQD The logging sheets in the Appendix (A1 to A4) and the summary log given in Figure 6 have been independently estimated, as no standard core log was available on 5 August 2002.

   Due to the top-value limitation of RQD it is unlikely that an ***oriented*** RQD_o (Barton, 2002) would in this case give an anisotropic value. As drilled, RQD is "a minimum". At 90° to NNE/SSW it would be even closer to 100%.

2. J_n It is assumed that obliquely cutting sets occasionally give a total of three local sets, but one set plus random to two sets is most frequent.

3. F The combined influence of each set, with artificial breaks excluded where possible, suggest 1 to 2 joints per metre as most frequently occurring. However, in places up to 5/m or as little as 0.5/m are seen.

4. J_v From 1 to three joints/m^3 is the most frequently occurring.

5. S A marked difference in joint spacing for set 1 and set 2, consistent with the dominant "horizontal" major principal stress, suggests 0.5 to 1 m and 1 to 2 m, respectively, as the most frequent ranges of spacing.

6. L Joint length or persistence cannot of course be estimated from core logging, but simple observations in the neighbourhood of the drill collars suggested at least significant continuity for set 1.

7. W The rock is obviously primarily fresh and unweathered (Grade I), but due to joint-related discolouration in places, a fraction of "Grade II" was added.

8. α/β Dip and dip direction data were not available. However the NNE-SSW orientation of the holes more or less at right angles to the dominant set 1 joints, suggests the tentative trend indicated in the lower hemisphere stereogram. Structural geologist's data is required to correct/supplement this.5

II – Joint Character (middle third of Figure 6)

9. J_r Considering the general character of set 1 and set 2 for ***characterization***, both J_r = 1.5 and J_r = 2 are relevant.

10. J_a A significant number of joints have hard mineral coatings, or evidence of slight weathering of the joint walls due to water flow.
    Frequent J_a values of 3 and 2, and less frequently 1 (fresh) were therefore logged with respect to overall ***characterization***.

11. JRC Estimates for set 1 and set 2 (upper and lower histograms) are based on observation and knowledge of the standard 100 mm roughness profiles reproduced in Figure 7.

12. a/L Amplitude of roughness (mm) measured over profile lengths ranging from 50 to 250 mm, were the basis for the a/L measurements shown in Figure 3, 4 and 8. The diagonal lines give approximate JRC (JRC_0 or JRC_n) values. Scaling for JRC_0 to JRC_n appropriate to in situ block size is described later.

13. JCS No Schmidt hammer measurements were performed on the core, which would need elaborate clamping equipment. (Measurements directly on the tunnel wall joint exposures will be performed in Phase 2 characterization.) In Figure 5, the predominant JCS (strictly JCS_0) estimates were based on engineering judgement, and were predominantly 100-150 MPa for set 1, and 150-200 MPa for set 2, for this predominantly diorite rock (with fine-grained granite intrusions).

14. ϕ_r Engineering judgement was used to estimate a predominant ϕ_r = 28-30°. (In Phase 2, a simple empirical equation based on Schmidt hammer measurements may be used.)

III – WATER, STRESS, STRENGTH (LOWER THIRD OF FIGURE 6)

15. J_W Where there was evidence of rust staining and/or sufficient joint sets for probable connectivity of the jointing, J_W = 0.66 was estimated. Predominantly J_W = 1.0 (almost dry) conditions were assumed. As noted in Figure 1 (Q-summary), there were greater numbers of J_W = 0.66 observed in hole KA 3386, but this was due to limited, concentrated areas of assumed inflow. (Subsequent study of the flow rate log for KF 0069 showed marked local increases of flow where RQD was lower and J_n higher.)

16. SRF An overall ***characterization*** value of SRF = 0.5 was assumed, relevant to "> 250 m depth, high stress, tight structure" (Barton, 2002, p. 213).

17. K No permeability measurements are incorporated in the estimates of Lugeon and K m/s given in Figure 5. The assumed, predominant 10^{-8} to 10^{-9} m/s (or 0.01 to 0.1 Lugeon, approx.) is based on an approximate Q-Lugeon correlation, where $L \approx 1/Q$ is a fairly common rule-of-thumb (Barton, 2002).

18. σ_c Uniaxial strengths in the region of 190 to 220 MPa are assumed from prior impressions of Äspö test data. The range 200-250 MPa is given highest frequency.

19. σ_1 Stress measurement data from Christiansson & Janson (2002) have been used to estimate the predominant 25 to 35 MPa range given in the histogram.

I ROCK MASS STRUCTURE

1.	RQD (Deere et al. 1967)			(Q)
2.	J_n	=	joint set number	(Q)
3.	F	=	joint frequency (per metre)	
4.	J_v	=	volumetric joint count (Palmström, 1983)	
5.	S	=	joint spacing (in metres)	
6.	L	=	joint length (in metres)	
7.	w	=	weathering	
8.	α/β	=	dip/dip direction of joints	

II JOINT CHARACTER

9.	J_r	=	joint roughness number	(Q)
10.	J_a	=	joint alteration number	(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	

III WATER, STRESS, STRENGTH

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

Figure 4-5. *Organization of logging data/estimates in Figure 5.*

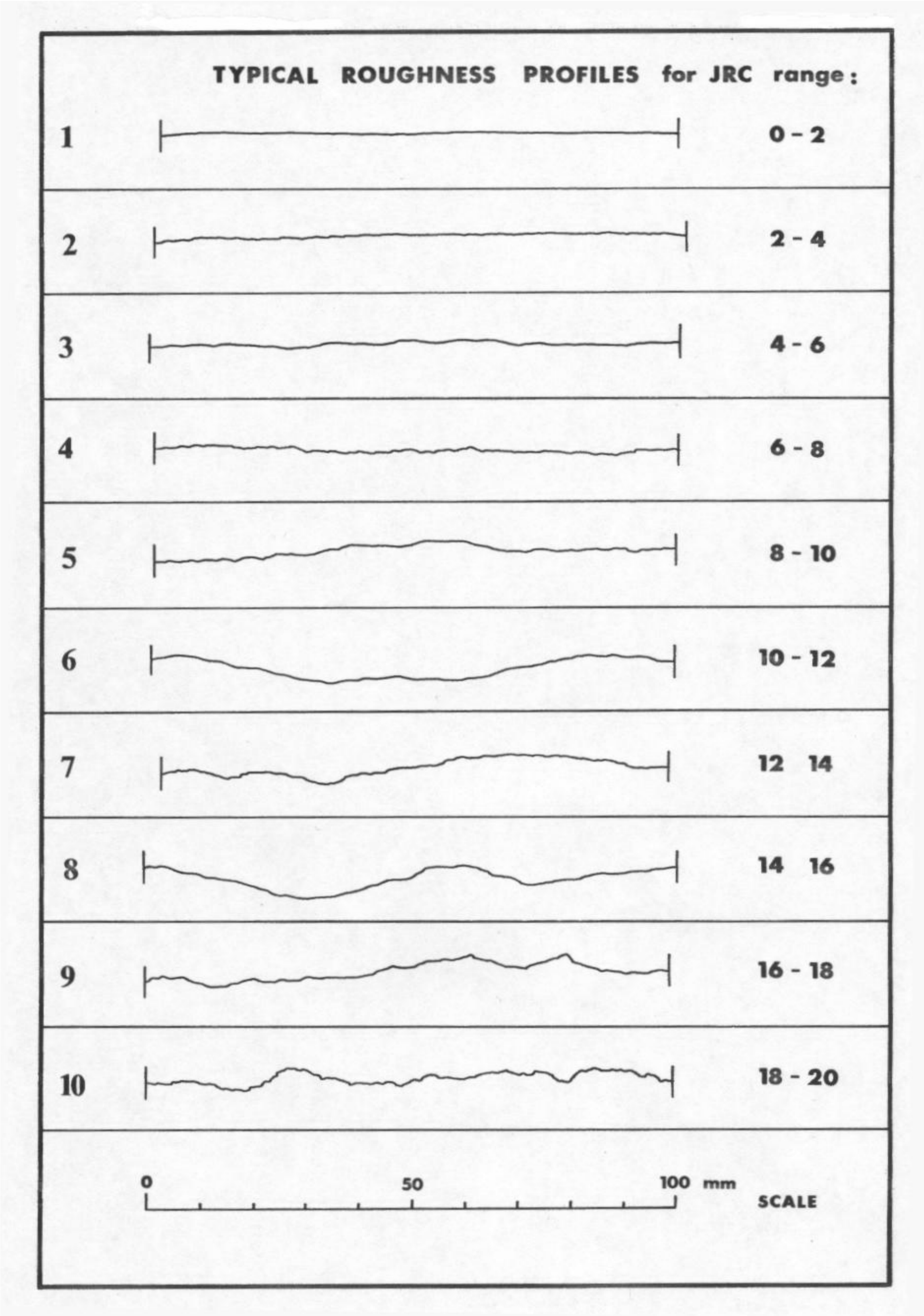


Figure 4-6. *Standard, 100 mm long JRC profiles. Barton & Choubey, .1977. ISRM 1978.*

5 Some Q-correlations for modelling

From section 3, we will operate with mean Q-values as follows:

KF 0069 $Q_{mean} \approx 44$

KA 3386 $Q_{mean} \approx 37$

We will further assume a mean σ_c = 210 MPa, undifferentiated between the two holes.

5.1 Q_c value estimates

Correlation to various engineering parameters, as detailed in Barton, 2002, can be based on the following Q_c values, where:

$$Q_c = Q \times \frac{\sigma_c}{100} \tag{1}$$

Therefore $$Q_c\ (KF0069) \approx 44 \times \frac{210}{100} = 92$$

$$Q_c\ (KF3386) \approx 37 \times \frac{210}{100} = 78$$

If σ_c (mean) should turn out to be differentiated in these two sections of the -450 m level, then wider separation of the Q_c values is one possibility. It is also possible that the slightly greater jointing frequency of KA 3386 is caused by a higher modulus and uniaxial strength, i.e. a stiffer rock mass attracting higher stress differences and fracturing more as a result. In this case the Q_c estimates might tend to converge or even "reverse".

If we take the conventional view that a lower Q-value may be associated with a lower σ_c value for purpose of present estimation, then we could tentatively use "mean values" of σ_c of respectively 200 MPa and 220 MPa for the potential N and S sites and utilise Q_c values of about ***100*** and ***75***, respectively. This will give a better feel for the influence of a slightly larger range of Q and σ_c, both of which will need to be updated in Phase 2 characterization.

5.2 Prediction of V_p

The following empirical equation can be used for "near-surface" correlation between V_p and Q_c:

$$V_p \approx 3.5 + \log Q_c \tag{3}$$

N-site $V_p \approx 3.5 + \log 100 = 5.5 \text{ km/s}$

S-site $V_p \approx 3.5 + \log 75 = 5.4 \text{ km/s}$

Taking into consideration the nearly 500 m depth of the site, the stress adjusted equation of Barton 2002 can be used:

$$V_p \approx 5 + 0.5 + \log Q_c \tag{4}$$

N-site $V_p \approx 6.0 \text{ km/s}$

S-site $V_p \approx 5.9 \text{ km/s}$

It may be noted from V_p-depth correlation that a "1000 m depth" line predicts V_p values of about 6.1 and 6.2 km/s. Such values might be relevant in the σ_H direction, sub-parallel or parallel to set 1 joints.

5.3 Possible EDZ effects on V_p estimates

Since V_p has been measured (estimated) from seismic cross-hole tomography at the Äspö ZEDEX site, it is relevant to also consider the likely ***classification*** values of Q, which try to reflect the possible adverse effect of high stress (or low σ_c/σ_1 ratios) on tunnel perimeter stability.

The relevant ranges of σ_c/σ_1 are about

200 to 220 MPa/25 to 35 MPa,

giving a logical range of about 8 to 6, which is within the Q-system "may be unfavourable for wall stability" category, where SRF = 2 is suggested. This would reduce our tentative Q ***characterization*** values of ***44*** and ***37*** for the two holes to ***11*** and ***9*** respectively, for ***classification*** (and EDZ) purposes, most noticeably for the arch and invert where the highest σ_θ value is operating.

The finally adopted Phase 1 Q_c values of 100 and 75 are likewise reduced to ***25*** and ***19***, respectively. Substitution in equation 4 gives "EDZ predictions" of:

N-site $V_p \approx 5.7\ \text{km/s}$

S-site $V_p \approx 5.6\ \text{km/s}$

The above ranges of V_p predictions for non-EDZ and EDZ-affected rock of 6.0 to 5.7 km/s, and 5.9 to 5.6 km/s are satisfactorily close to the seismic tomography results of about 5.9 to 6.2 km/s recorded by Cosma et al., 2001. As suggested above, a σ_H-affected V_p value might also climb to about 6.1 or 6.2 km/s, with the Q_c values assumed.

5.4 Prediction of E_{mass}

The foregoing emphasis on V_p, and its treatment as the first predicted parameter is deliberate, as most other parameters as needed by modellers, have not been directly measured at Äspö.

The importance of V_p is that links to the ***static*** modulus of deformation E_{mass} have been suggested (Barton, 2002). In the following we will first examine the "conventional" near-surface correlation between Q_c and E_{mass}:

$$E_{mass} \approx 10\ Q_c^{1/3} \tag{5}$$

Therefore:

N-site $E_{mass} \approx 10 \times 100^{1/3} = 46\ \text{GPa}$

S-site $E_{mass} \approx 10 \times 75^{1/3} = 42\ \text{GPa}$

The "500 m depth" estimate of E_{mass}, from Barton 2002 (Table 2, p. 195) is as follows:

$$E_{mass} \approx 10 \times 10^{(1.5+0.5\log Q_c)/3} \tag{6}$$

Therefore:

N-site $E_{mass} \approx 68\ \text{GPa}$

S-site $E_{mass} \approx 65\ \text{GPa}$

These compare with average laboratory triaxial E-moduli of about 74 to 65 GPa on samples from the vertical and horizontal holes used for Doorstopper gauge (DDGS) stress measurements (Christiansson & Janson, 2002), and average E-moduli of 70 and 60 GPa from uniaxial tests on cores from the same vertical and horizontal boles. There was therefore some evidence of anisotropy, or possible heterogeneity due to feldspar crystals, or influence from oriented micro-fractures. The above authors gave the following overall mean values and ranges, from their investigations:

Vertical hole	E-modulus = 72.5 ± 21 GPa
Horizontal hole	E-modulus = 56.2 ± 26 GPa

At this stage a "modeller's compromise", stressed E_{mass} value of 65 GPa can be tentatively recommended.

5.5 Possible EDZ effects on E_{mass} estimates

Considering, as before, the ***classification*** value of SRF of probably 2, and the reduced mean Q_c (EDZ) values of 25 and 19 (as in Section 5.3 for V_p), we can obtain the following range of E_{mass} (EDZ) values from the "near surface" equation 5, and from the "500 m depth" equation 6:

N-site	$E_{mass}\ (\text{near} - \text{surface}) \approx 29\ \text{GPa}$
S-site	$E_{mass}\ (\text{near} - \text{surface}) \approx 27\ \text{GPa}$

N-site	$E_{mass}\ (500\ \text{m depth}) \approx 54\ \text{GPa}$
S-site	$E_{mass}\ (500\ \text{m depth}) \approx 52\ \text{GPa}$

Stretching the empirical method to its logical conclusion one might claim that around the excavated test tunnel the radial E_{mass} value might be as low as 27 to 29 GPa, and the tangential E_{mass} value as low as 52 to 54 GPa. These would be in contrast to possible undisturbed values, unaffected by excavation, of 65 to 68 GPa. In other words we are tentatively equating the "conventional", near-surface moduli estimates with the radial direction of loading, as usually performed in plate-load testing.

5.6 Estimation of deformation

The Q-system has been linked for many years to estimates of tunnel or cavern deformation (or ***convergence*** which may be twice as large). A central trend of measured data is:

$$\Delta\,(\text{mm}) \approx \frac{\text{SPAN}\,(\text{m})}{\text{Q}} \tag{7}$$

but there is a wide scatter, and "refined" equations have been suggested (Barton, 2002) taking into account the possible influence of the competence factor or ratio of stress to strength. We therefore can also test:

$$\Delta_v \approx \frac{\text{SPAN}}{100\ \text{Q}}\sqrt{\frac{\sigma_v}{\sigma_c}} \tag{8}$$

$$\Delta_h \approx \frac{\text{HEIGHT}}{100\ \text{Q}}\sqrt{\frac{\sigma_h}{\sigma_c}} \tag{9}$$

We will assume the following for simplicity: SPAN = 5000 mm, and HEIGHT = 7500 mm (as planned for the Pillar Drift), Q(mean) = 10 (the classification value appropriate to the presence of a tunnel), $\sigma_v \approx 15$ MPa, $\sigma_h \approx 30$ MPa, σ_c(mean) = 210 MPa. From equations 8 and 9:

$\Delta_v = 1.3$ mm

$\Delta_h = 2.8$ mm

The prediction from the central trend of recorded data (equation 7) would be $\Delta \approx 0.5$ mm concerning the vertical deformation, and (if HEIGHT was substituted for SPAN) $\Delta \approx 0.75$ mm. In all the above cases one would be justified in doubling the values of "Δ" to obtain convergence, as measured by a ***tape extensometer***, which of course is already too late to record the total deformation, since access is required. However this, or near-tunnel-face MPBX installations, must necessarily be the source of the numerous convergence and deformation measurements reviewed in Barton, 2002.

6 Empirical strength estimation

In the recent Barton, 2002 publication on classification and characterization techniques in the Q-system, and the possibility for correlation with various parameters useful for modelling and design studies, it was suggested that the "crushing strength" of the rock mass could be estimated using a formula derived for TBM penetration rate prediction (Barton, 2000):

$$\mathrm{SIGMA}_{cm} \approx 5\,\gamma\,Q_c^{1/3}\ \mathrm{MPa} \tag{10}$$

This was made orientation-sensitive, by recommending the use of RQD_o, the RQD oriented in the loading (or tunnelling) direction, and the use of the J_r/J_a ratio most appropriate to the loaded direction (i.e. its weakening or strengthening effect). The estimate of "crushing strength" was given a further "anisotropy correction" by allowing the user to evaluate (and compare)

$$\mathrm{SIGMA}_{tm} \approx 5\,\gamma\,Q_t^{1/3}\ \mathrm{MPa} \tag{11}$$

where Q_t is defined as $Q \times I_{50}/4$ (in contrast to Q_c which is defined as $Q \times \sigma_c/100$). The I_{50} value, or point load strength using 50 mm diameter samples, may be 1/25 times the value of σ_c when rock is isotropic, but can be as little as 1/75 times the value of σ_c when strongly anisotropic (schistose, foliated) rock is present.

Considering just the first of these equations for the moderately homogeneous diorite and fine-grained granite intrusions, we may utilise an approximate mean density (γ) of 2.7 t/m^3 and Q_c ***characterization*** values of 100 and 75 (as before) to obtain the following estimates:

N-site $\mathrm{SIGMA}_{cm} = 63\ \mathrm{MPa}$

S-site $\mathrm{SIGMA}_{tm} = 57\ \mathrm{MPa}$

Although not presented as a "stress correction" in Barton, 2002, the matching of TBM cutter force (F) with SIGMA_{cm} or SIGMA_{tm} in the Q_{TBM} method of prognosis (Barton, 2000) also included a tunnel depth (or biaxial-stress-at-the-tunnel-face) correction of $\sigma_\theta/5$, where the biaxial stress at the face (σ_θ) was assumed to be about 5 MPa at 100 m depth, making tunnelling more difficult at greater depths than this. Confined, 3DEC models reported by Staub et al., 2002 showed ultimate strengths of about 180 to 240 MPa in the recent Äspö studies. The effect of confining stress on crushing strength is obviously complicated in the case of rock masses, and the resulting strength will be particularly sensitive to boundary conditions. Clearly a tunnel wall, or an overstressed web between two large diameter boreholes is not under the same biaxial (semi-triaxial) boundary conditions as the rock under a TBM's cutter on an otherwise biaxially (semi-triaxially) stressed tunnel face.

One may also speculate whether it is shear strength or "crushing strength" that is involved in a rock failure process. If "shear strength" is the more correct term for $SIGMA_{cm}$, then it could be argued that the "crushing strength" was twice the above values, namely 126 or 114 MPa respectively. Strong non-linearity appeared to start at vertical stress levels of about 130 to 140 MPa in the 3DEC models referred to above.

6.1 Cohesive and frictional components CC and FC

In the recent development of Q-value correlations, it was discovered that the Q-value numerically resembled the product of ***cohesion*** and the ***friction coefficient***, and perhaps could be expressed in units MPa. It was also suggested that, since the Q-parameter ratings had been derived from the need for given amounts of shotcrete and rock bolts, there would likely be uncertainty in the assumed values of ***cohesion*** and ***friction coefficient*** in the case of the most massive rock that did not need such rock support (as basically at Äspö).

Barton (2002) presented the above "***cohesion***" and "***friction coefficient***" as tentative components CC and FC, the "cohesive and frictional components":

$$CC = \frac{RQD}{J_n} \times \frac{1}{SRF} \times \frac{\sigma_c}{100} \tag{12}$$

$$FC = \tan^{-1}\left(\frac{J_r}{J_a} \times J_w\right) \tag{13}$$

To test these values we can use the weighted mean values of the Q-parameters for the two holes KF 0069 and KA 3386, which are given in Section 3 of this report. A mean σ_c value of 210 MPa is assumed, and the ***classification*** SRF value of 2 is used, since near-excavation behaviour is assumed to have developed the Q-parameter ratings. Presumably the four times larger CC values obtained with SRF = 0.5 are without "stress damage".

N-site

$$CC = \frac{98.3}{3.3} \times \frac{1}{2} \times \frac{210}{100} = 31\,\text{MPa}$$

$$FC = \tan^{-1}\left(\frac{1.75}{2.2} \times 0.93\right) = 36°$$

S-site

$$CC = \frac{97.5}{3.9} \times \frac{1}{2} \times \frac{210}{100} = 26\,\text{MPa}$$

$$FC = \tan^{-1}\left(\frac{1.99}{2.4} \times 0.90\right) = 37°$$

In a rock support discussion, bolting might be needed to supplement the moderate frictional strength, whereas shotcrete would certainly not be needed to supplement the high cohesive strength.

As one might expect from their entirely separate development, the earlier $SIGMA_{cm}$ estimates of 63 and 57 MPa are not here mutually consistent with the above CC and FC estimates, considering Mohr circle construction and linear c (= CC?) and ϕ (= FC?) behaviour.

However, experience with much larger Q-parameter data bases in poorer rock conditions has suggested a reasonable consistency with regard to "fit" between $SIGMA_{cm}$ and CC and FC in Mohr circle construction. Possibly, as suggested by Barton 2002, this has to do with the more "accurate" assessment of shotcrete and bolting needs (and therefore of the chosen Q-parameter ratings) when quality was poorer, and support needs were easier to ascertain, in the original Q-system tunnel case records.

7 Scaling of JRC and JCS

Since the test tunnel (and boreholes) are designed to be roughly perpendicular to the major horizontal stress (which reportedly plunges at some 10° to 30°), the most frequent set 1 joints will not feature in eventual 2D discontinuum models, though obviously will in 3D models with joints (respectively UDEC and 3DEC, or similar).

In a first stage of discontinuum modelling (based on Phase 1 characterization), only the obliquely intersecting set 2 (and eventual, occasional set 3 – or random joints) would need to be modelled. Examples of the roughness of these joints were shown in Figures 3 and 4, and are similar to four other profiles of these joints photographed during the logging.

For purposes of preliminary estimation of full scale JRC_n and JCS_n values, relevant to in situ block sizes of L_n, we will utilise the measurements of a/L (and therefore JRC_n for specific profile lengths) given in Figure 8, and the approximate (estimated) histograms of JCS_0 and S (spacing) given in Figure 5.

Set 2 JRC_n (mean) ≈ 6 at $L_n = 0.2$ (from Figure 8)

JCS_o (mean) ≈ 140 MPa (from Figure 5)

Concerning relevant block size (along the direction of set 2), the angle of intersection of set 2 joints with the core of about 30°, suggest theoretically that the relevant L_n value should be equal to S_1 (mean)/cos 30°.

Set 2 $L_n \approx S_1(\text{mean})/\cos 30° \approx 0.84/0.87 \approx 1.0$ m (from Figure 5)

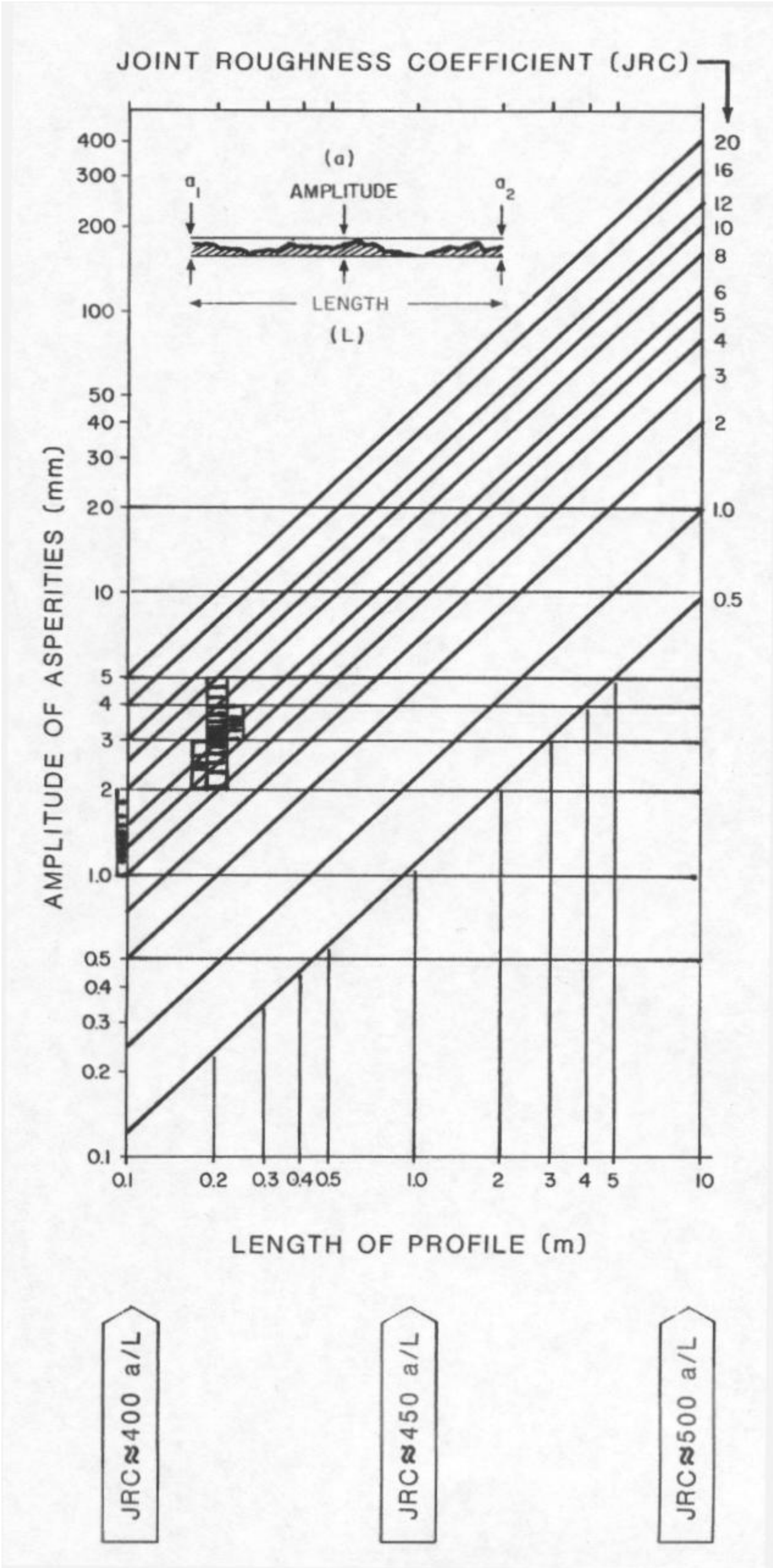


Figure 7-1. *a/L (amplitude/length) estimate for set 1 (left) and set 2 .(right).*

Figure 9 shows the general trends of the suggested correction for block size, on JRC and JCS. The corresponding empirical equations which will be used here are:

$$JRC_n \approx JRC_o \left[\frac{L_n}{L_0} \right]^{-0.02\ JRC_o} \qquad (14)$$

$$JCS_n \approx JCS_o \left[\frac{L_n}{L_0} \right]^{-0.03\ JRC_o} \qquad (15)$$

Since our "L_0" scale is already averaging 0.2 m for the case of set 2 profiles, we will scale JRC with the (L_n/L_0) ratio of 1.0/0.2, and substitute $JRC_0 = 6$, to obtain the lower final JRC_n estimate.

The results obtained are as follows for recommended set 2 modelling in distinct element codes:

Set 2 $JRC_n \approx 5$

$JCS_n \approx 100$ MPa (approximate, rounded figures due to level of uncertainty)

$\phi_r \approx 29°$

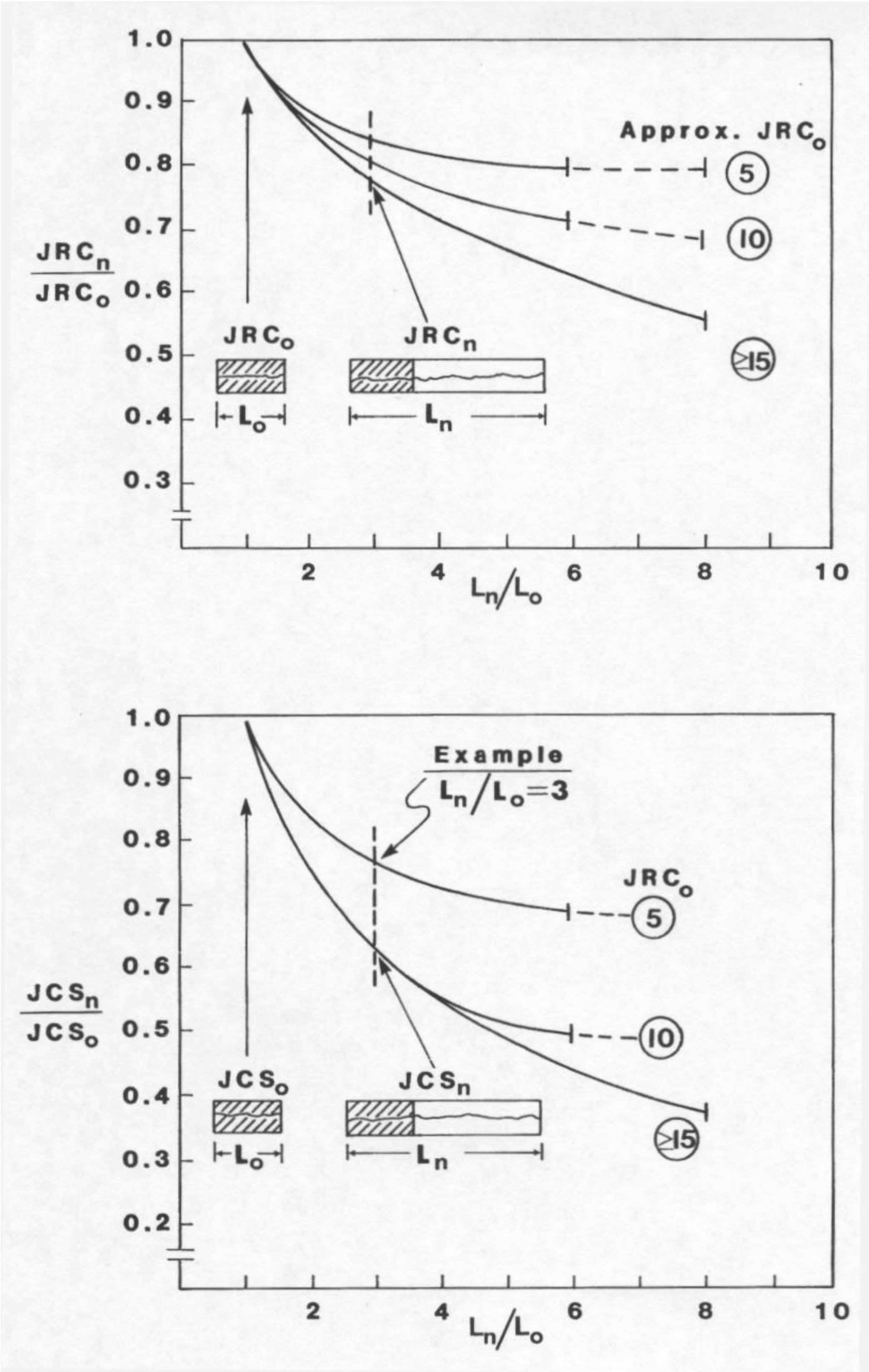


Figure 7-2. *Empirically derived scale effects on JRC and JCS. .Bandis et al., 1981.*

8 Conclusions and recommendations

1. Histogram-style Q-logging of two cores, drilled to the NNE from TAS F (KF 0069), and drilled to the SSW from TAS A (KA 3386) respectively, form the basis of this report. The rock is predominantly diorite, with intrusions of fine-grained granite from about 32 to 53 m depth in KF 0069, and from about 35 to 46 m depth in KA 3386. The holes were drilled perpendicularly to the σ_H and to the predominant sub-vertical set 1 joints.

2. The cores were logged from the point of view of ***characterization***, giving general rock mass conditions distant from excavations. When "EDZ" near-tunnel conditions are required the logging is a ***classification*** (of e.g. rock support needs) and, among other factors such as blast damage, a higher SRF value may be used. In this report, respective values of SRF = 0.5 and 2 have been used, in view of the fairly low mean ratio of $\sigma_c/\sigma_1 \approx 210/30 \approx 7$.

3. The northerly site (KF 0069) showed Q(mean) = 44, and the southerly site (KA 3386) showed Q(mean) = 37. Set 1 (sub-parallel to σ_H) dominates the joint frequency, but there are obliquely cutting ($\approx 30°$) joints of one, and maybe up to two other sets. The sample as a whole suggests a typical range of Q from 15 to 100, with a mean of about 40.

4. A broader geotechnical logging of the rock mass has been attempted, also based on histogram logging, with brief commentary on some nineteen relevant parameters (which include the basic six Q-parameters). These can assist modellers with a more general picture of the rock mass, prior to more accurate tunnel logging data for Phase 2 modelling.

5. Correlation of Q or Q_c (= $Q \times \sigma_c/100$) with various engineering parameters has been attempted, including estimates of stressed ("500 m depth") values of V_p (for comparison with ZEDEX seismic tomography measurements), and stressed estimates of E_{mass}. In both cases a ***characterization*** value and a ***classification*** value (EDZ related) have been provided. For example we see a potential range of 5.6 to 6.0 km/s for V_p, and 52 to 68 GPa for E_{mass}, when the above distinction (EDZ, non-EDZ) is included. Lower radial E_{mass} values are discussed.

6. Empirically based estimates of deformation that might be modelled (or measured if there were pre-installed MPBX) are given. Distinction is made between the horizontal (σ_H-affected) deformation of the planned 7.5 m high tunnel, and the vertical (σ_v-affected) deformation of the 5 m span. Values of Δ_h = 2.8 mm and Δ_v = 1.3 mm were obtained.

7. Empirical “crushing strength” estimation based on Q_c-values, and empirical ***cohesive component*** (CC) and ***frictional component*** (FA) estimation based on Q-parameter based groupings (Barton, 2002) were attempted. “Crushing strength” ($SIGMA_{cm}$) values of 57 to 63 MPa are estimated, but it is pointed out that these TBM-derived estimates may actually represent shear strength, in which case theoretical (Mohr circle diameter) values of 114 to 126 MPa might be more relevant. CC and FC estimates range from 31 to 36 MPa and 36 to 37°, respectively.

8. Finally, set 2 (obliquely cutting) joint parameters JRC, JCS and ϕ_r were estimated based on the profiling of roughness that was performed. Although Schmidt hammer testing for JCS was not attempted in this Phase 1 (pre-tunnel) characterization, estimates of JCS and ϕ_r were made in histogram form. The results were corrected to a very approximate 1 m average block size (making a 60° angle to set 1 joints). The recommended values for eventual set 2 modelling in any Phase 1 UDEC-BB modelling are: $JRC_n \approx 5$, $JCS_n \approx 100$ MPa, $\phi_r \approx 29°$.

9 References

Bandis, S., Lumsden, A. & Barton, N. 1981. Experimental studies of scale effects on the shear behaviour of rock joints. Int. J. of Rock Mech. Min. Sci. and Geomech. Abstr. 18, 1-21.

Barton, N. & Choubey, V. 1977. The shear strength of rock joints in theory and practice. Rock Mechanics 1/2:1-54. Vienna: Springer. Also NGI-Publ. 119, 1978.

Barton, N., Løset, F., Smallwood, A., Vik, G., Rawlings, C., Chryssanthakis, P., Hansteen, H. & Ireland, T. 1992. Geotechnical Core Characterization for the UK Radioactive Waste Repository Design. 1992 Proc. of ISRM Symp. EUROCK, Chester, UK.

Barton, N. 2000. TBM Tunnelling in Jointed and Faulted Rock. 173p. Balkema, Rotterdam.

Barton, N. 2002. Some new Q-value correlations to assist in site characterization and tunnel design. Int. J. Rock Mech. & Min. Sci. Vol. 39/2, pp.185-216.

Christiansson, R. & Janson, T. 2002. Test with three different stress measurement methods in two orthogonal bore holes. Proc. of North American Rock Mechanics Symposium, NARMS 2002, Toronto.

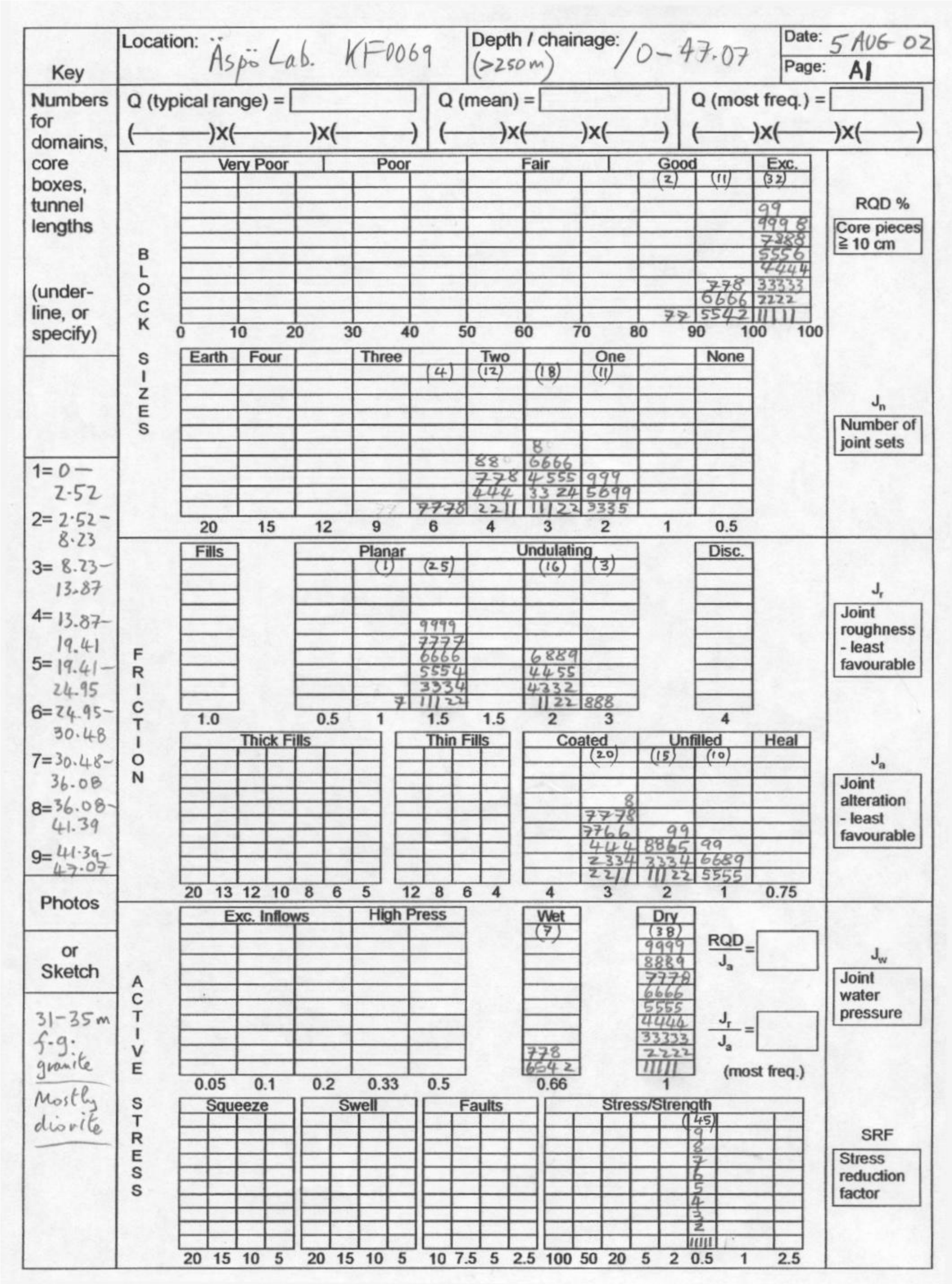
Cosma, C., Olsson, O., Keskinen, J. & Heikkinen, P. 2001. Seismic characterization of fracturing at the Äspö Hard Rock Laboratory, Sweden, from the kilometre scale to the meter scale. Int. J. Rock Mech.& Min. Sci. 38, (2001), 859-865, Special Issue, Application of Geophysics to Rock Engineering , Pergamon, Elsevier Science Ltd.

ISRM, 1978. Suggested methods for the quantitative description of discontinuities in rock masses, (Coordinator, Barton, N.) Int. J. Rock Mech. Sci. and Geomech. Abstr., Vol. 15, pp. 319-368, Pergamon.

Staub, I., Fredriksson, A. & Outters, N. 2002. Strategy for a descriptive rock mechanics model. Development and testing of the theoretical approach. SKB R-02-02, Swedish Nuclear Fuel and Waste Management Co. Stockholm.

10 List of figures

Appendix



Key | Location: Äspö Lab. KF0069 | Depth / chainage: 0 – 47.07 (>250 m) | Date: 5 AUG 02 | Page: A1

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

Q (typical range) = ( )x( )x( ) | Q (mean) = ( )x( )x( ) | Q (most freq.) = ( )x( )x( )

1= 0 – 2.52
2= 2.52 – 8.23
3= 8.23 – 13.87
4= 13.87 – 19.41
5= 19.41 – 24.95
6= 24.95 – 30.48
7= 30.48 – 36.08
8= 36.08 – 41.39
9= 41.39 – 47.07

Photos

or Sketch

31–35 m f.g. granite

Mostly diorite

BLOCK SIZES

RQD % — Core pieces ≧ 10 cm

Very Poor | Poor | Fair | Good (2) (11) | Exc. (32)

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

J_n — Number of joint sets

Earth | Four | Three (4) | Two (12) (18) | One (11) | None

20 15 12 9 6 4 3 2 1 0.5

FRICTION

J_r — Joint roughness - least favourable

Fills | Planar (1) (25) | Undulating (16) (3) | Disc.

1.0 0.5 1 1.5 1.5 2 3 4

J_a — Joint alteration - least favourable

Thick Fills | Thin Fills | Coated (20) | Unfilled (15) (10) | Heal

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 (7) | Dry (38)

0.05 0.1 0.2 0.33 0.5 0.66 1

$\frac{RQD}{J_a}$ =

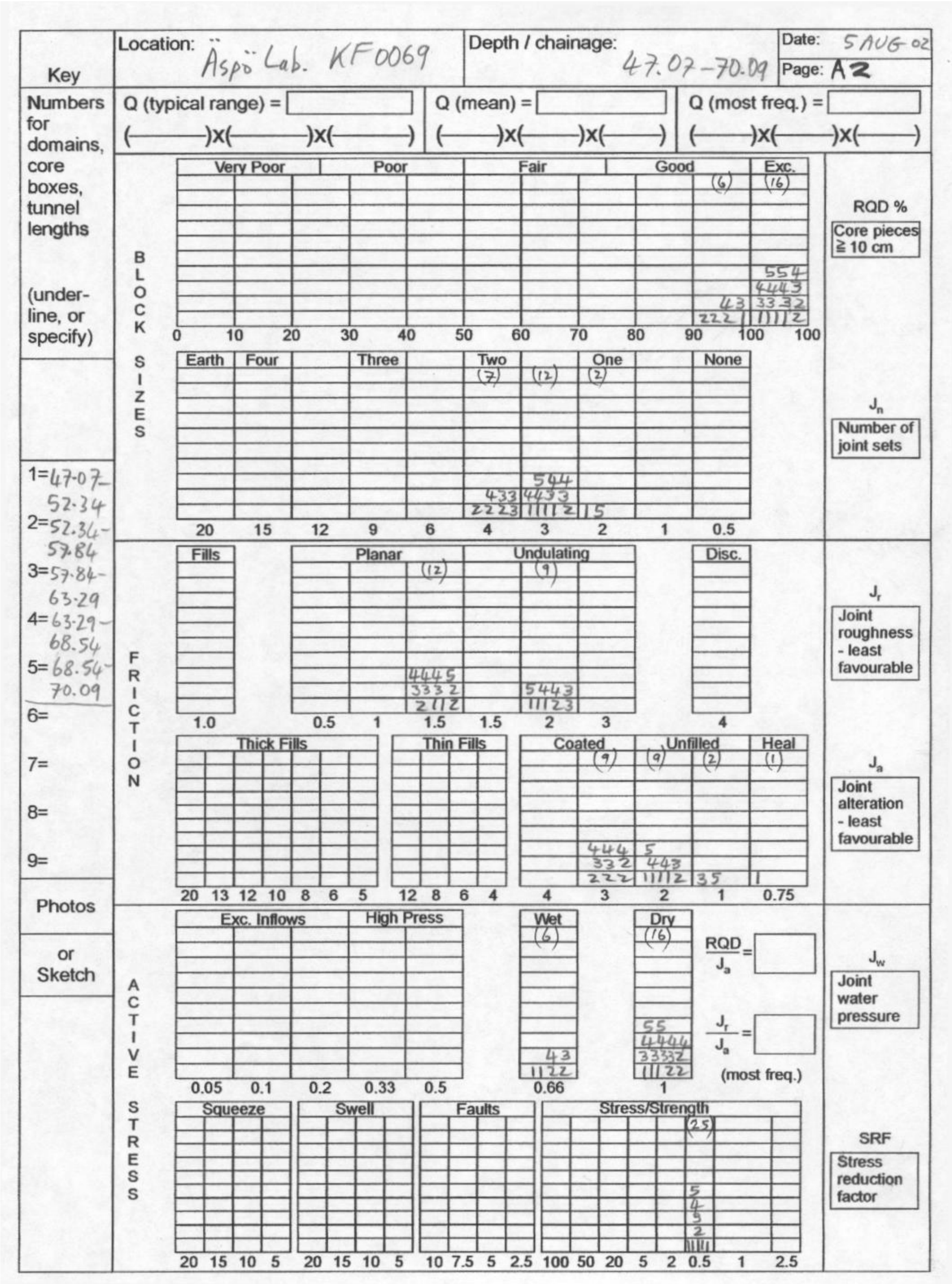
$\frac{J_r}{J_a}$ = (most freq.)

SRF — Stress reduction factor

Squeeze | Swell | Faults | Stress/Strength (45)

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

Figure A1



Key
Location: Äspö Lab. KF0069
Depth / chainage: 47.07–70.09
Date: 5 AUG 02
Page: A2
Numbers for domains, core boxes, tunnel lengths (under-line, or specify)
Q (typical range) =
Q (mean) =
Q (most freq.) =
1=47.07–52.34
2=52.34–57.84
3=57.84–63.29
4=63.29–68.54
5=68.54–70.09
6=
7=
8=
9=
Photos
or Sketch
BLOCK SIZES
Very Poor
Poor
Fair
Good
Exc.
(6)
(16)
554
4443
43
3332
222
11112
0 10 20 30 40 50 60 70 80 90 100 100
RQD %
Core pieces ≧ 10 cm
Earth
Four
Three
Two
One
None
(7)
(12)
(2)
544
433
4433
2223
11112
15
20 15 12 9 6 4 3 2 1 0.5
J_n
Number of joint sets
FRICTION
Fills
Planar
Undulating
Disc.
(12)
(9)
4445
3332
2112
5443
11123
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
(9)
(9)
(2)
(1)
444
332
222
5
443
11112
35
1
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
(6)
(16)
43
1122
55
4444
33332
11122
0.05 0.1 0.2 0.33 0.5 0.66 1
RQD/J_a =
J_r/J_a =
(most freq.)
J_w
Joint water pressure
Squeeze
Swell
Faults
Stress/Strength
(25)
5
4
3
2
1111
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

Figure A2

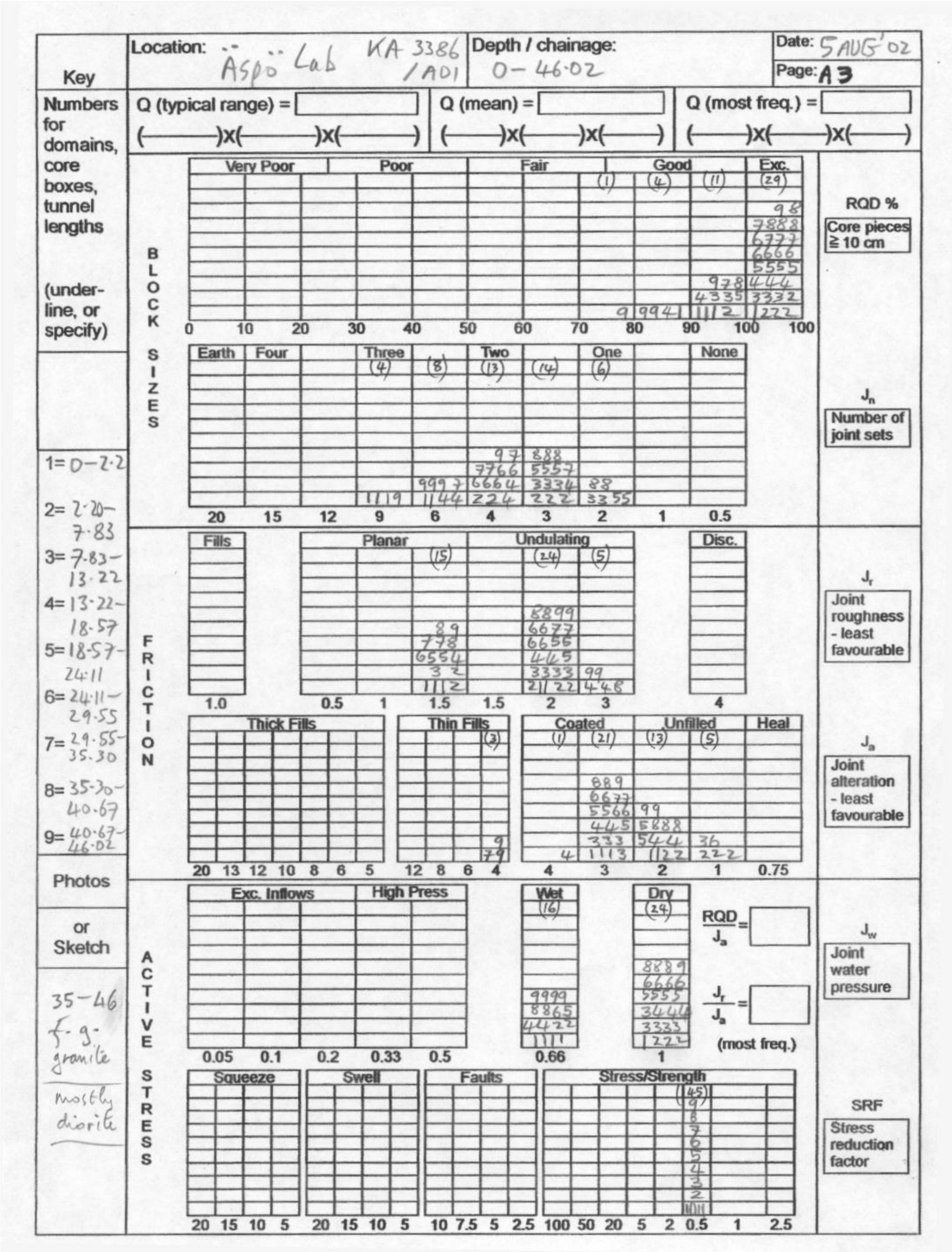

Key
Location: Äspö Lab KA 3386 /A01
Depth / chainage: 0-46.02
Date: 5 AUG '02
Page: A3
Numbers for domains, core boxes, tunnel lengths
(under-line, or specify)
Q (typical range) =
Q (mean) =
Q (most freq.) =
BLOCK SIZES
Very Poor
Poor
Fair
Good
Exc.
0 10 20 30 40 50 60 70 80 90 100 100
RQD %
Core pieces ≧ 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
1= 0-2.2
2= 2.20-7.83
3= 7.83-13.22
4= 13.22-18.57
5= 18.57-24.11
6= 24.11-29.55
7= 29.55-35.30
8= 35.30-40.67
9= 40.67-46.02
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
Photos
or Sketch
35-46 f.g. granite
mostly diorite
ACTIVE STRESS
Exc. Inflows
High Press
Wet
Dry
0.05 0.1 0.2 0.33 0.5 0.66 1
RQD / J_a =
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

Figure A3

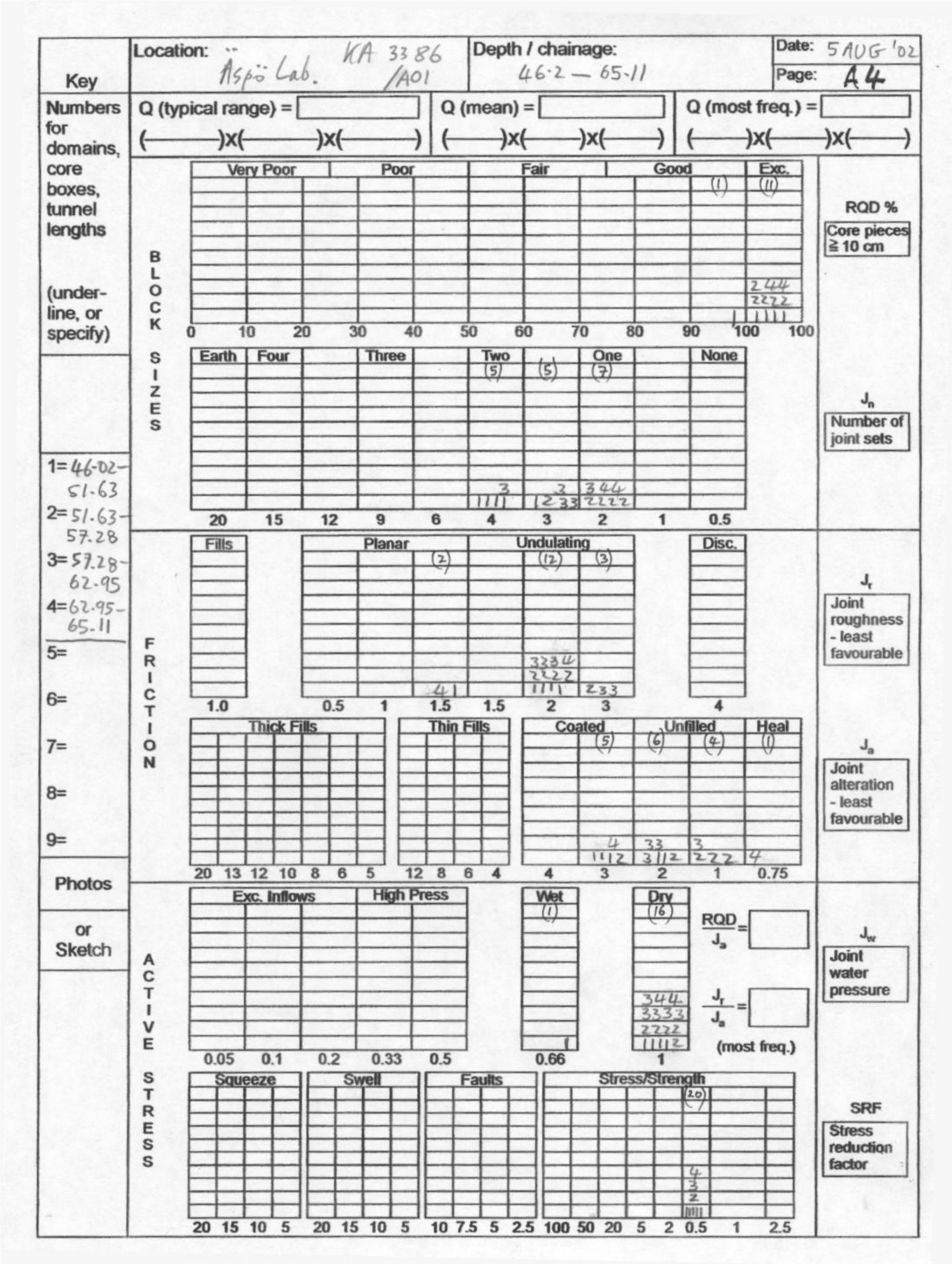

Location: Äspö Lab. KA 3386 /A01
Depth / chainage: 46.2 — 65.11
Date: 5 AUG '02
Page: A4
Key
Numbers for domains, core boxes, tunnel lengths
(under-line, or specify)
1= 46.02-51.63
2= 51.63-57.28
3= 57.28-62.95
4= 62.95-65.11
5=
6=
7=
8=
9=
Photos
or Sketch
Q (typical range) =
Q (mean) =
Q (most freq.) =
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
RQD / J_a =
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

Figure A4