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Forsmark site investigation

Rock mechanics characterisation of borehole KFM03A

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August 2005

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

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Abstract

The characterisation of the rock mass along borehole KFM03A was performed by means of the Q and RMR empirical systems. On average, the rock along the borehole is classed as "very good rock" by both the empirical systems, although toward the "good rock" (RMR = 84 and Q = 37). The fractured rock (deformation zones) exhibit values slightly lower (RMR = 79 and Q = 11). The worse rock quality is found in the rock units dominated by pegmatitic granite.

The mechanical properties of the rock mass were determined from the quantification of the rock mass quality. The deformation modulus of the rock mass varies between 15 and 75 GPa, with an average of 66 GPa. The Poisson's ratio is around 0.20. The equivalent uniaxial compressive strength, friction angle and cohesion of the rock mass were obtained by means of the relation RMR-GSI-Hoek & Brown's Criterion. The compressive strength is around 65 MPa and it is highest for the rock units dominated by metagranite and granodiorite. For a confinement stress between 10 and 30 MPa, the equivalent friction angle is estimated around 47° and the equivalent cohesion around 23 MPa, with minor differences between competent and fractured rock.

The uncertainty on the estimation of the rock quality and the derived mechanical parameters is also quantified in term of confidence on the determination of the mean property value. The uncertainty on the parameters derived for the fractured rock (deformation zones) is larger than the uncertainty determined for the competent rock. The uncertainty decreases when the whole borehole is considered.

The analysis of P-wave velocity measurements was also carried out and seem to be well correlated to the orientation of the foliation.

Sammanfattning

Bergmassan längs borrhål KFM03A karakteriserades med hjälp av de empiriska system Q och RMR. Båda systemen klassade berget som ”mycket bra” även vid gränsen mot ”bra berg” (RMR = 84 and Q = 37). Sprucket berg (deformationszonerna) visa lägre värde (RMR = 79 and Q = 11). De sämsta partierna består till stor del av pegmatitisk granit.

Flera mekaniska egenskaper för bergmassan kunde uppskattas baserat på bergkvaliteten. Deformationsmodulen varierar mellan 15 och 75 GPa, med ett medelvärde runt 66 GPa. Ett Poissonstal runt 0.20 beräknades för bergmassan. Bergmassans hållfasthet togs fram med hjälp av korrelationen mellan RMR-GSI-Hoek & Browns kriterium. Den enaxliga tryckhållfastheten visade sig vara runt 65 MPa och är högst i bergdomäner dominerade av metagranit och granodiorit. För en spänningsnivå mellan 10 och 30 MPa är den ekvivalent friktionsvinkeln och kohesionen 47° respektive 23 MPa, med små skillnader mellan kompetent och sprucket berg.

Osäkerheten i uppskattningen av bergkvalitén och mekaniska bergegenskaper definieras i term av möjlig variationsintervall för medelvärdet. Osäkerheten är störst för parametrarna beräknade på sprucket berg jämfört med de mera intakta partierna. Osäkerheten minskar när man bedömer den över hela borrhålet.

P-våghastigheten analyserades med stöd av foliationens orienteringen. En god korrelation har observerats mellan de två parametrarna.

Contents

1 Introduction

1.1 Background

The telescopic borehole KFM03A is a peripheral placed borehole inside the Forsmark candidate area. The borehole reaches a depth of about 1,001 m and is drilled with a bearing angle of 271° and inclination of 86°. The borehole core diameter for the depths between 100 and 1,001 m is 51 mm. The complete core was recovered and pictures of the borehole walls were continuously recorded by BIPS.

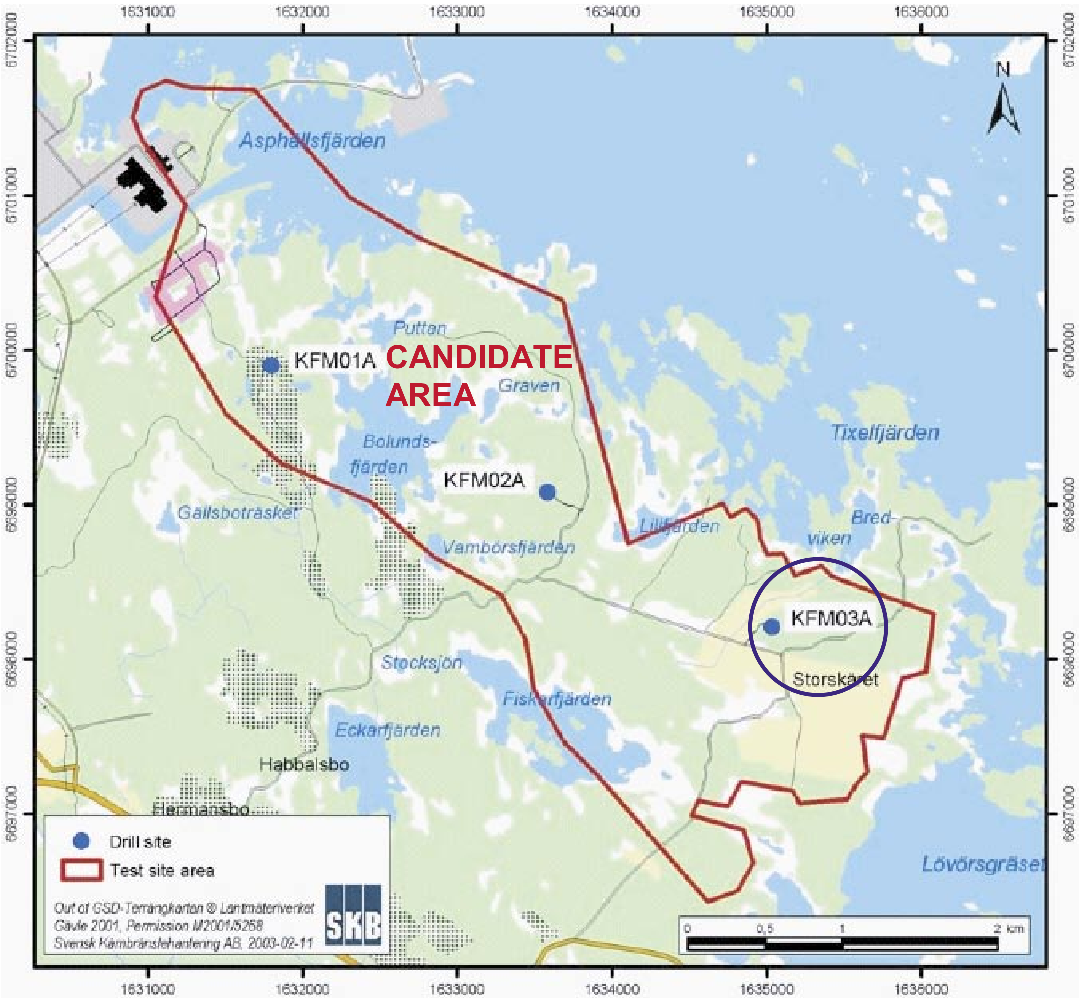

Figure 1-1. Overview of the Forsmark site with indication of the candidate area and borehole KFM03A.

1.2 Objectives

The objectives of this study are as follows:

- Evaluate the rock mass quality along borehole KFM03A by means of the empirical systems RMR and Q;
- Quantitatively characterise the rock mass by determining its deformation modulus, Poisson's ratio, uniaxial compressive strength, cohesion and friction angle;
- Give summarising properties for the pseudo-homogeneous rock units identified in the geological single-hole-interpretation;
- Discuss the results of the characterisation and list the main conclusion of the work.

1.3 Scope

The characterization of the rock mass along the borehole is performed mainly based on data that come directly from the borehole (BOREMAP data). This enables for a rock local quality determination. When comparing the results for different depths, the spatial variation along borehole KFM03A can be highlighted. This Rock Mechanics Report is structured as follows:

- Summary of the BOREMAP data on rock types and fractures. The fracture sets occurring along the borehole are illustrated together with their frequency and spacing;
- Summary of the mechanical properties of the common rock types at the site and of the rock fractures (see also Appendix A);
- Application of the RMR and Q empirical systems for determination of the rock quality along borehole KFM03A (see also Appendix B). The determination of the input parameters is illustrated as well as some spatial variation, scale effect and uncertainty;
- Determination of the continuum equivalent mechanical properties of the rock mass based on empirical relations with RMR and Q. The deformation modulus, Poisson's ratio, uniaxial compressive strength, cohesion and friction angle of the rock mass are determined and shown as a function of depth. The uncertainties of the deformation modulus determination are also treated (see also Appendix C).
- Discussion of the results.
- Processing and storage of the data in SICADA.
- Appendices.

2 Boremap data

Borehole KFM03A was mapped by examining the core and the BIPS pictures taken on its wall /Petersson et al. 2003/. The geological parameters obtained and stored in SKB's geological database SICADA, and used for the rock mass characterisation, were:

- Frequency of the fractures
- RQD evaluated on core lengths of 1 m
- Rock types, rock alteration and structural features.

Each fracture observed along the borehole was classified in the group of "broken" or "unbroken" ("sealed"). The group "broken" includes all naturally open fractures and those originally sealed that were broken during drilling procedure. The fractures in the group "broken" were classified into the groups "open" or "sealed" based on the geological evaluation of the core. The confidence of this evaluation was expressed by three levels: "certain", "probable" and "possible". The rock mechanics characterisation in this report is based on the properties of the "open" and "partly open" fractures. The following geological features of the fractures were observed:

- Depth of occurrence
- Mineralization or infilling
- Roughness and surface features
- Alteration conditions
- Orientation (strike and dip)
- Width and aperture.

A direct estimation of the Q-parameter Joint Alteration Number (J_a) was performed by the geologists. The information listed above is contained in the geological and rock mechanics digital database SICADA by SKB (downloaded on March 5, 2004).

For the rock mechanics evaluation of the geological information, some more parameters were determined:

- Bias correction of the orientation and spacing by Terzaghi's weighting
- Assignation of each fracture to a fracture set or to the group of random fractures.

The rock mass along the borehole was partitioned into pseudo-homogeneous rock units during the "geological single-hole interpretation" of the borehole /Carlsten et al. 2004/ (see also section 4.2). Each rock unit presents a typical rock type, rock type density, fracture frequency, alteration and geophysical response. The "geological single-hole interpretation" also identified possible "Deformation Zones" based on the information available along the borehole.

The recognition of the main fracture sets in the rock mass along the borehole was based, not only of the BOREMAP information directly available, but also on the indications of earlier studies for the construction of the Unit 3 of the Nuclear Power Plant and for the SFR Repository for low and intermediate active nuclear waste. Figure 2-1 shows the summary pole plot of the fracture set orientation. Some of the open fractures were not assigned to any fracture set and constitute the group of "random fractures".

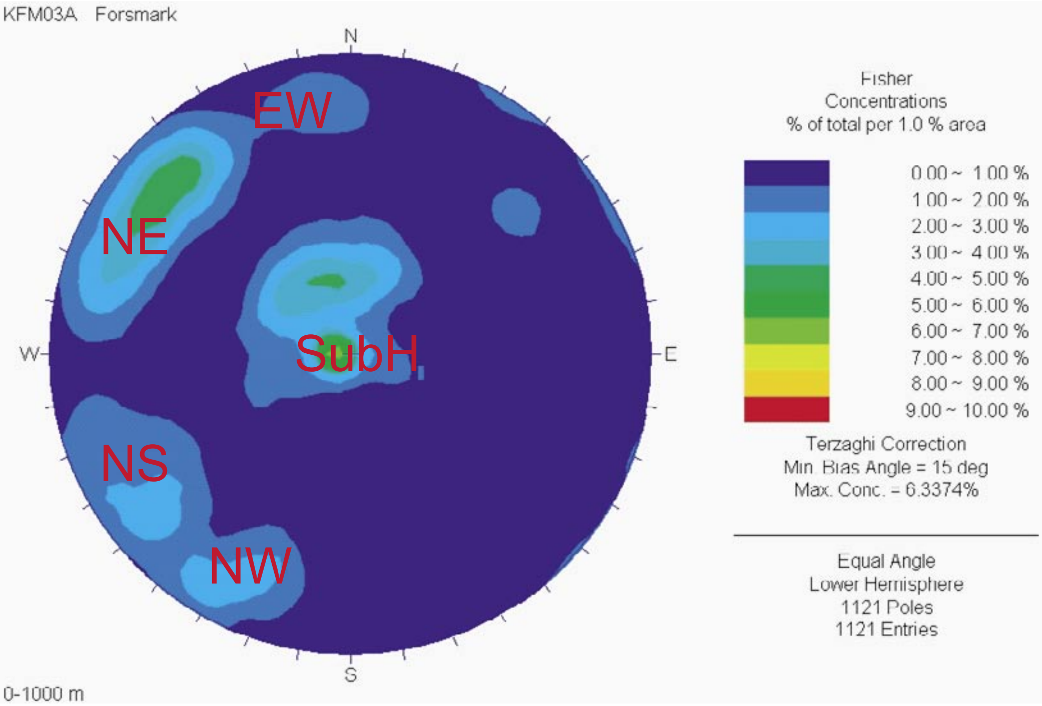

***Figure 2-1.** Equiangle pole plot of the fractures logged along borehole KFM03A and indication of the main fracture sets. The borehole orientation is 271/86 (strike/dip).*

Once the fracture sets were identified within each rock unit, the mean orientation and Fisher's constant were determined (Table 2-2). Based on the orientation pole concentrations shown in Figure 2-1, the fractures were assigned to the fracture sets for every 5 or 30 m core length. In this way, not only the number of fractures for each occurring set could be calculated, but also the frequency and spacing of each fracture set were determined. For the fracture spacing the Terzaghi's correction was applied considering the linear sampling of the fractures applied by the drilling.

The total frequency of the fractures gives an idea of the degree of fracturing of the core, as shown in Figure 2-2 where the frequency is averaged for each 5 m core length. Here, some zones of higher fracture frequency are observed at the depth between 360–415 m (Deformation Zone DZ1; frequency about 7 fractures/m) and between 800 and 815 m (DZ 4; frequency around 5 fractures/m). The frequency peaks of the sub-horizontal fracture set also occur at those depths. The peak in the total frequency at about 800 m is mainly due to frequency of sub-horizontal fractures.

The Rock Quality Designation, RQD, that give the sum of the length of core pieces longer than 100 mm every metre of borehole core, is also obtained from the SICADA Database and plotted in Figure 2-2. Here, average values for every 5 m core length are presented. RQD presents values down to 80 at about 375 and 800 m depth. RQD is in average otherwise relatively high.

By counting the number of fracture occurring in each 5 m section of core, the plot of the number of fracture sets occurring at the same depth can be obtained (Figure 2-2). For borehole KFM03A, the number of fracture sets occurring in the same borehole section of 5 m does not usually exceed three.

Table 2-1. Set identification from the fracture orientation mapped for borehole KFM03A (SICADA, 04-03-05). The orientations are given as strike/dip (right-hand rule).

Depth (m)	Number of fractures	EW	NW	NE	NS	SubH
100–220	101	053/77	295/81		325/75	057/14
220–293	48				331/78	089/10
293–356	44			010/86	336/75	108/15
356–377	80				334/64	243/07
377–399	67		306/53			069/13
399–448	69	082/79		015/82		078/11
448–455	20	090/75		038/75		080/21
455–638	187		310/79	046/79	341/81	079/20
638–646	17					078/17
646–803	131		291/78	086/79	136/71	043/16
803–816	40			023/79		075/19
816–942	112			032/75		017/02
942–949	25			044/79		036/08
949–1,000	56			041/76		057/08

Table 2-2. Fisher's constant of the fracture sets identified for borehole KFM03A (SICADA, 04-03-05).

Depth (m)	Number of fractures	EW	NW	NE	NS	SubH
100–220	101	129.22	68.72		59.68	21.26
220–293	48				38.76	16.85
293–356	44			24.33	26.33	7.62
356–377	80				125.41	20.74
377–399	67		26.07			16.93
399–448	69	91.78		71.61		10.80
448–455	20	190.51		81.70		8.86
455–638	187		56.72	178.13	117.52	11.60
638–646	17					11.51
646–803	131		83.19	104.26	112.22	11.96
803–816	40			67.00		14.60
816–942	112			49.06		34.63
942–949	25			233.07		19.53
949–1,000	56			77.56		30.67

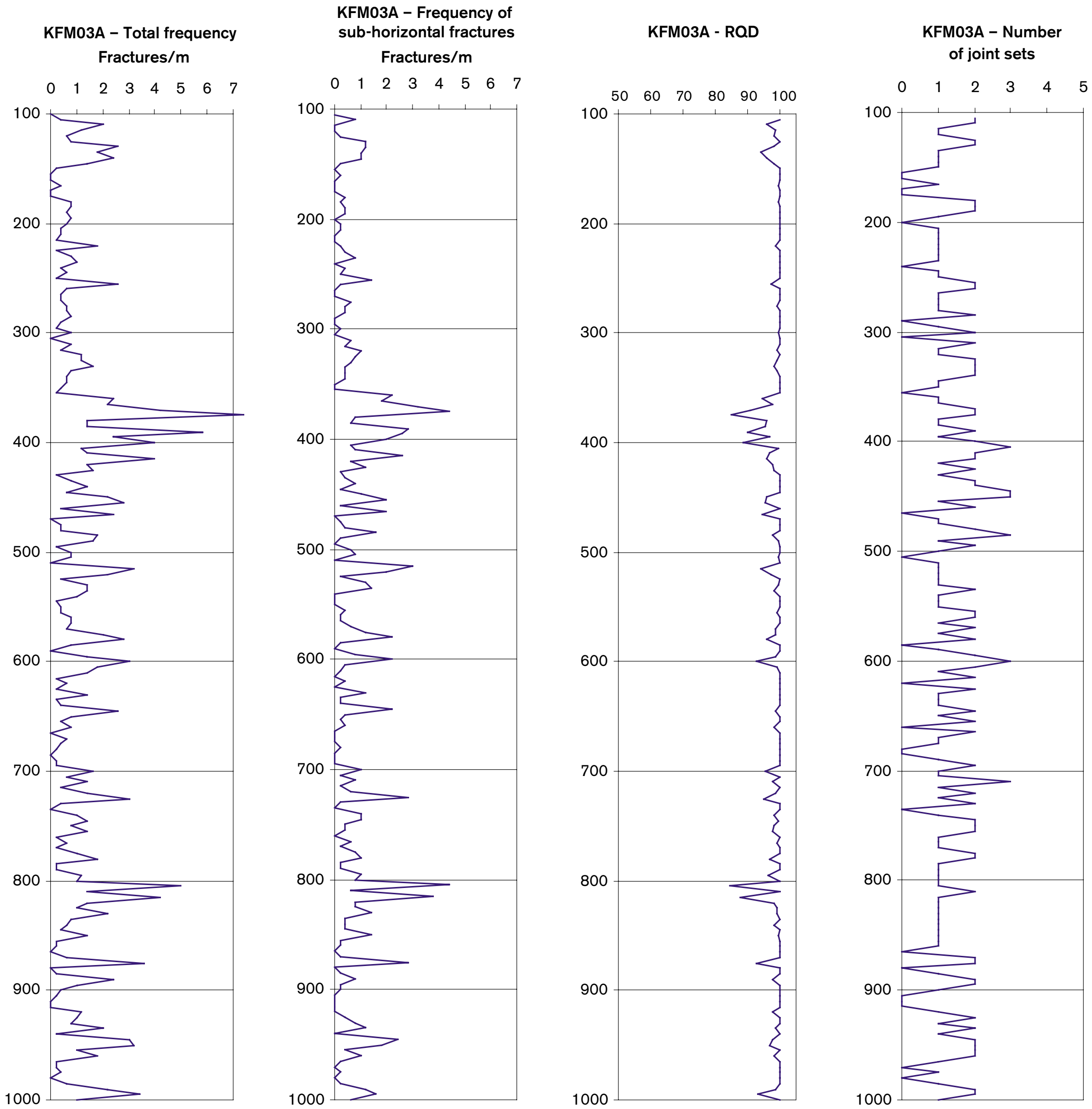

Figure 2-2. Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM03A. The values are averaged for each 5 m length of borehole.

The spacing of each of the fracture sets occurring in borehole KFM03A is shown in Figure 2-3. The sub horizontal fracture set SubH, occurs along the whole borehole with rather varying spacing down to some decimetres. The set EW, NW, NE and NS appear along continuous core sections of length of about 40 to 200 m. Low fracture spacing are experienced between 900 and 940 m, although RQD does not significantly diminishes at those depths.

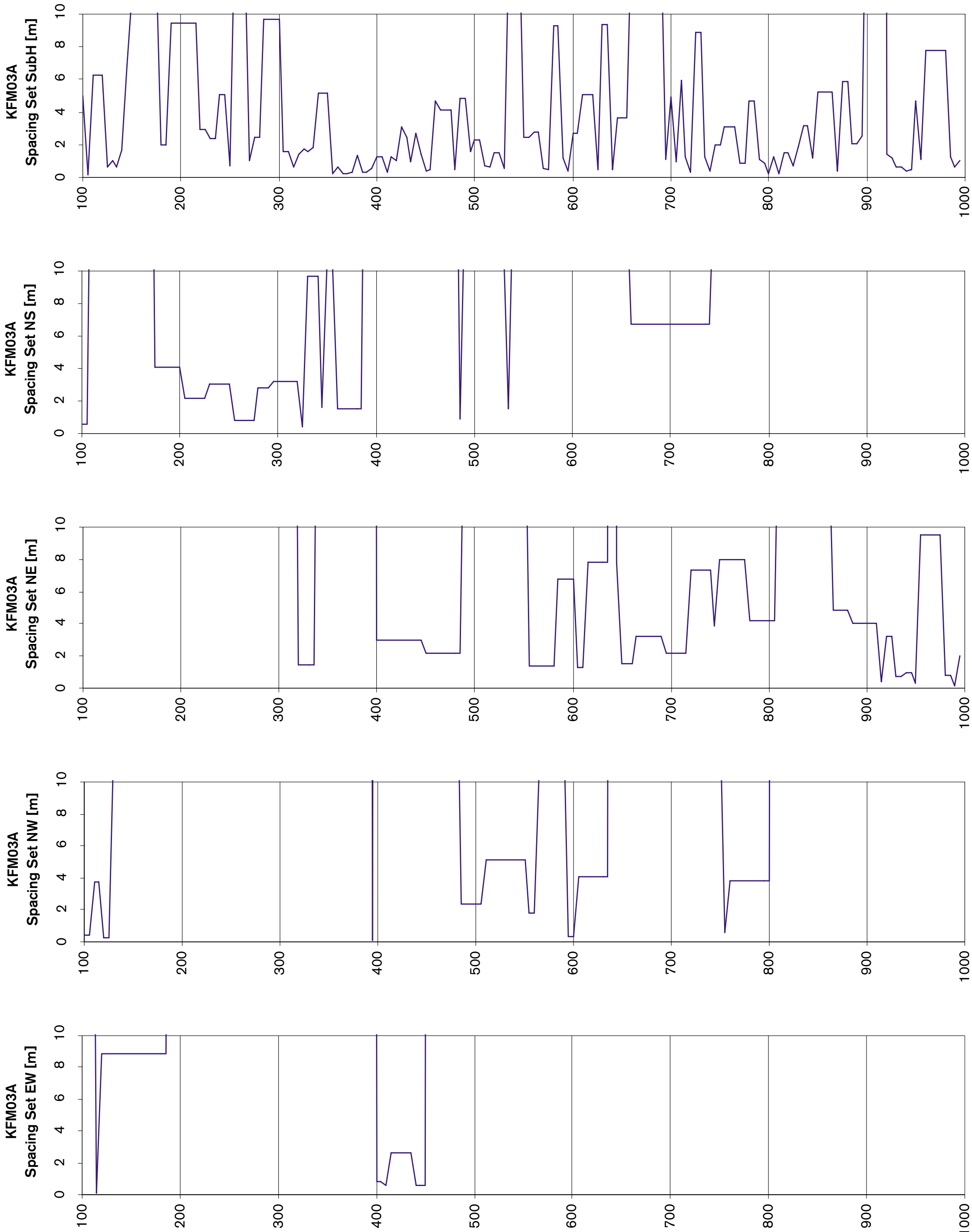

Figure 2-3. *Fracture spacing with depth for the five facture sets in borehole KFM03A. The values are averaged for each 5 m length of borehole.*

3 Mechanical tests

A campaign of laboratory tests was carried out on core samples from borehole KFM01A, KFM02A, KFM03A and KFM04A. The results were delivered to SKB's database SICADA on July 30, 2004. The data contain:

- Uniaxial (68) and triaxial (59) compressive tests on intact rock
- Indirect tensile strength tests on intact rock (143 Brazilian Tests)
- Shear tests (96) on fracture samples (9)
- Tilt tests (142) on fracture samples.

Two representative rock types were sampled on the core of KFM03A: granite (medium-grained metagranite, rock code 101057) and tonalite (medium-grained metatonalite, rock code 101051).

3.1 Intact rock density

The density of the intact rock in borehole KFM03A varies according to the rock types. The tonalite exhibits a density of 2.76 g/cm^3 while the granite to granodiorite has a density that varies depending on the grain size: 2.65 g/cm^3 for medium-grained and 2.81 g/cm^3 for the fine to medium-grained granite, respectively. Wet samples give an increased density by 0.1–0.4%. The porosity of the samples varies between 0.3% and 0.4%.

3.2 Intact rock strength

Uniaxial compressive tests were performed on the samples of granite and tonalite. Table 3-1 shows the range of variation and the mean value of the laboratory results. The uniaxial compressive strength of the tonalite is about 30% lower than that of the granite.

A set of representative mechanical properties of the intact rock based on the laboratory data has been used for determining the empirical ratings for the RMR and Q systems. These values consider the broader variability due to the presence of: i) occurrences of different rock types within a pseudo-homogeneous rock unit; ii) possible sampling bias on preferably very good rock; ii) presence of sealed fractures that have not been taken into account otherwise in the empirical characterisation; iii) accounting for alteration within the sections with higher fracture frequency and within the deformation zones. The rock mechanics properties used in this report are:

- Uniaxial compressive strength of the intact rock
- The Hoek and Brown's parameters of the intact rock obtained from triaxial tests
- The Young's modulus and Poisson's ratio of the intact rock.

The values of these parameters are listed in Table 3-2.

Table 3-1. Summary of the results of Uniaxial Compressive Strength tests (UCS) performed on intact rock samples from boreholes KFM01A–KFM04A.

Rock type	Number of samples	Minimum UCS (MPa)	Mean UCS (MPa)	Frequent UCS (MPa)	Maximum UCS (MPa)	UCS's standard deviation (MPa)
Granite to granodiorite, metamorphic, medium-grained	52	166	225	223	289	22
Tonalite to granodiorite, metamorphic*	8	140	156	155	176	13

* These samples were collected along borehole KFM03A at 278–310 m depth.

Table 3-2. Mechanical properties of the intact rock used for the empirical characterisation and of the rock mass. The same set of properties is used to determine the mechanical properties of the rock mass.

Rock type	Material property	Minimum	Mean	Frequent	Maximum
Granite to granodiorite	UCS (MPa)	100	200	210	300
	Young's modulus E (GPa)	40	75	75	90
	Poisson's ratio v (–)	0.17	0.24	0.24	0.31
	Hoek & Brown's m (–)	25	30	30	35
Tonalite to granodiorite	UCS (MPa)	100	150	150	200
	Young's modulus E (GPa)	40	75	75	90
	Poisson's ratio v (–)	0.20	0.27	0.27	0.34
	Hoek & Brown's m (–)	7	9.5	9.5	12

3.3 Rock fracture properties

35 tilt tests were carried out on samples of rock fracture from borehole KFM03A /Chryssanthakis, 2004/. Based on the fracture orientation, the fractures were grouped into sets according to Section 2. The values of the basic and residual friction angle, of the Joint Roughness Coefficient JRC and Joint Compressive Strength JCS are rather consistent between the different fracture sets. Consequently, from a strength point of view, they can be assumed to coincide with the parameters characterising the group of all fractures (Table 3-3).

The direct shear tests on the fractures from the four boreholes give the peak and residual strength properties in Table 3-4, which are in good accordance with the values obtained from tilt tests in Table 3-3.

Table 3-3. Summary of the results of tilt tests performed on rock joints from borehole KFM03A /SICADA, 2004-07-30/.

Fracture set	Number of samples	Basic friction angle	JRC (100)	JCS (100)	Residual friction angle
Set EW	1	32	4	78	27
Set NW	3	32–33	3–7	78–91	28–29
Set NE	2	31–32	7–9	88–117	26–29
Set NS	3	30–34	4–8	60–61	23–27
Set SubH	16	30–34	4–7	34–94	23–30
Random	9	31–35	2–8	43–99	22–31
All fractures	35*	32 (1)**	6 (1)**	73 (17)**	27 (1)**

* This number includes the testing results of one sealed fracture.
**The ranges of variation of the parameters are reported. For all fractures, instead, the average value and the standard deviation of the parameters (between brackets) is listed.

Table 3-4. Mean on friction angle and cohesion for the Coulomb's Criterion of all tests on samples from boreholes KFM01A–KFM04A /SICADA, 2004-07-30/.

	Average	
	Friction angle (°)	Cohesion (MPa)
Peak envelope	34.6	0.67
Residual envelope	30.8	0.49

4 Characterisation of the rock mass along the borehole

According to the methodology for rock mass characterisation for the site investigations /Andersson et al. 2002; Röshoff et al. 2002/, two empirical classification systems should be used for the purpose of determination of the mechanical property of the rock mass: the Rock Mass Rating, RMR, and the Rock Quality Index, Q. These classification systems are applied here for the "characterisation" of the rock mass, in contraposition to their general use for "design" of underground excavations. This implies that constrains due to the shape, orientation, function and safety of a potential excavation are not considered.

4.1 Equations for RMR and Q

The very well known relations for RMR /Bieniawski, 1989/ and Q /Barton, 2002/ are reported here for convenience of the reader. The basic equation for the RMR /Bieniawski, 1989/ is:

$$\begin{aligned} RMR = RMR_{strength} + RMR_{RQD} + RMR_{spacing} + RMR_{conditions} + \\ + RMR_{water} + RMR_{orientation} \end{aligned} \tag{1}$$

where the subscripts strength, RQD, spacing, conditions, water, orientation refer to the strength of the intact rock, to the Rock Quality Designation, to the conditions and spacing of the fracture, to the groundwater conditions and the orientation of the fracture sets with respect to the hypothetical tunnel orientation, respectively. In the source, each rating is provided with a description and a table.

The basic equation for Q /Barton, 2002/ is:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \tag{2}$$

where, besides RQD, Jn depends on the number of fracture sets, Jr and Ja on the roughness and alteration of the fractures, Jw on the groundwater conditions and the Stress Reduction Factor, SRF, takes into account the stresses in the rock mass. Also these parameters are described and tabulated in the source. The parameter Qc can be obtained by multiplying Q by the uniaxial compressive strength of the intact rock divided by 100 MPa. Qc is used for the determination of the deformation modulus Em, cohesive and frictional components CC and FC, respectively.

Table 4-1. Rock mass classification based on RMR and Q.

RMR rating	100–81	80–61	60–41	40–21	20–0
Rock class	I	II	II	IV	V
Classification	Very good	Good	Fair	Poor	Very poor
Q number	> 40	10–40	4–10	1–4	0.1–1
Classification	Very good	Good	Fair	Poor	Very poor

4.2 Partitioning the borehole into rock domains

The "geological single-hole interpretation" /Carlsten et al. 2004/ provides a partitioning of borehole KFM03A into pseudo-homogeneous sections that also applies for the rock mechanics analysis. Four different rock type groups are identified together with five possible deformation zones.

The rock type groups can be shortly described as:

A) Medium-grained metagranite to granodiorite;

B) Medium-grained metatonalite to metagranodiorite;

C) Fine to medium-grained metatonalite;

D) Pegmatitic granite.

For Rock Mechanics purposes, the partitioning according to rock type groups was kept to investigate possible differences in the rock quality. The fractured zones were accurately checked and only the ones that would correspond to considerably reduced rock mass quality were considered as separated objects in the Rock Mechanics analysis. In Table 4-2, the rock units, rock type groups and the decision process for the choice of the parameters of the deformation zones for Rock Mechanics are reported.

The rock mechanics characterisation in this report is performed on borehole/core sections of 5 and 30 m within each rock unit.

Table 4-2. Partitioning of borehole KFM03A: Rock units, rock types and deformation zones /Carlsten et al. 2004/.

Rock unit	Depth (m)	Rock type	Depth (m)	Deformation zones
RU1	100–220	A		
RU2	220–293	B		
RU3	293–349	C		
RU4	349–377	D	356–399	DZ1: Wide fracture aperture and three crushed zones
RU3	377–399	C		
RU1	399–1,001	A	448–455	DZ2: Fractured rock
			638–646	DZ3: Fractured rock
			803–816	DZ4: Fractured rock
			942–949	DZ5: Fractured rock

4.3 Characterisation with RMR

For each 5 and 30 m sections of borehole, the geomechanical parameters from borehole logging were scrutinized (see also Appendix B). The possible minimum, average, most frequent and possible maximum rating for RMR was determined for each borehole section, sometimes through averaging processes. The plots in Figure 4-1 and Figure 4-2 are obtained for the RQD, fracture condition, spacing rating that results into the RMR ranges shown on the right for 5 and 30 m core sections, respectively.

The ratings for tunnel orientation and water pressure were assumed for "fair conditions" and for a "completely dry" borehole, as prescribed for rock mass characterisation.

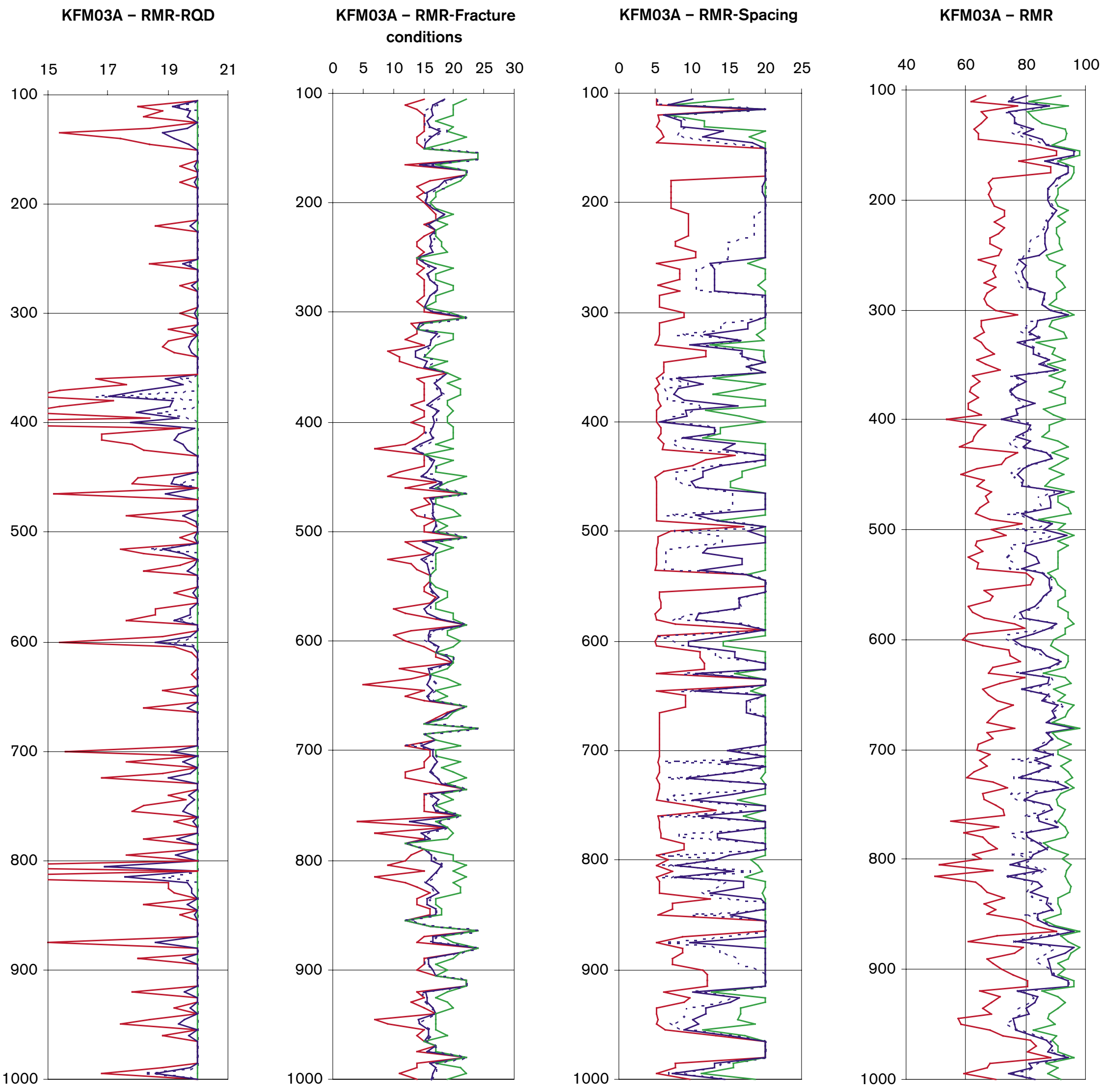

Figure 4-1. *Ratings for RMR characterisation and resulting RMR values for borehole KFM03A. The ratings for RQD, fracture conditions, fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the possible minimum, average, most frequent and possible maximum values observed every core section 5 m long, respectively.*

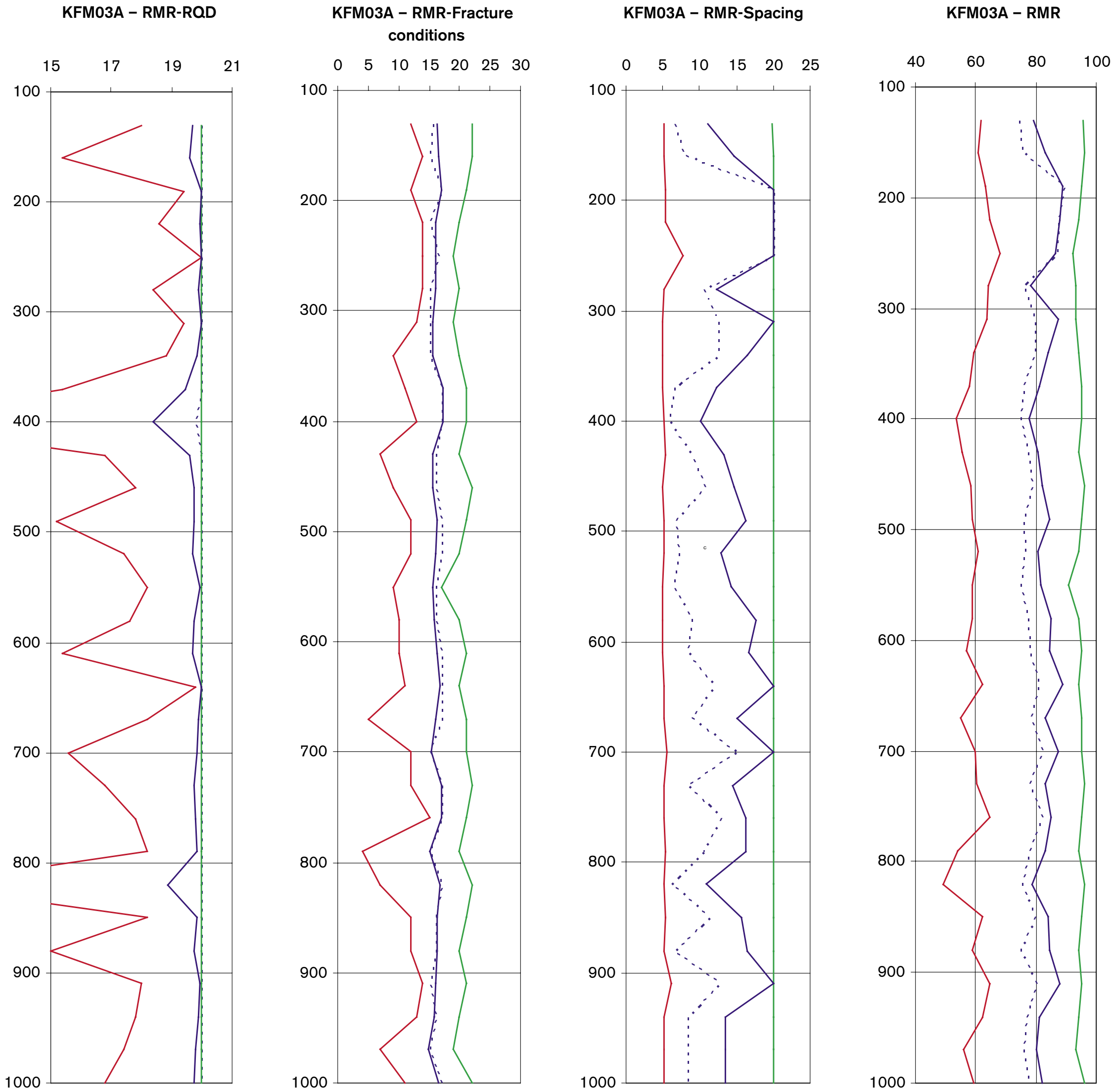

Figure 4-2. RMR and RMR Ratings as a function of depth for borehole KFM03A. Possible minimum, average, most frequent and possible maximum value is plotted in red, blue, dashed blue and green, respectively. Core sections of 30 m are considered.

The RMR values were also summarised for each rock type group, for competent rock, fractures zones and for the whole borehole as shown in Table 4-3. When referring to the rock quality classes in Table 4-1, the rock mass along borehole KFM03A can be described as "very good" along most of its length (lower range of this class). There are not differences in quality between the rock type groups A and C (granite to granodiorite), and B (tonalite). Group D shows a slightly lower rock quality in the upper range of the rock class "good rock".

Table 4-3. Summary of RMR values for borehole KFM03A (core sections of 5 m).

Rock unit	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation
A	72.1	84.5	84.9	96.0	5.4
B	77.5	83.5	85.3	87.3	3.5
C	72.1	82.6	83.1	94.0	5.4
D	74.7	79.1	76.6	91.0	6.1
Competent rock	74.4	85.1	85.4	96.0	5.1
Fractured rock	72.1	78.8	76.7	91.0	5.1
Whole borehole	72.1	84.5	84.9	96.0	5.4

The rock mass according to RMR has different quality at different depth. In detail:

1) "good" rock (RMR about 75) between 100 and 140 m, 240 and 285 m (RU2 in tonalite), 350 and 400 m (RU3, RU4 and DZ2), 920 and 960 m (DZ5), and between 980 and 1,000 m, respectively;
2) "good" rock (RMR about 80) between 400 and 460 m (DZ3) and between 570 and 620 m depth;
3) "very good" rock (RMR about 85) between 150 and 240 m and between 285 and 350 m depth;
4) "very good" rock (RMR about 90) between 460 and 570, 620 and 920, and between 950 and 980 m depth.

The characterisation based on 30 m core sections evens most of the variations of the rock quality along the borehole. The mean RMR results in a rock quality value of 80 except for a few sporadic points where RMR is lower than 80 at about 285, 400, 820 m depth, respectively.

4.4 Characterisation with Q

The input numbers for the Q systems and the resultant rock quality index for 5 m and 30 m are plotted in Figure 4-3 and Figure 4-4, respectively. As for RMR, the Q numbers are obtained through the choice of possible minimum, average, most frequent and possible maximum values of the geomechanical parameters logged along the borehole. The fracture-set, roughness and alteration numbers are also obtained for each borehole section of 5 or 30 m (see also Appendix B). The Q-number quantifying the stress and faulting conditions SRF is assigned to the fractured zones based on consideration about their width, depth, degree of fracturing and alteration, but also based on the ratio between the uniaxial compressive strength of the intact rock and the major rock stress that can be around 50 MPa at 500 m depth /SKB, 2004/. The fractured zones listed in Table 4-2 were assigned a SRF of 2.5. The Q-number that quantify the water conditions was assumed equal to 1 (dry borehole), as it is usually done for rock mass characterisation.

According to the Q system, the rock along borehole KFM03A can be classified as "very good rock" as the average Q is much larger than 100 and the most frequent value is about 40 corresponding to "very good rock". The rock type group A and B show higher quality than the others. The rock in C and D can to be classified as "good rock" even if D has a frequent Q value that is about half the Q value of C. On average, the fractured zones can be classified at the limit between the classes "fair" and "good rock" in the Q system. "Very poor rock" was not observed along the borehole.

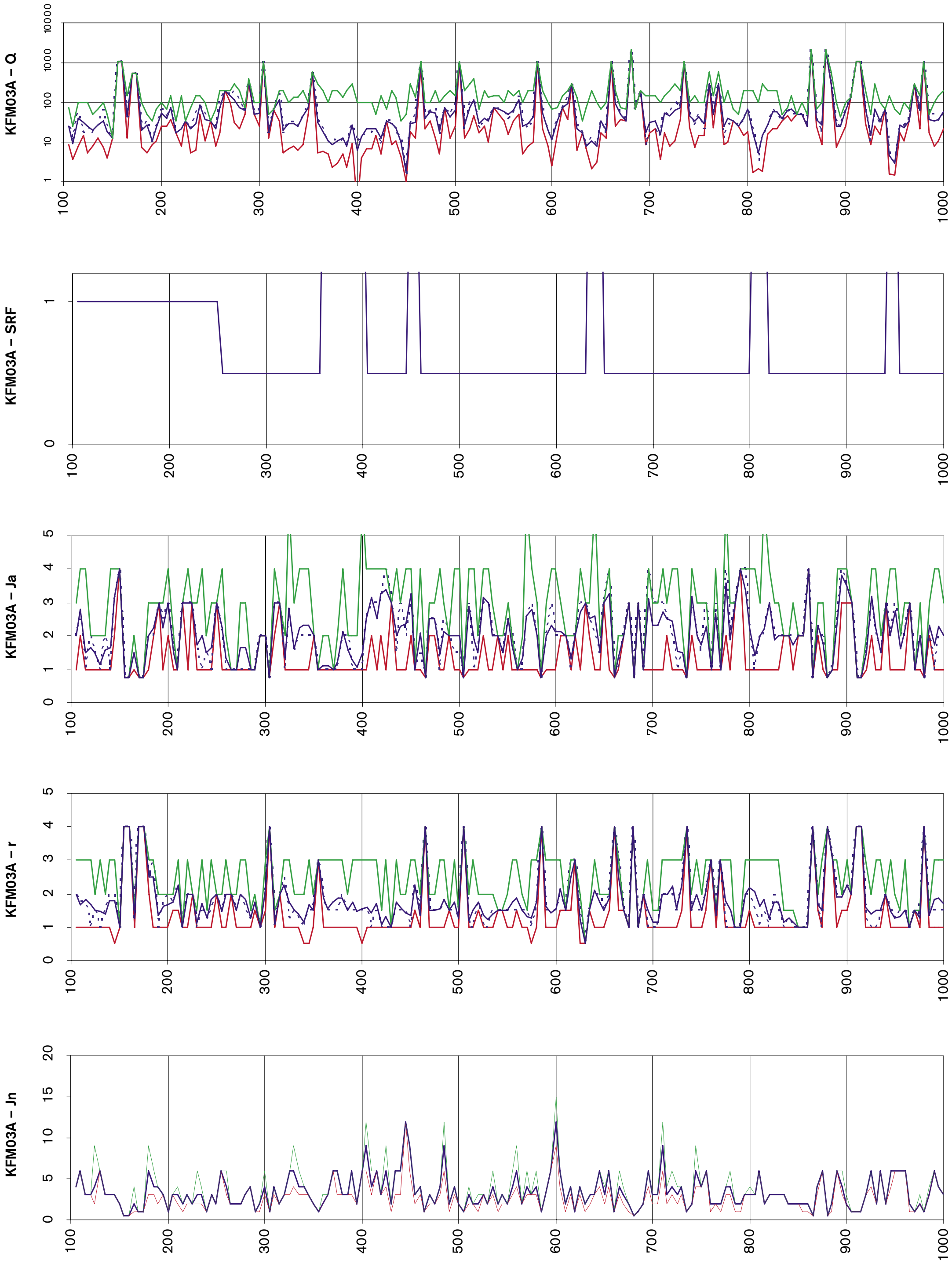

Figure 4-3. *Numbers for Q characterisation and resulting Q values for borehole KFM03A. The number for fracture set number, fracture roughness, fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the possible minimum, average, and most frequent and possible maximum values observed every core section 5 m long, respectively.*

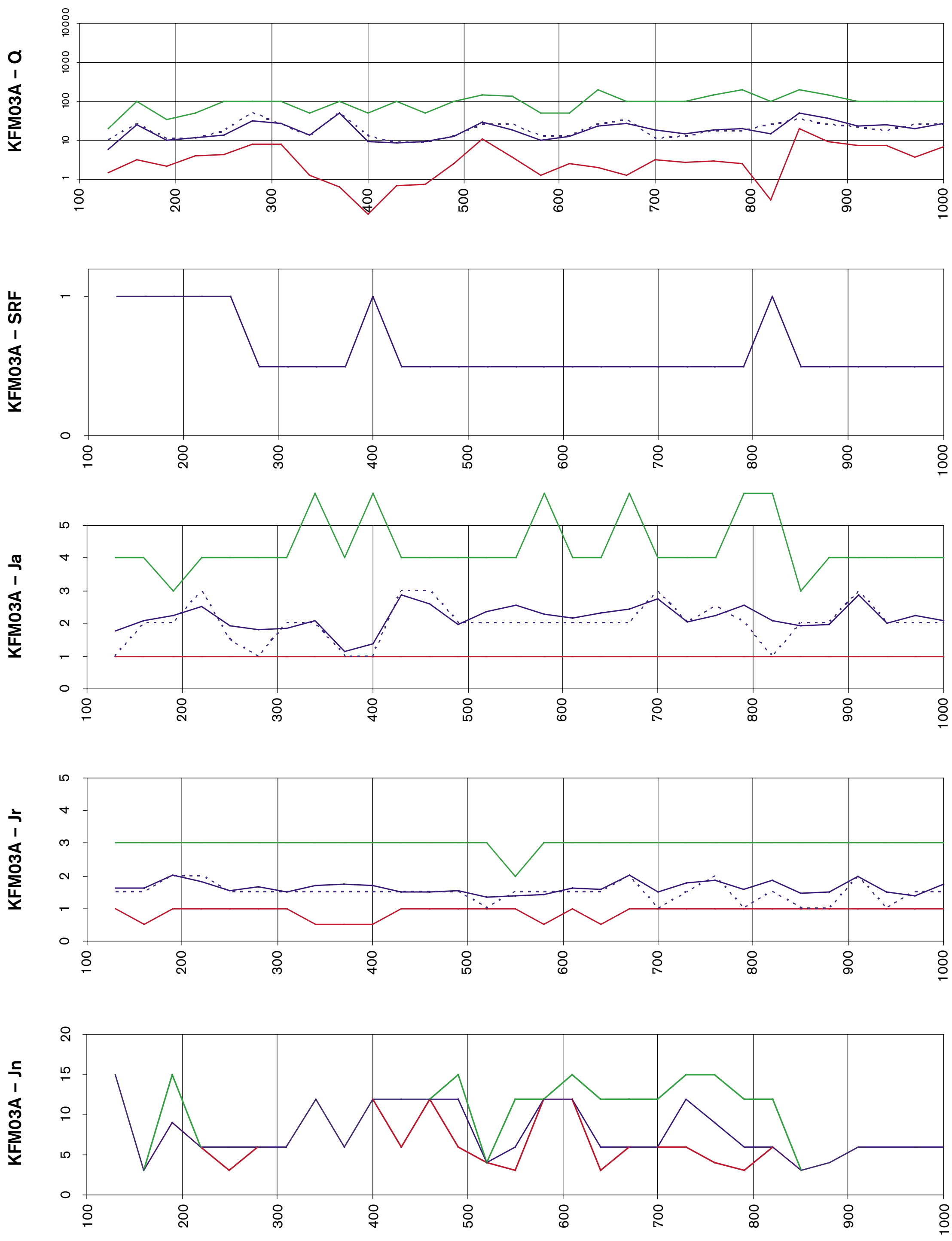

Figure 4-4. *Q and Q numbers as a function of depth for borehole KFM03A. Possible minimum, average, most frequent and possible maximum values is plotted in red, blue, dashed blue and green, respectively. Core lengths of 30 m are considered.*

Table 4-4. Summary of the Q values for borehole KFM03A (core sections of 5 m).

Rock unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q
A	1.8	156.4	37.4	2,133.3
B	21.3	89.2	62.5	350.0
C	6.1	106.5	30.3	1,066.7
D	8.6	113.6	14.8	600.0
Competent rock	1.8	167.8	40.2	2,133.3
Fractured rock	3.0	47.6	10.8	600.0
Whole borehole	1.8	156.4	37.4	2,133.3

More in detail, the rock quality according to Q also varies with depth according to the following classes:

1) "poor" rock (Q between 1 and 4) at 450 m and 950 m;
2) "fair" rock (Q between 4 and 10) between 370 and 400 m, 635 and 645 m and at 810 m depth;
3) "good" rock (Q between 10 and 40) between 100 and 150 m, 180 and 250 m, 330 and 370 m, 400 and 450 m, 695 and 715 m, 775 and 805 m, and between 920 and 945 m;
4) "very good" (Q > 40) on average in the rest of the borehole.

4.5 Evaluation of uncertainties

The empirical classification systems for characterisation of the rock mass are affected by the uncertainties on the geological and rock mechanical data and intrinsic uncertainties due to the structure of the empirical systems themselves. The uncertainty on a single parameter can widely vary depending on the acquisition technique, subjective interpretation or size of the sample population. But uncertainty can also derive from the way the values of the indexes and ratings are combined with each other. Different operators may obtain and combine the ratings and indices in slightly different ways. The value of Q or RMR for a certain section of borehole may result from the combination of the possible ratings that range from a minimum to maximum value in a certain rock mass volume.

In this report, it was decided to correlate the uncertainty on Q and RMR to the range of their possible values derived from the width of the interval between the minimum and maximum occurring value of each index or rating for each core section. The range of the possible minimum and maximum values of RMR and Q is obtained by combining the ratings and indices in the most unfavourable and favourable way, respectively.

The spatial variability of the geological parameters adds more variability to the indices and ratings and this also mirrors onto the uncertainty on the mean value. For removing the spatial variability, the differences between maximum possible and mean value, and minimum possible and mean value are evaluated for each 5 m borehole section and normalised by the mean value. Each obtained value is considered as a sample from a statistical population of variation intervals. The concept of "confidence interval of a population mean" can then be applied to quantify the uncertainty. According to the "Central Limit Theorem" /Peebles, 1993/, the 95% confidence interval $\Delta_{conf\,mean}$ of the mean is obtained as:

$$\Delta_{conf\ mean} = \pm \frac{1.96\,\sigma}{\sqrt{n}} \tag{3}$$

where σ is the standard deviation of the population and n is the number of values of the each sample. In KFM03A, there are on average 18 sections of 5 m within each rock unit in competent rock, and there are around 3 sections of 5 m within each deformation zone. In practice, two confidence intervals are determined by the proposed technique, one related to the maximum value of RMR and Q, and the other related to the minimum value:

$$\begin{aligned} \Delta P_{+conf\ mean} &= \frac{P_{MAX} - P_{MEAN}}{\sqrt{n}} \\ \Delta P_{-conf\ mean} &= \frac{P_{MEAN} - P_{MIN}}{\sqrt{n}} \end{aligned} \tag{4}$$

where P is the rating, either RMR or Q, with its possible maximum and minimum values and mean value, respectively. This technique also applies to the rock mechanical parameters derived from the empirical systems (in Section 3), such as: deformation modulus, Poisson's ratio, uniaxial compressive strength, friction angle and cohesion of the rock mass.

In Table 4-5, the confidence of the mean value is summarised for the competent and fractured rock along borehole KFM03A. The uncertainty on the mean value is larger for the fractured rock (deformation zones) than for the competent rock. This is due to the local variability of the geological feature that can give rise to different interpretations. The confidence is generally higher for RMR than for Q due to the wide range of variation of the Q values for very good rock mass. However, this kind of variations is compatible with the use of Q for design applications.

For borehole sections of 30 m (Table 4-6), the confidence interval of the mean RMR and Q increases about three times with respect to sections of 5 m for the competent rock, and two times for the fractured rock. The largest variations are experienced by the confidence interval of Q. These large values can be explained by the facts that: i) the characterisation results are somewhat scale-dependent; ii) there variability of each geological parameter in a 30 m long borehole section is higher than within a range of 5 m; this imply that iii) the values composing the characterisation results for sections of 30 m in a certain rock unit, in general, might be reduced to one fourth the value for sections of 5 m.

The confidence span of RMR and Q seem to depend on the scale of the determination. The uncertainty spans increase significantly when passing from core section lengths of 5 m to lengths of 30 m. However, RMR is much less sensitive than Q, which experiences confidence intervals about three times larger than for RMR. This can be explained with the fact that Q contains parameters that regard the borehole section as a whole (J_n), thus are more sensitive to scaling. Differently, the ratings of RMR are determined based on singular minimum features observed along the borehole section and do not change when the length of borehole section is increased. Among these uncertainties, the ratings estimated based on expert judgement due to lack of data are also included.

Table 4-5. Confidence on the mean values of RMR and Q for borehole KFM03A and borehole sections of 5 m.

	Competent rock		Fractured rock	
	Lower confidence on the mean	**Upper confidence on the mean**	**Lower confidence on the mean**	**Upper confidence on the mean**
RMR	–4%	+2%	–12%	+10%
Q	–10%	+27%*	–39%*	+936%*

* These values are large because Q can span over several order of magnitude for the same rock mass.

Table 4-6. Confidence on the mean values of RMR and Q for borehole KFM03A and borehole sections of 30 m.

	Competent rock		Fractured rock	
	Lower confidence on the mean	**Upper confidence on the mean**	**Lower confidence on the mean**	**Upper confidence on the mean**
RMR	–13%	+6%	–30%	+19%
Q	–35%	+201%*	–97%*	+319%*

* These values are large because Q can span over several order of magnitude for the same rock mass.

5 Mechanical properties of the rock mass

5.1 Rock mass deformability

The deformability of the rock mass can be quantified by the equivalent continuum parameters: deformation modulus E_m and Poisson's ratio ν_m. These parameters describe the rock mass as an elastic medium.

5.1.1 Deformation modulus of the rock mass

By means of some empirical formulas /Serafim and Pereira, 1983; Barton, 2002/, it is possible to obtain an estimation of the equivalent deformation modulus of the rock mass. In this report, the determination is done for core sections of 5 and 30 m (see also Appendix C). In Figure 5-1, the plots of the possible minimum, average, most probable and possible maximum expected deformation modulus are given. Comparing the mean values obtained independently by means of RMR and Q, a rather good agreement can be observed. Larger discrepancies are found for the depths between 175 and 250 m due to the difference in SRF for characterisation that, from a value of 1.0 above 250 m, becomes 0.5 below 250 m /Barton, 2002/.

In general, Q gives deformation moduli lower and more varying than RMR (Table 5-1). By combining the two results, the mean deformation modulus for the competent rock varies in the range 54–68 GPa, with extreme values between 48 and 75 GPa. The upper cut-off value of the mean deformation modulus of 75 GPa has been applied to reflect the physical limit represented by the deformation modulus of the intact rock. For the fractured rock, the mean deformation modulus should vary between 28 and 52 GPa. The relatively high values are explained by the fact that the fractured zones often concern rock that is relatively good.

Table 5-1. Summary of the deformation modulus Em derived from RMR and Qc for borehole KFM03A (core sections of 5 m).

Rock unit	Mean Em* from RMR (GPa)	Mean Em* from Qc (GPa)
A	66.2	45.4
B	66.8	46.9
C	63.2	42.0
D	51.6	38.4
Competent rock	67.6	46.8
Fractured rock	52.4	31.1
Whole borehole	66.2	45.4

* The average Em has a physical threshold in the Young's modulus of the intact rock, which is 75 GPa.

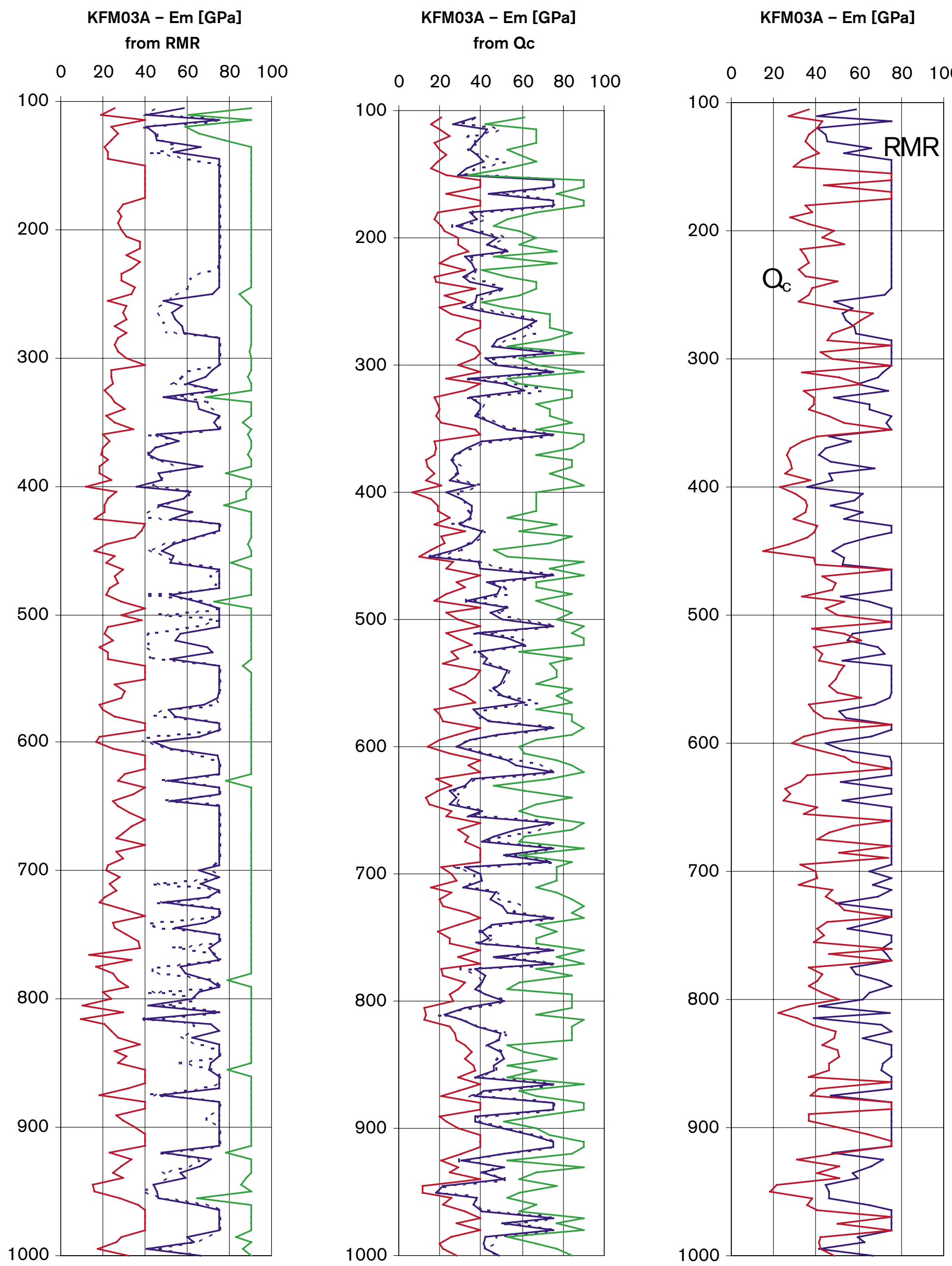

Figure 5-1. *Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m for borehole KFM03A. A comparison of the mean values along the borehole is given in the graph on the right.*

Figure 5-2 and Figure 5-3, the histograms of the deformation modulus of the rock mass obtained by means of RMR and Q are shown for the purpose of comparison. It should be noticed that the application of a cut-off of 75 GPa affects the distribution of Em obtained from RMR. For this reason, Em from RMR exhibits a peak at this value. However, the shapes of the distributions of Em from Q and RMR are rather similar for the rock types A and D. For the rock types B and C, the comparison is performed on a small data set and this affects the shape of the distributions. In fact, when all competent rock, or fractured rock, or the whole borehole, respectively, is considered, the agreement on the shape of the frequency distributions of Em from Q and RMR is much better.

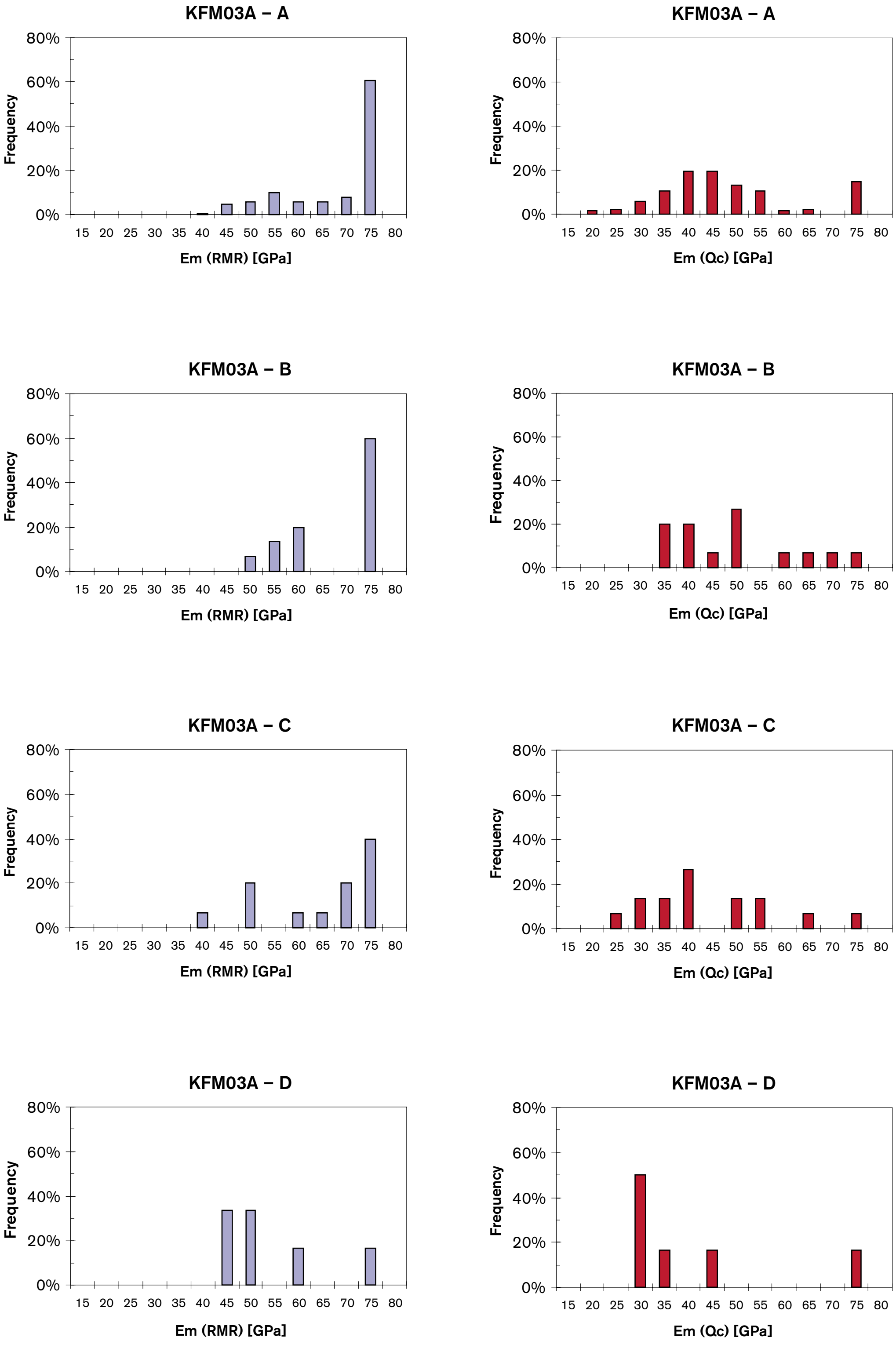

Figure 5-2. *Histograms of the deformation modulus of the rock mass Em derived from RMR and Q (through Qc) (core sections of 5 m) for the four rock type groups in borehole KFM03A. The histograms show the properties of both the competent rock and the deformation zones.*

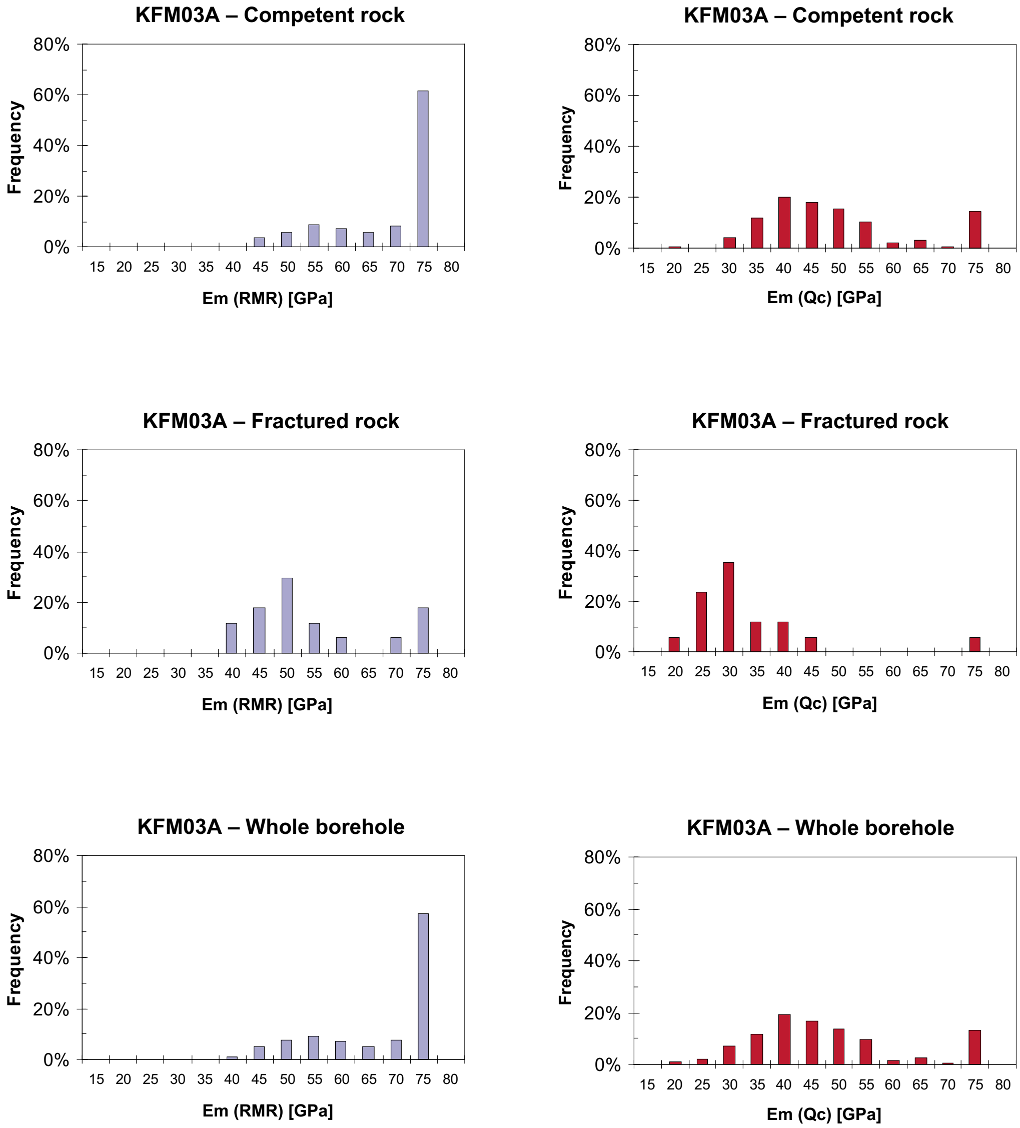

Figure 5-3. *Histograms of the deformation modulus Em derived from RMR and Q (core sections of 5 m) for competent and fractured rock, and for the whole borehole KFM03A, respectively.*

5.1.2 Poisson's ratio of the rock mass

The Poisson's ratio of the rock mass is often determined as a fraction of the Poisson's ratio of the intact rock. This fraction is determined by the ratio between the deformation modulus of the rock mass and that of the intact rock. For borehole KFM03A, the Poisson's ratio of the competent rock can be estimated about 0.19, while that of the fractured rock is around 0.13 (Table 5-2).

Table 5-2. Estimation of the minimum and maximum Poisson's ratio of the rock mass at different depth for borehole KFM03A.

v (–)	Minimum	Maximum
100–200	0.11	0.24
200–400	0.14	0.22
400–1,000	0.12	0.22

5.1.3 Uncertainty

The confidence intervals for the mean deformation modulus calculated from Q_c are almost the same as those calculated from RMR (Table 5-3). Even if the deformation modulus from RMR is generally larger than that from Q_c, the minimum possible deformation modulus obtained from Q_c is approximately as large as that obtained from RMR.

As a consequence of the large confidence interval of RMR and Q_c, the confidence intervals for the deformation modulus are also relatively large. This depends on the fact that the rock mass is composed by four different rock type groups. The results in Table 5-3 apply to the whole borehole and not to each rock type group.

The confidence on the mean value of the Poisson's ration can can be assumed to coincide with that of the deformation modulus because they are directly related by the following equation:

$$\nu_m = \nu \times \frac{E_m}{E} \tag{5}$$

where E and ν are the Young's modulus and the Poisson's ratio of the intact rock, respectively (see Table 3-2).

Table 5-3. Confidence on the mean values of the deformation modulus E_m from RMR and Q_c for borehole KFM03A and borehole sections of 5 m.

Deformation modulus (GPa)	Competent rock		Fractured rock	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
E_m (RMR)	–13%	+8%	–35%	+49%
E_m (Q_c)	–9%	+14%	–22%	+108%

5.2 Rock mass strength

The rock mass strength is quantified by the uniaxial compressive strength, the cohesion and the friction angle of the rock mass. The uniaxial compressive strength represents the strength of the rock mass when no confinement pressure is applied. The friction angle and the cohesion describe the rock mass strength envelope between a certain range of stresses. In this report, friction angle and cohesion are provided for the stress intervals 0–5 MPa and 10–30 MPa. The correspondent parameters FC and CC from Q_c are also reported.

5.2.1 Uniaxial compressive strength of the rock mass

As shown in Table 5-4, the uniaxial compressive $UCS_{m\ (H\ \&\ B)}$ according to the Hoek & Brown's Criterion /Hoek et al. 2002/ strength for the rock mass along KFM03A, obtained from of RMR, agrees with that determined from Q and Q_c. The uniaxial compressive strength of the rock mass should range between 70 and 100 MPa, while that of the fracture zones should vary between 30 and 50 MPa. The variation of the rock mass compressive strength from RMR and Q for the different rock units can be seen in Figure 5-4.

5.2.2 Cohesion and friction angle of the rock mass

In Table 5-5 and Table 5-6, the strength of the rock mass is summarised in terms of cohesion and friction angle for low confinement stress (0–5 MPa). In each table, the values obtained from RMR and Q are compared. As for the deformation modulus, some cut-offs are applied to limit the strength of the rock mass to that of the intact rock.

For low confinement stress, results from RMR give much smaller cohesion and larger friction angle. For the whole borehole, the cohesion should be about 8 MPa and the friction angle 61°. Furthermore, major differences can be seen between the competent and the fractured rock. The high values of the frictional component derive from the fact that the cohesion of the intact rock at low confinement stress (between 0 and 5 MPa) has been assigned as upper boundary.

For high confinement stress, the cohesion of the rock mass varies on average between 20 and 23 MPa. For the same level of stress, the friction angle of the rock mass varies between 46° and 48° for all rock type groups. Fractured rocks have friction angle very close to the average for competent rock (47°).

In Figure 5-5 and Figure 5-6 the variation of the frictional and cohesive parameters from Q and RMR are presented and compared as a function of depth.

Table 5-4. Summary of the uniaxial compressive strength of the rock mass derived from RMR and Q (core sections of 5 m) for borehole KFM03A.

Rock unit	Average mean UCS from RMR (MPa)	Average mean Qc from Q (MPa)
A	65.7	93.4
B	46.2	103.7
C	36.6	82.5
D	52.0	60.5
Competent rock	67.4	99.4
Fractured rock	48.7	36.3
Whole borehole	65.7	93.4

Table 5-5. Summary of the friction angle of the rock mass derived from RMR and Q for borehole KFM03A (core sections of 5 m). Results for low (0–5 MPa) and high (10–30 MPa) confinement stress are shown.

Rock unit	Low confinement (0–5 MPa)		High confinement (10–30 MPa)
	Mean ϕ' (°)	Mean FC (°)	Mean ϕ' (°)
A	61.2	42.3	48.3
B	60.3	44.9	46.0
C	61.3	42.7	48.0
D	61.2	57.3	47.1
Competent rock	61.2	41.5	48.4
Fractured rock	61.2	49.1	47.1
Whole borehole	61.2	42.3	48.3

Table 5-6. Summary of the cohesion of the rock mass derived from RMR and Q for borehole KFM03A (core sections of 5 m). Results for low (0–5 MPa) and high (10–30 MPa) confinement stress are shown.

Rock unit	Low confinement (0–5 MPa)		High confinement (10–30 MPa)
	Mean c' (MPa)	Mean CC (MPa)	Mean c' (MPa)
A	8.4	26.2	23.2
B	6.1	27.0	20.3
C	7.7	24.9	22.5
D	6.4	21.5	21.2
Competent rock	8.6	26.9	23.4
Fractured rock	6.2	19.8	21.0
Whole borehole	8.4	26.2	23.2

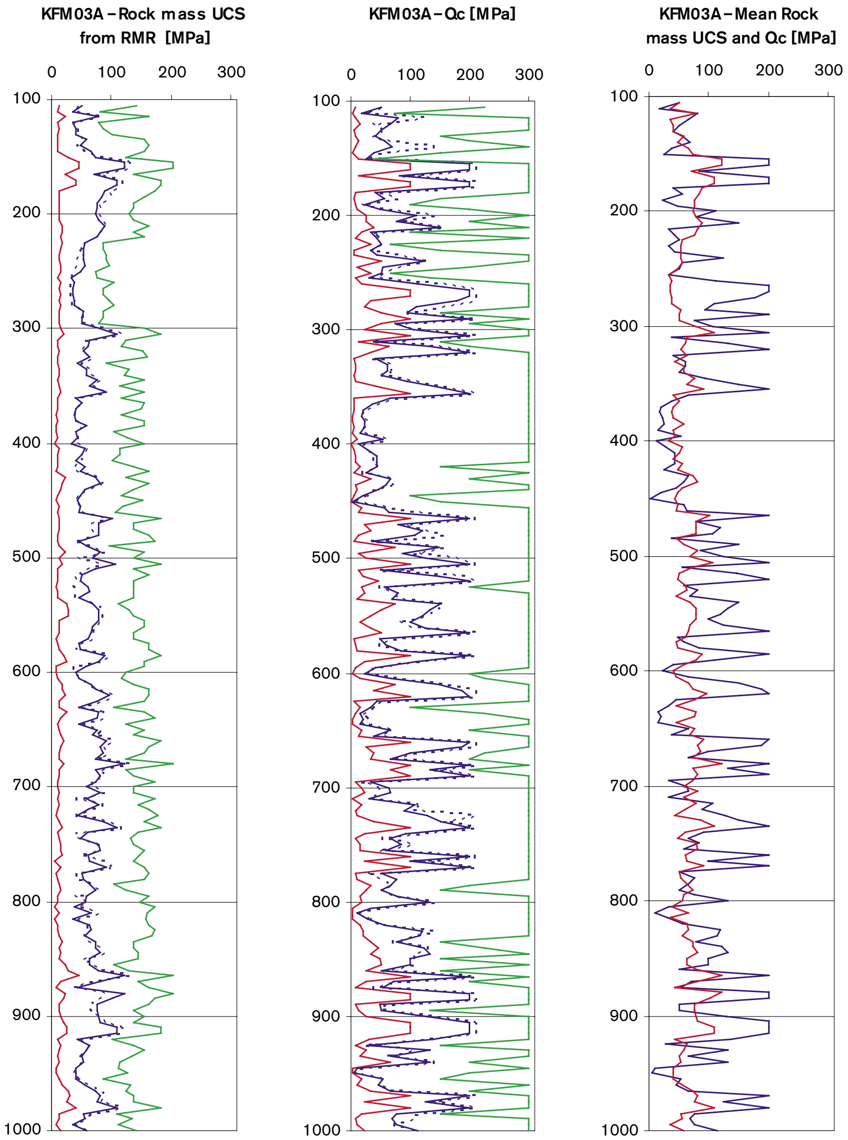

Figure 5-4. Variation of the rock mass compressive strength from RMR and Q for borehole KFM03A.

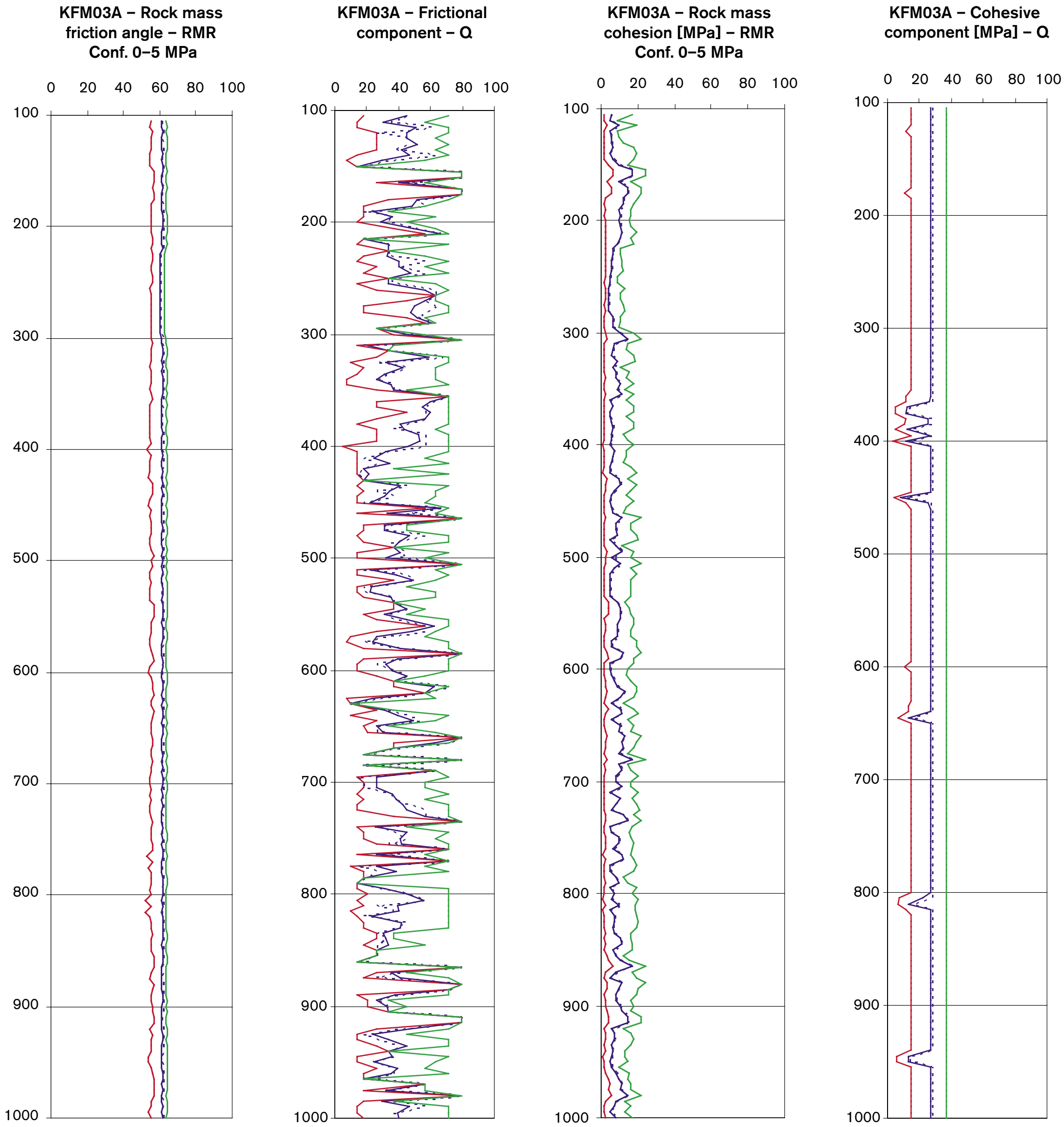

Figure 5-5. *Variation of the rock mass friction angle and cohesion from RMR and Q for borehole KFM03A under stress confinement between 0 and 5 MPa.*

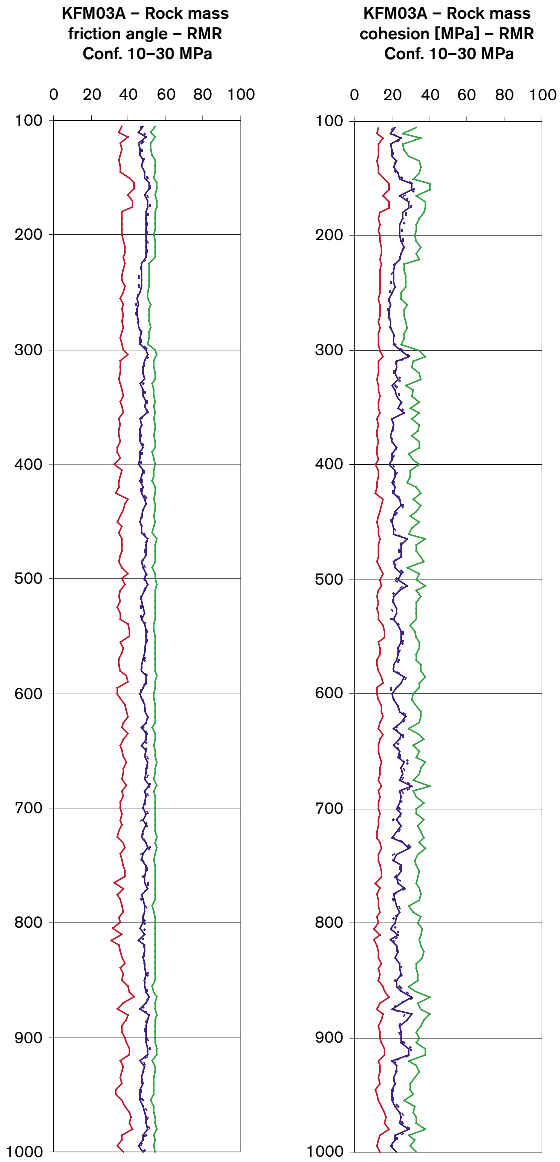

Figure 5-6. *Variation of the rock mass friction angle and cohesion from RMR and Q under stress confinement between 10 and 30 MPa for borehole KFM03A.*

5.2.3 Uncertainty

The confidence on the mean values of the equivalent uniaxial compressive strength $UCS_{m\,(H\&B)}$ of the rock mass, and of the friction angle and cohesion of the rock mass obtained by linear approximation of the Hoek & Brown's failure criterion by the Coulomb criterion are given in Table 5-7. As it can be seen, the confidence interval on the parameters obtained for competent rock is smaller than that obtained for the fractured rock. This is due to the fact that in fractured rock the geomechanical properties may widely change and can be combined in various ways depending on the operator performing the characterisation. The large upper confidence limit for the $UCS_{m\,(H\&B)}$ of the rock mass is due to the fact that very good rock sections tend to have high strength.

Table 5-7. Confidence on the mean values of the equivalent friction angle and cohesion from RMR for borehole KFM02A and borehole sections of 5 m. The uncertainty on the equivalent uniaxial compressive strength $UCS_{m\ (H\&B)}$ obtained by means of the Hoek & Brown's criterion is also listed.

	Competent rock		Fractured rock	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
$UCS_{m\ (H\&B)}$	–18%	+27%	–46%	+128%
ϕ'	–5%	+1%	–15%	+9%
c'	–10%	+10%	–23%	+35%

6 P-wave velocity along the borehole

P-wave velocity measurements were carried out on 68 samples taken from the core of borehole KFM03A at different depths /Chryssanthakis and Tunbridge, 2004/. The measurements were taken along six core diametrical orientation, where the first measurement was taken parallel to the strike of the foliation in the rock. By analysing the tensor of the velocity, the directions of the principal velocity components relatively to the foliation were determined, as well as the anisotropy ratio.

In Figure 6-1, the principal P-wave velocities along the borehole are shown. It can be observed that the velocity has four troughs at about 400, 510, 700 and 800 m depth, respectively. These troughs are often related to the deformation zones or lies in the vicinity of them. Below 500 m the velocity slowly decreases towards the bottom of the borehole but it is generally higher than 4,500 m/s. The difference between the maximum and minimum principal velocity is rather constant along the whole borehole. The anisotropy ratio is in average 1.1 while the maximum P-velocity has an average value of 5,647 m/s.

The absolute orientation of the rock foliation is contained in the BOREMAP data. Thus, the absolute principal velocity orientation can be obtained by combining the information from the two sources. The orientation of the maximum velocity follows the orientation of the foliation rather well.

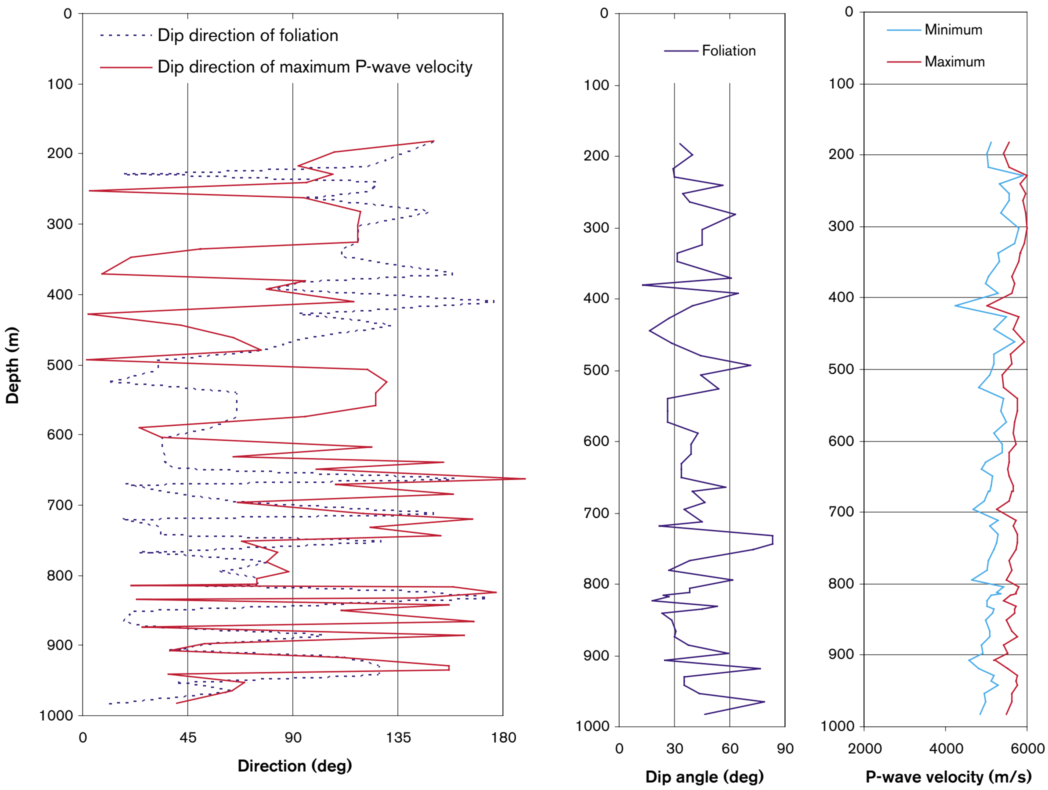

Figure 6-1. *Dip direction of the maximum P-wave compared with the dip direction of the foliation for borehole KFM03A. The dip angle of the foliation and the values of the maximum and minimum P-wave velocities are also shown.*

7 Discussion

Figure 7-1 shows the characterisation results for KFM03A in terms of Q and RMR. The correlation between Q and RMR found in this report is compared with several other empirical relations obtained for the purpose of tunnel design and found in the literature. For the characterisation applied to borehole section lengths of 5 m, the diagram shows a slight overestimation of RMR as a function of Q. This is due to the difference between the approach for characterisation of the rock mass and that for design of underground structures. Moreover, the version of the Q-system adopted here applies favourable SRF factors for charactarisation /Barton, 2002/. This produces higher values of Q than the original Q-system for depth larger than 250 m. Considering that the empirical relations apply on average, however, the characterisation results can be considered satisfactory. The relation between Q and RMR for core section length of 30 m does not agree very well with the relations found in the literature. This is probably due to the small amount of values available and to the different effect of the averaging processes on the Q and RMR results when a longer core section length is considered.

The linear regression of the data shown in Figure 7-1 and Figure 7-2 can be expressed in mathematical terms as:

$$RMR_{(5\,m)} = 2.72 \cdot \ln(Q) + 73.95 \quad (R^2 = 0.431) \tag{6}$$

$$RMR_{(30\,m)} = 0.23 \cdot \ln(Q) + 82.75 \quad (R^2 = 0.002) \tag{7}$$

These relations imply that small values of Q (e.g. 0.1) are associated to moderately high values of RMR (e.g. 62–70).

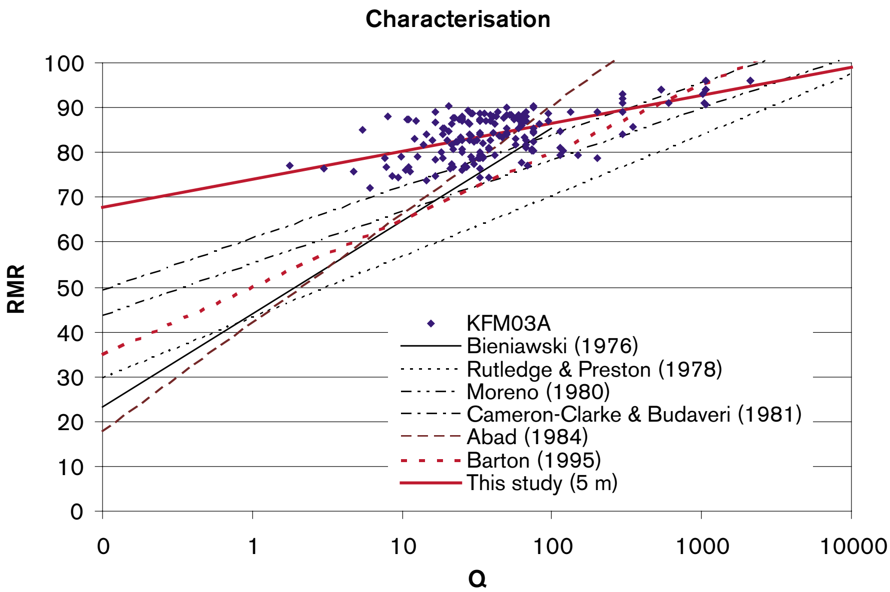

Figure 7-1. Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM03A (core sections of 5 m). The characterisation results are compared with other relations for design from the literature.

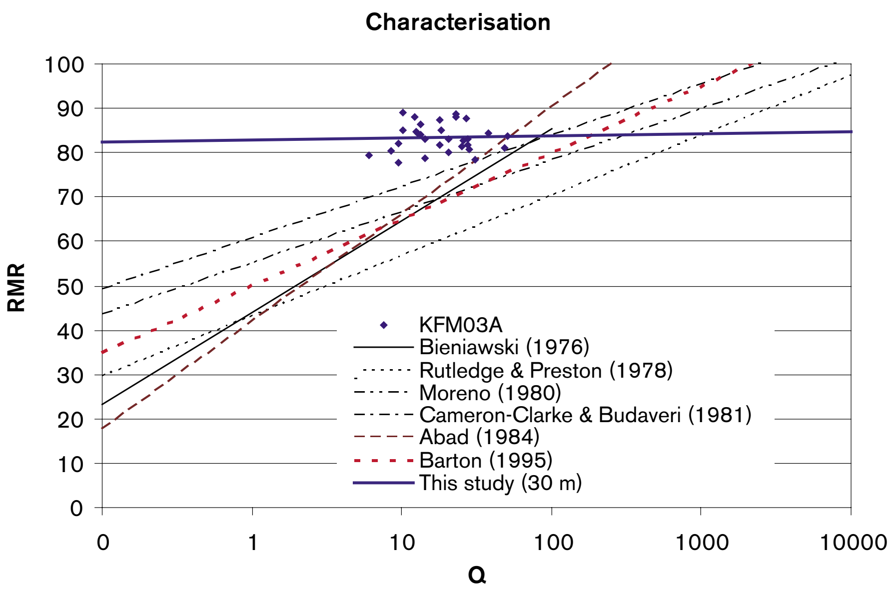

Figure 7-2. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM03A (core sections of 30 m). The characterisation results are compared with relations for design from the literature.*

The effects of the averaging processes when increasing the analysed core section length can be observed in Figure 7-3, where the deformation modulus obtained from RMR and Qc are compared at different scales. The longer the core section length, the smother the profiles. Furthermore, the values from RMR are almost unchanged on average, while the values from Q reduce about 25%. This can be explained by the increase of number of fracture set intercepted by a section of 30 m compared with one of 5 m. This leads to a decrease of the Q parameter that takes into account the number of fracture sets contemporary occurring (J_n), and thus reduction of Q.

The results obtained from the characterisation of the rock mass can be summarized in terms of strength as shown in Figure 7-4. Here, the approximated Hoek & Brown's failure criteria of the rock mass are provided for the "competent rock" and the "fractured rock". The values are given on average for the whole borehole.

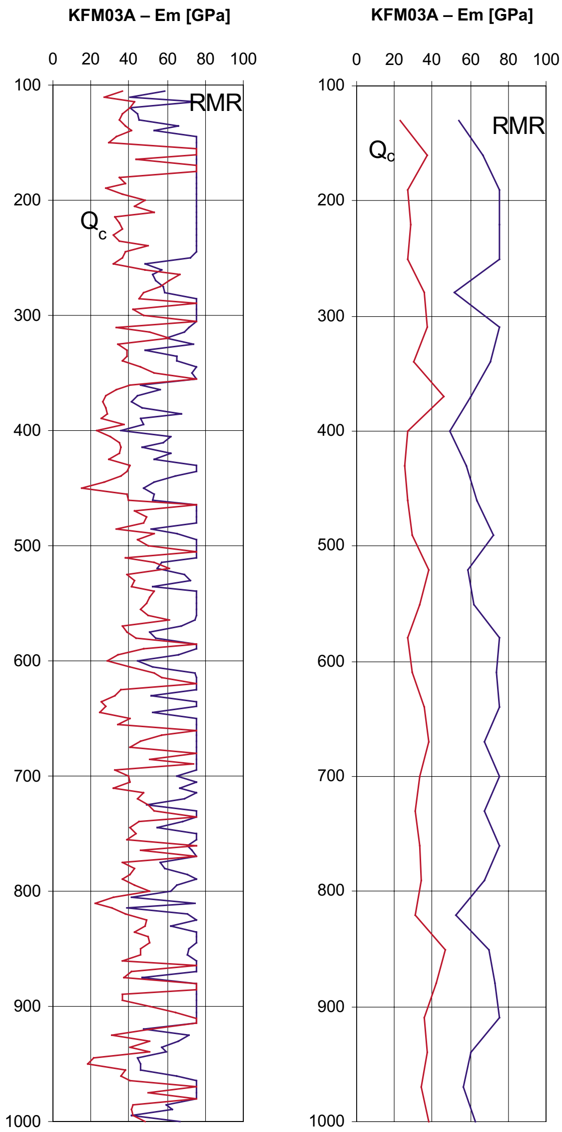

Figure 7-3. *Scale effect on the deformation modulus of the rock mass obtained from RMR and Q.*

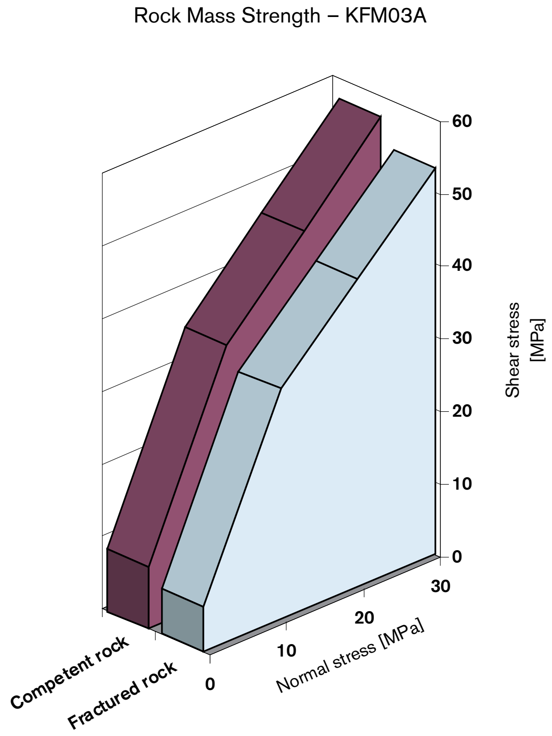

Figure 7-4. *Approximated Hoek & Brown's failure criteria for the "competent rock" and "fractured rock" along borehole KFM03A.*

8 Conclusions

The data provided by the BOREMAP mapping of the core and of the walls of borehole KFM03A are analysed to estimate the mechanical properties of the rock mass. The empirical systems Q and RMR in their latest versions are used for the determination. The determination is carried out for the purpose of "characterisation" of the rock mass, thus all design considerations and recommendations are left outside the scope of this report. This way of performing the characterisation is in line with the methodology for setting up the rock mechanics site descriptive model of the Forsmark site /Andersson et al. 2002/.

The characterisation by means of the Q and RMR system is carried out at two scales: for borehole sections of 5 and 30 m. The analysis of the results indicates that RMR is less sensitive than Q to the change of the scale of investigation. RMR and RMR-derived parameters stay almost the same when applying the method to longer section of borehole/core, while Q and Q-derived properties diminish for longer sections of borehole. For this reason, more credit is given to the parameters derived from the RMR system, which also has a wider range of empirical relations to obtain the mechanical properties of the rock mass (often by means of the Geological Strength Index, GSI /Hoek and Brown, 1998/).

On average, the rock along the borehole is classed as "very good rock" by both the empirical systems, although toward the class of "good rock". In fact, for the competent rock, the average RMR and Q is 84 and 156, respectively. The fractured rock (deformation zones according to the single-hole interpretation) has lower RMR and Q, on average 79 and 48, respectively. It is interesting to notice that the most frequent values of Q are much lower than the mean values. The frequent Q values are 38 and 11 for the competent and fractured rock, respectively. When comparing the rock type groups A, B, C, D, it results that the worse rock quality belongs to the group D of pegmatitic granite.

The mechanical properties of the rock mass were also determined based on the rock mass quality and the properties of the intact rock. The deformation modulus of the rock mass varies between 15 and 75 GPa, with an average of 66 GPa (Q gives low values). The fractured rock has deformation modulus 20–30% lower than the competent rock. The Poisson's ratio is estimated around 0.20.

The equivalent uniaxial compressive strength of the rock mass obtained by means of the relation RMR-GSI-Hoek & Brown's Criterion is around 67 MPa for the competent rock and 49 MPa for the fractured rock, respectively. The strength is highest for the rock type A, and lowest for group B and C. For a confinement stress of about 10–30 MPa, the equivalent friction angle is estimated between 47° and 48°, while the equivalent cohesion between 21 and 23 MPa, where the lower values apply to the fractured rock.

The evaluation of the uncertainty on the rock quality determination by means of Q and RMR is also attained by studying the influence of the maximum and minimum possible values of all the ratings and numbers involved in the characterisation. Besides, the uncertainty of the determination of the mechanical properties of the rock mass was calculated. For all cases, the uncertainty is given as the range of variation of the mean value. The uncertainty is usually larger for the fractured rock than for the competent rock. For example, the uncertainty on the mean value of the deformation modulus of the competent rock ranges between –32% and +16%, while that on the friction angle ranges between –13% and +6%.

The P-wave velocity was also measured in 68 positions on the borehole core. The velocity is rather high (about 5,700 m/s) and has an anisotropy ratio of 1.1 on average. The orientation of the maximum velocity seems to follow the orientation of the foliation and lineation in the rock quite well.

The results obtained in this report are formatted in a suitable way and sent to SICADA for storage after quality control.

9 Data delivery to SICADA

The results of the rock mass characterisation are delivered to SKB's database SICADA. The characterisation of the rock mass by means of the RMR and Q systems for rock mechanics purposes is assigned to the activity group "Rock Mechanics". For each borehole, data are given for the pseudo-homogenous sections (rock units) of drill-core/borehole and the deformation zones identified by the geological "single-hole" interpretation. For each rock unit or deformation zone, six values of RMR and Q resulting from the characterisation are delivered to the database: the minimum RMR and Q, average RMR/most frequent Q, and the maximum RMR and Q, respectively. Among the rock mechanics properties, the uniaxial compressive strength of the intact rock (UCS) and the deformation modulus (E_m) of the rock mass are also delivered to SICADA. For the deformation modulus, two sets of values are given for each rock unit and deformation zone, one value obtained by means of RMR and one for Q, respectively, each of which consisting of minimum, average and maximum deformation modulus of the rock mass. Before storage into the database, quality assessment routines are performed on the methods and on the delivered data.

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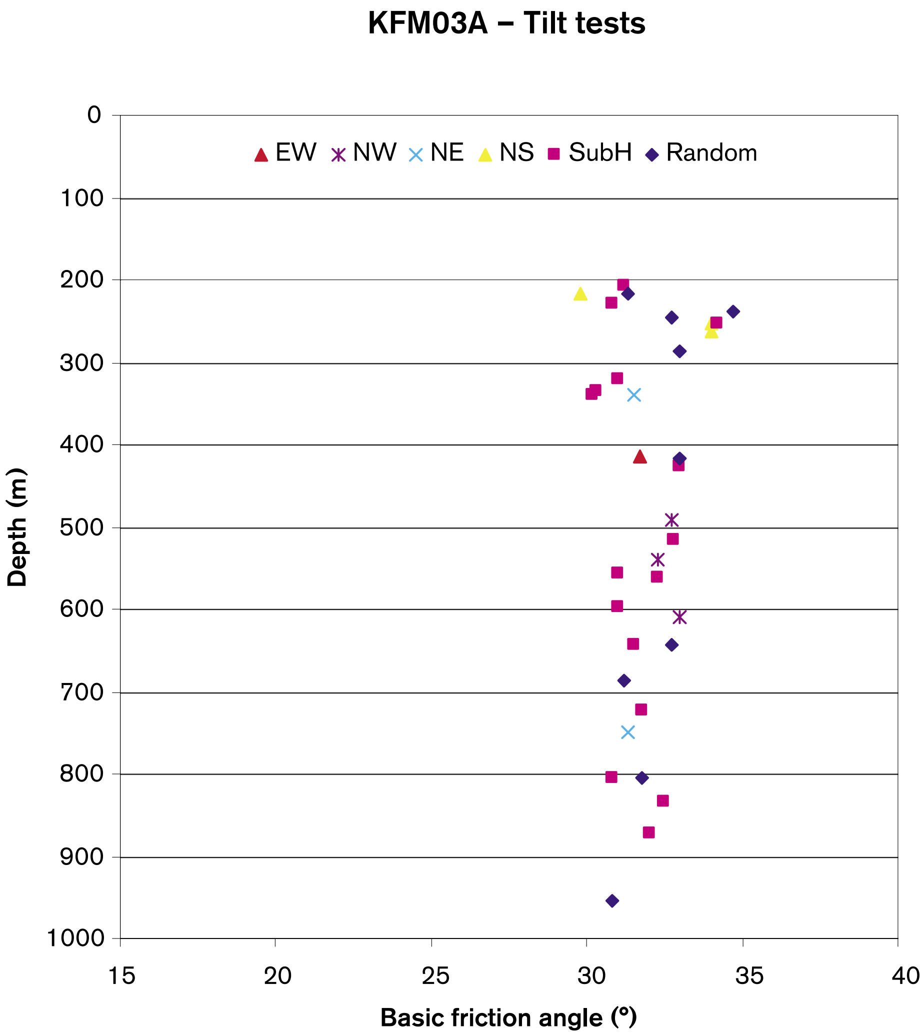
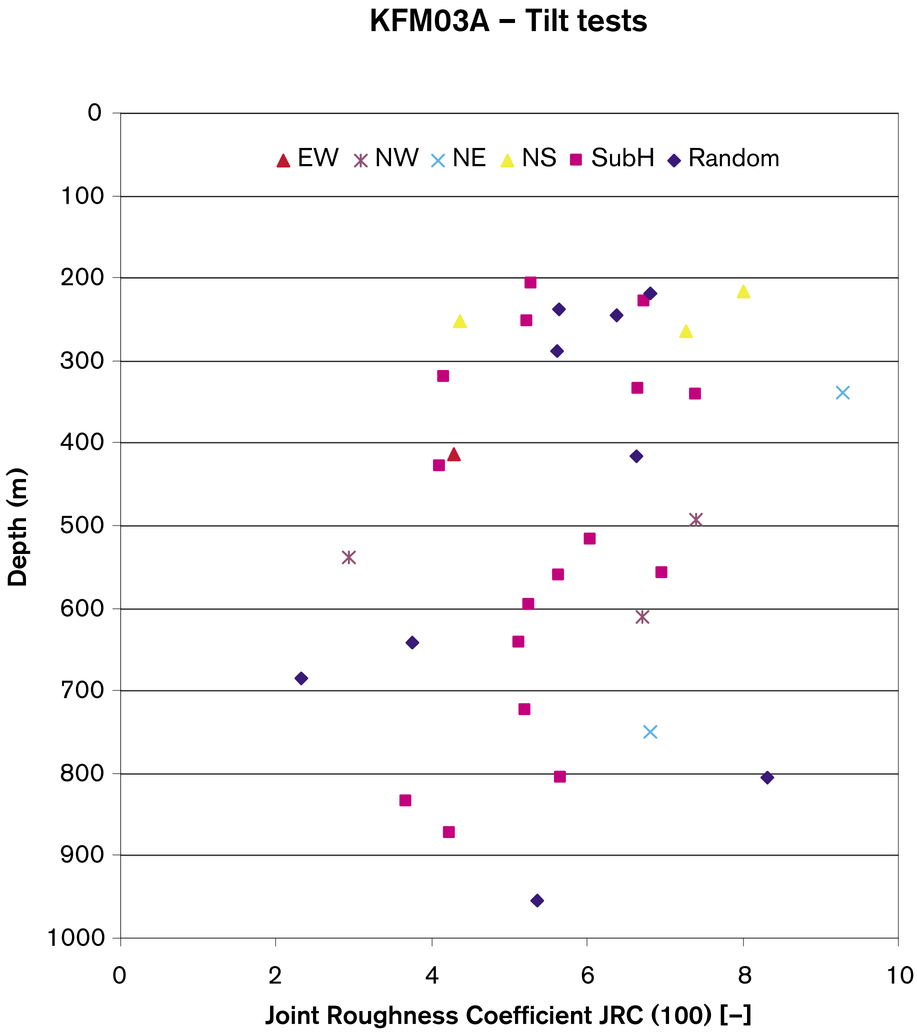
Appendix A

Rock fracture properties

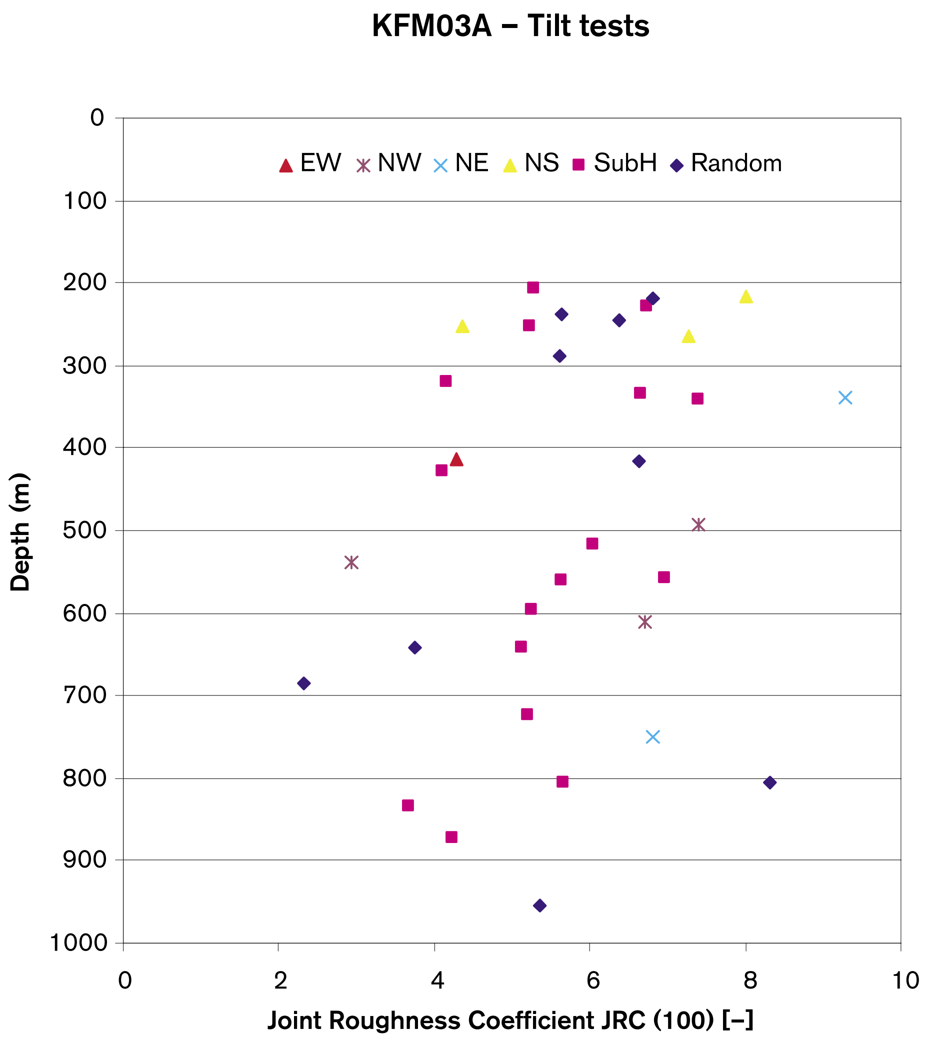
A.1 Tilt test results



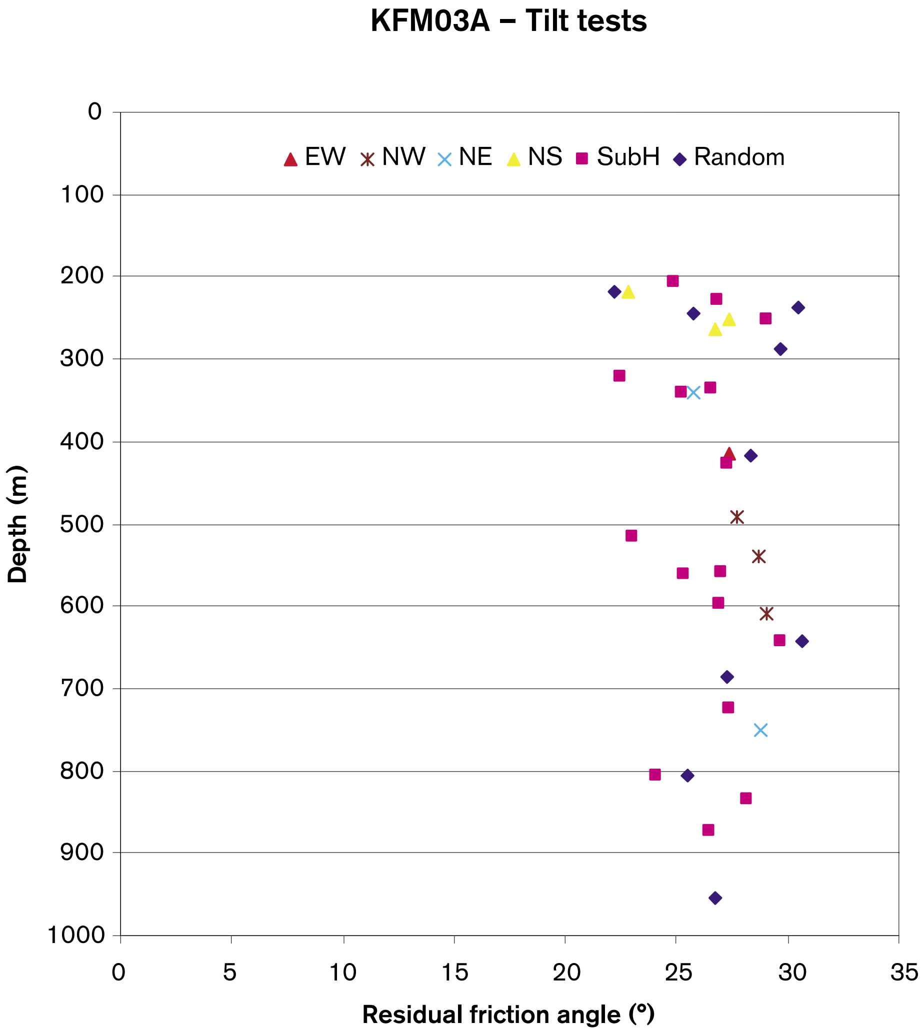
Variation of the basic friction angle of the tested fractures from KFM03A.



Variation of the Joint Roughness Coefficient JRC of the tested fractures from KFM03A.

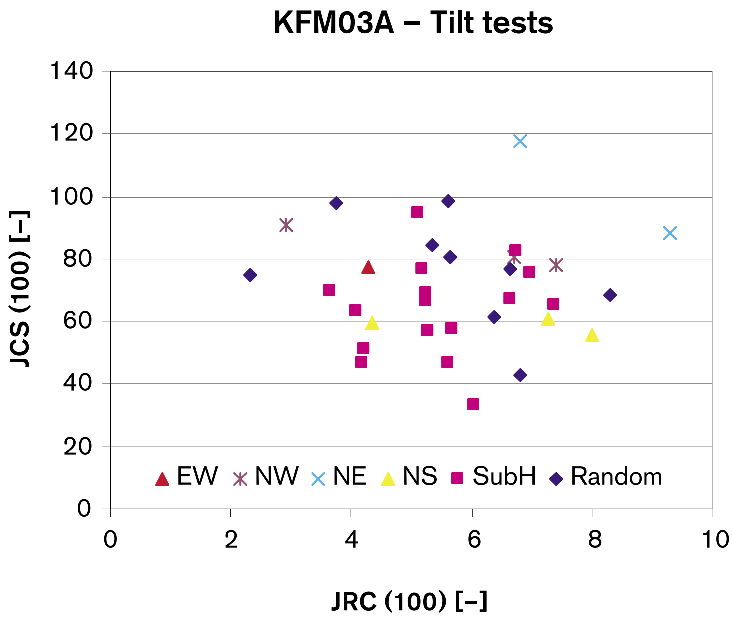


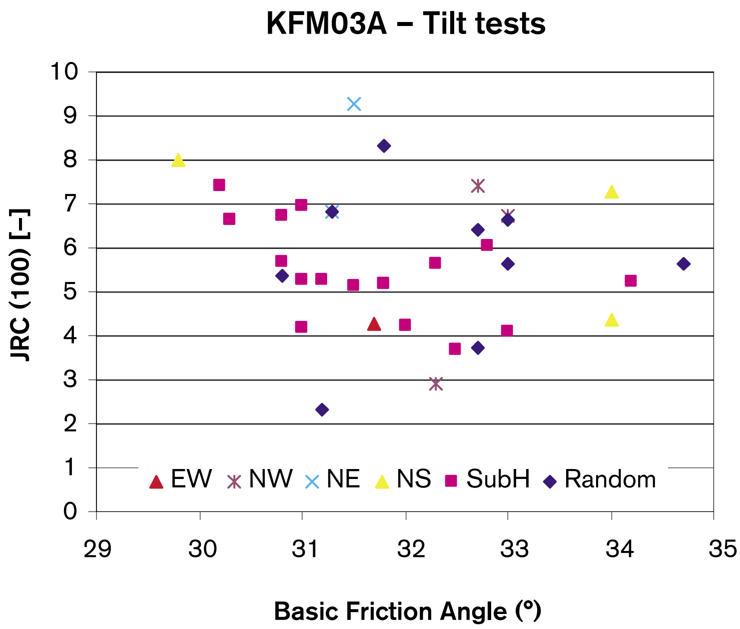
Variation of the Joint Compressive Strength JCS of the tested fractures from KFM03A.

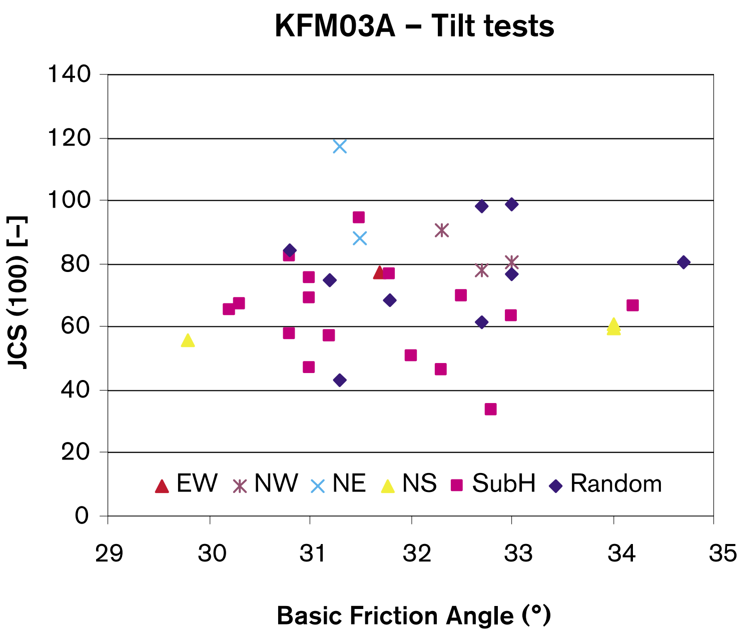


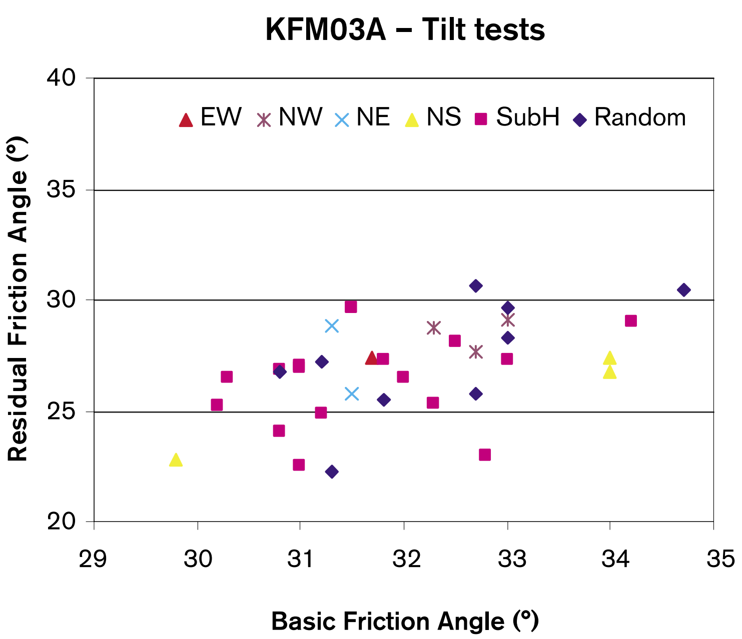
Variation of the residual friction angle of the tested fractures from KFM03A.

A.2 Correlations






KFM03A – Tilt tests
JCS (100) [–]
Basic Friction Angle (°)
EW
NW
NE
NS
SubH
Random
0
20
40
60
80
100
120
140
29
30
31
32
33
34
35


KFM03A – Tilt tests
Residual Friction Angle (°)
Basic Friction Angle (°)
EW
NW
NE
NS
SubH
Random
20
25
30
35
40
29
30
31
32
33
34
35

Appendix B

Characterisation of the rock mass

B.1 RMR

B.1.1 RMR values along borehole KFM03A (core sections of 5 m)

Depth (m)	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Possible min RMR	Possible max RMR
100–220	74.4	86.2	87.4	96.0	6.4	61.6	98.0
220–295	77.5	83.5	85.3	87.3	3.5	64.1	93.1
295–350	77.4	84.6	84.2	94.0	4.3	62.9	96.0
350–355	91.0	91.0	91.0	91.0	0	71.6	93.0
355–380	74.7	76.8	76.5	79.9	1.9	61.3	93.0
380–400	72.1	77.2	76.9	83.1	4.5	53.4	93.0
400–450	76.7	81.4	81.1	88.8	3.9	57.7	94.0
450–455	79.1	79.1	79.1	79.1	0	66.4	88.3
455–635	75.8	84.9	85.7	93.9	4.7	58.9	96.0
635–645	78.7	83.1	83.1	87.5	6.3	65.5	95.0
645–805	74.6	85.8	86.9	96.0	4.6	51.2	98.0
805–815	73.6	79.3	79.3	85.0	8.0	49.8	93.6
815–940	76.9	86.7	87.2	96.0	5.3	60.7	98.0
940–950	75.9	76.2	76.2	76.5	0.5	57.3	89.7
950–1,000	74.5	83.7	82.7	94.0	5.8	59.4	96.0

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM03A.

B.1.2 Summary of RMR values for borehole KFM03A (core sections of 5 m)

Rock unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Possible min RMR	Possible max RMR
A	72.1	84.5	84.9	96.0	5.4	49.8	98.0
B	77.5	83.5	85.3	87.3	3.5	64.1	93.1
C	72.1	82.6	83.1	94.0	5.4	53.4	96.0
D	74.7	79.1	76.6	91.0	6.1	61.3	93.0
Competent rock	74.4	85.1	85.4	96.0	5.1	51.2	98.0
Fractured rock	72.1	78.8	76.7	91.0	5.1	49.8	95.0
Whole borehole	72.1	84.5	84.9	96.0	5.4	49.8	98.0

B.1.3 Summary of RMR values for borehole KFM03A (core sections of 30 m)

Rock unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Possible min RMR	Possible max RMR
A	78.7	83.6	83.2	88.9	3.0	49.2	96.0
B	78.4	82.4	82.4	86.4	5.6	64.1	93.1
C	77.7	83.0	83.9	87.6	5.0	53.4	95.0
D	81.2	81.2	81.2	81.2	0	57.9	95.0
Competent rock	78.4	84.3	84.3	88.9	3.0	54.1	96.0
Fractured rock	77.7	80.5	80.5	83.1	1.9	49.2	96.0
Whole borehole	77.7	83.4	83.2	88.9	3.2	49.2	96.0

B.2 Q

B.2.1 Q values along borehole KFM03A (core sections of 5 m)

Depth (m)	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Possible min Q	Possible max Q
100–220	9.4	157.5	27.9	1,066.7	3.8	1,066.7
220–295	21.3	89.2	62.5	350.0	5.6	400.0
295–350	18.8	140.5	47.6	1,066.7	5.3	1,066.7
350–355	600.0	600.0	600.0	600.0	600.0	600.0
355–380	8.6	16.3	11.1	32.7	2.4	300.0
380–400	6.1	13.1	10.0	26.3	0.2	300.0
400–450	1.8	18.9	21.6	33.3	1.0	200.0
450–455	28.7	28.7	28.7	28.7	17.8	300.0
455–635	8.0	138.8	51.7	1,066.7	2.6	1,066.7
635–645	7.7	9.2	9.2	10.8	2.2	200.0
645–805	16.0	191.3	43.6	2,133.3	1.8	2,133.3
805–815	5.5	10.1	10.1	14.7	1.9	300.0
815–940	14.6	307.9	59.7	2,133.3	7.5	2,133.3
940–950	3.0	3.9	3.9	4.8	1.5	150.0
950–1,000	23.3	168.0	38.1	1,066.7	7.8	1,066.7

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM03A.

B.2.2 Summary of Q values for borehole KFM03A (core sections of 5 m)

Rock unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Possible min Q	Possible max Q
A	1.8	156.4	37.4	2,133.3	0.2	2,133.3
B	21.3	89.2	62.5	350.0	5.6	400.0
C	6.1	106.5	30.3	1,066.7	0.2	1,066.7
D	8.6	113.6	14.8	600.0	2.4	600.0
Competent rock	1.8	167.8	40.2	2,133.3	1.0	2,133.3
Fractured rock	3.0	47.6	10.8	600.0	0.2	600.0
Whole borehole	1.8	156.4	37.4	2,133.3	0.2	2,133.3

B.2.3 Summary of Q values for borehole KFM03A (core section of 30 m)

Rock unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Standard deviation	Possible Min Q	Possible Max Q
A	6.0	19.8	18.1	50.7	10.2	0.3	200.0
B	13.4	22.1	22.1	30.7	12.2	4.2	100.0
C	9.5	16.6	13.5	26.8	9.0	0.1	100.0
D	48.6	48.6	48.6	48.6	0	0.6	100.0
Competent rock	6.0	20.8	18.3	50.7	10.2	1.2	200.0
Fractured rock	8.5	19.8	14.3	48.6	14.5	0.1	100.0
Whole borehole	6.0	20.6	18.1	50.7	11.1	0.1	200.0

Appendix C

Rock mass properties

C.1 Deformation modulus

C.1.1 RMR

Deformation modulus Em derived from RMR along for borehole KFM03A (core sections of 5 m).

Rock units	Depth (m)	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation Em (GPa)	Possible min Em (GPa)	Possible max Em (GPa)
A	100–220	40.8	67.7	75.0	75.0	12.6	19.5	90.0
B	220–295	48.8	66.8	75.0	75.0	10.3	22.6	90.0
C	295–350	48.5	68.2	71.6	75.0	8.3	21.0	90.0
D	350–355	75.0	75.0	75.0	75.0	0	34.7	90.0
D	355–380	41.4	47.0	46.0	56.0	5.4	19.1	90.0
C	380–400	35.7	49.2	47.0	67.3	13.2	12.2	90.0
A	400–450	46.4	59.7	60.0	75.0	10.0	15.6	90.0
A	450–455	53.3	53.3	53.3	53.3	0	25.7	90.0
A	455–635	44.2	67.6	75.0	75.0	10.3	16.7	90.0
A	635–645	52.2	63.6	63.6	75.0	16.1	24.4	90.0
A	645–805	41.3	69.4	75.0	75.0	8.7	10.7	90.0
A	805–815	39.0	56.9	56,9	74.9	25.4	9.9	90.0
A	815–940	47.0	69.9	75.0	75.0	8.6	18.6	90.0
A	940–950	44.3	45.1	45.1	46.0	1.2	15.2	90.0
A	950–1,000	41.0	64.1	65.6	75.0	12.2	17.2	90.0

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM03A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from RMR for borehole KFM03A (core sections of 5 m).

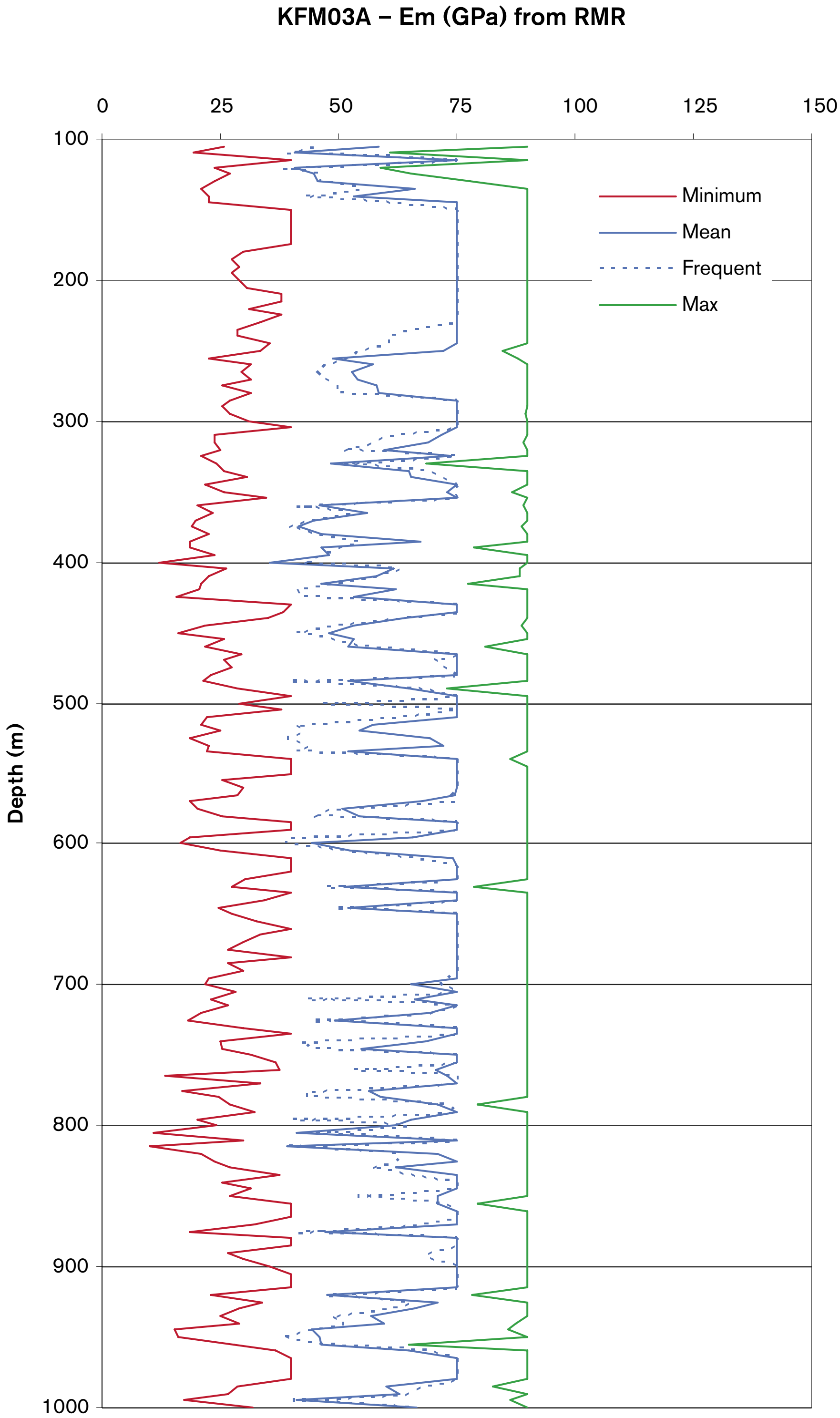
Rock unit	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation Em (GPa)	Possible min Em (GPa)	Possible max Em (GPa)
A	35.7	66.2	74.4	75.0	11.4	9.9	90.0
B	48.8	66.8	75.0	75.0	10.3	22.6	90.0
C	35.7	63.2	67.3	75.0	12.7	12.2	90.0
D	41.4	51.6	46.3	75.0	12.4	19.1	90.0
Competent rock	40.8	67.6	75.0	75.0	10.2	10.7	90.0
Fractured rock	35.7	52.4	46.5	75.0	12.9	9.9	90.0
Whole borehole	35.7	66.2	74.4	75.0	11.4	9.9	90.0

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from RMR for borehole KFM03A (core sections of 30 m).

Rock unit	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation	Possible min Em (GPa)	Possible max Em (GPa)
A	52.1	67.1	67.5	75.0	7.6	9.6	90.0
B	51.4	63.2	63.2	75.0	16.7	22.6	90.0
C	49.2	64.8	70.4	75.0	13.8	12.2	90.0
D	60.2	60.2	60.2	60.2	0	15.8	90.0
Competent rock	51.4	68.9	72.2	75.0	7.4	12.7	90.0
Fractured rock	49.2	58.0	57.8	67.4	6.3	9.6	90.0
Whole borehole	49.2	66.4	67.5	75.0	8.4	9.6	90.0

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.



Variation of the deformation modulus of the rock mass obtained from RMR with depth for borehole KFM03A. The values are given every 5 m.

C.1.2 Q

Deformation modulus Em derived from Q along borehole KFM03A (core sections of 5 m).

Rock unit	Depth (m)	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation Em (GPa)	Possible min Em (GPa)	Possible max Em (GPa)
A	100–220	26.6	43.9	38.2	75.0	15.4	15.5	90.0
B	220–295	31.7	46.9	45.4	75.0	13.1	17.7	90.0
C	295–350	33.5	46.9	45.7	75.0	12.6	17.4	90.0
D	350–355	75.0	75.0	75.0	75.0	0	40.0	90.0
D	355–380	25.8	31.0	28.1	40.3	5.9	13.4	90.0
C	380–400	23.0	28.6	27.0	37.5	6.4	6.3	90.0
A	400–450	15.2	32.3	35.1	40.5	7.3	10.0	84.3
A	450–455	38.6	38.6	38.6	38.6	0	26.1	90.0
A	455–635	25.2	47.8	46.9	75.0	12.9	13.7	90.0
A	635–645	24.9	26.3	26.3	27.8	2.1	13.0	84.3
A	645–805	31.7	48.6	44.3	75.0	14.1	12.1	90.0
A	805–815	22.2	26.5	26.5	30.9	6.1	12.3	90.0
A	815–940	30.8	51.1	49.2	75.0	14.0	19.6	90.0
A	940–950	18.2	19.7	19.7	21.2	2.2	11.3	76.6
A	950–1,000	36.0	48.9	42.4	75.0	14.4	19.9	90.0

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM02A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from Q for borehole KFM03A (core sections of 5 m).

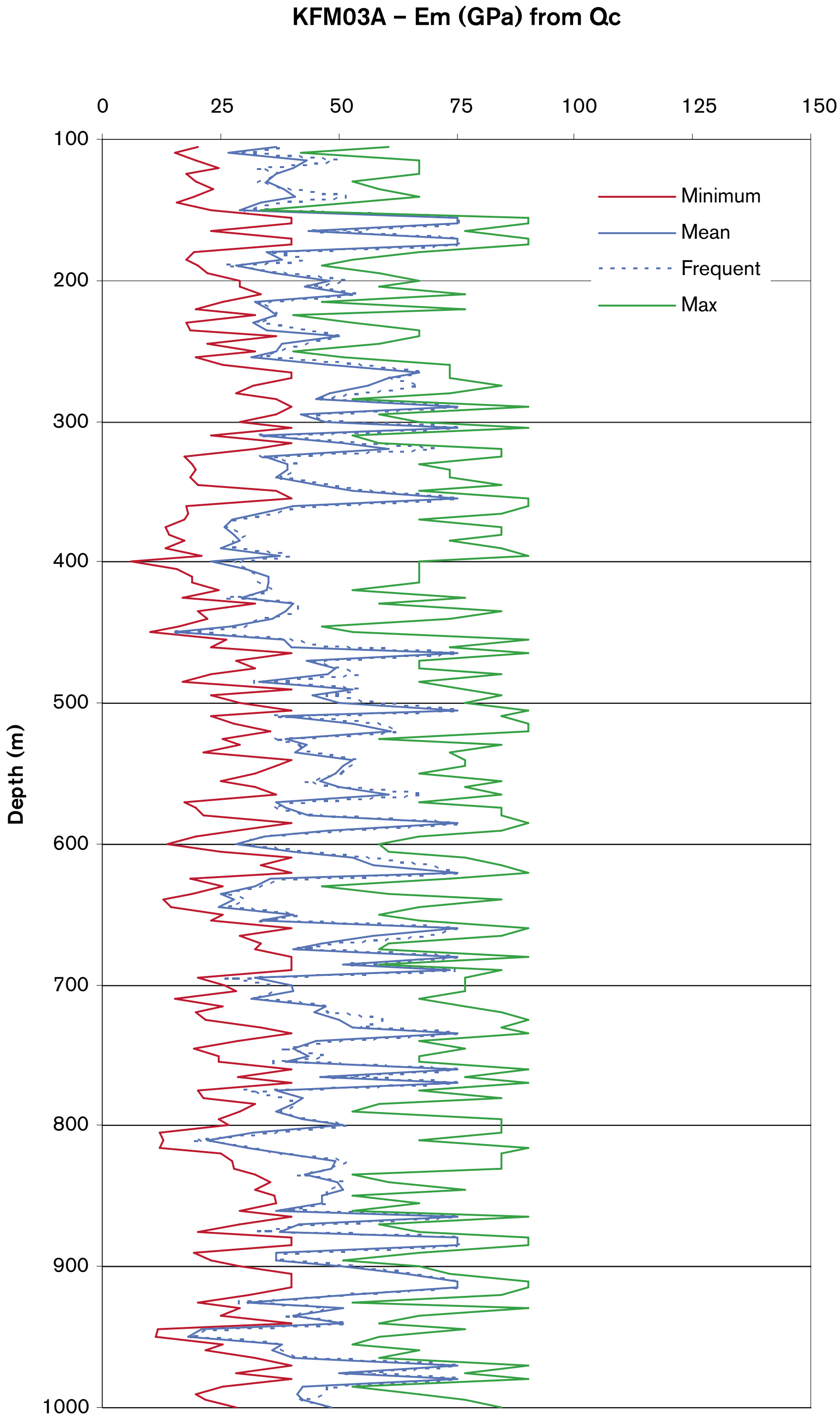
Rock unit	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation Em (GPa)	Possible min Em (GPa)	Possible max Em (GPa)
A	15.2	45.4	41.8	75.0	14.6	6.3	90.0
B	31.7	46.9	45.4	75.0	13.1	17.7	90.0
C	23.0	42.0	39.3	75.0	13.9	6.3	90.0
D	25.8	38.4	30.7	75.0	18.7	13.4	90.0
Competent rock	15.2	46.8	43.1	75.0	13.9	10.0	90.0
Fractured rock	18.2	31.1	27.8	75.0	12.9	6.3	90.0
Whole borehole	15.2	45.4	41.8	75.0	14.6	6.3	90.0

The shading in yellow indicates the location of the potential deformation zones identified in borehole KFM02A. The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.

Summary of the deformation modulus Em derived from Q for borehole KFM03A (core sections of 30 m).

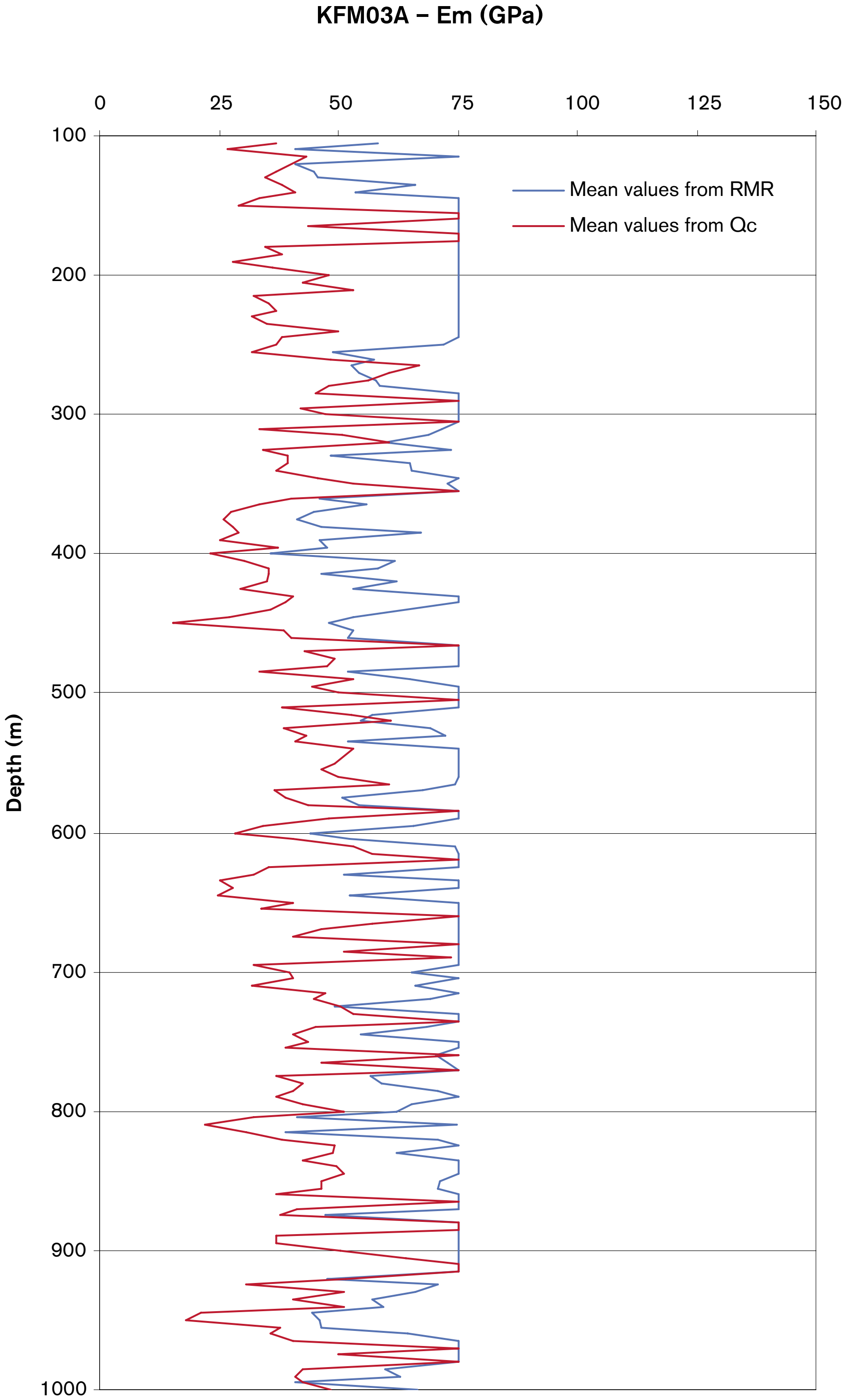
Rock unit	Minimum mean Em (GPa)	Average mean Em (GPa)	Frequent mean Em (GPa)	Maximum mean Em (GPa)	Standard deviation	Possible min Em (GPa)	Possible max Em (GPa)
A	22.9	33.2	33.1	46.6	5.6	6.7	84.3
B	27.2	31.5	31.5	35.8	6.1	16.1	58.5
C	26.7	31.5	30.0	37.7	5.6	5.0	66.9
D	46.0	46.0	46.0	46.0	0.0	8.6	66.9
Competent rock	22.9	33.5	33.2	46.6	5.5	10.7	84.3
Fractured rock	25.7	32.6	30.6	46.0	7.5	5.0	66.9
Whole borehole	22.9	33.3	33.1	46.6	5.9	5.0	84.3

The maximum mean Em and the maximum confidence Em have a physical threshold in the Young's modulus of the intact rock, which is 75 and 90 GPa, respectively.



Variation of the deformation modulus of the rock mass obtained from Q_c with depth for borehole KFM03A. The values are given every 5 m.

C.1.3 Comparison



Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc for different depths for borehole KFM03A.

C.2 Uniaxial compressive strength

C.2.1 RMR

Summary of the uniaxial compressive strength of the rock mass derived from RMR for borehole KFM03A (core sections of 5 m).

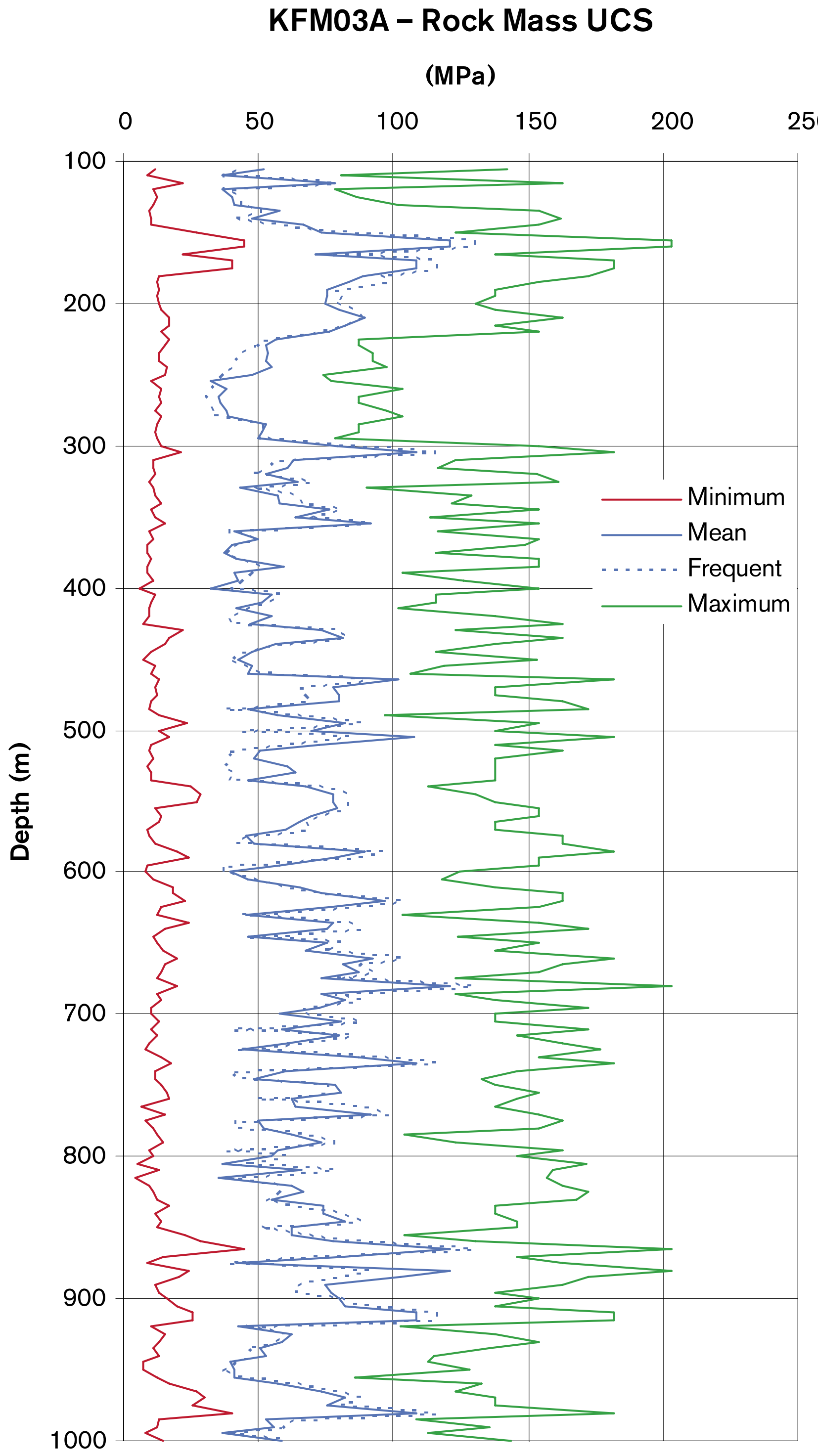
Depth (m)	Minimum mean UCS	Average mean UCS	Frequent mean UCS	Maximum mean UCS	Standard deviation	Possible min UCS	Possible max UCS
100–220	36.6	74.4	75.4	121.3	24.8	9.0	203.3
220–295	32.6	46.2	50.2	56.1	8.5	10.3	103.3
295–350	43.3	66.2	63.0	108.5	17.3	9.7	182.0
350–355	64.1	78.0	78.0	91.9	19.6	11.8	154.0
355–380	37.1	41.9	41.1	49.7	4.7	8.8	154.0
380–400	32.1	43.8	41.9	59.3	11.3	5.7	154.0
400–450	41.5	55.1	53.1	81.1	12.9	7.2	162.8
450–455	47.4	47.4	47.4	47.4	0	11.7	118.8
455–635	39.5	67.5	68.6	107.8	17.3	7.7	182.0
635–645	46.4	61.1	61.1	75.8	20.8	11.1	172.1
645–805	37.0	71.2	73.1	121.3	18.2	5.0	203.3
805–815	35.0	50.4	50.4	65.7	21.7	4.7	159.1
815–940	42.0	75.3	74.3	121.3	22.4	8.6	203.3
940–950	39.6	40.3	40.3	41.0	1.0	7.0	128.1
950–1,000	36.8	64.3	57.9	108.5	21.2	8.0	182.0

Summary of the uniaxial compressive strength of the rock mass derived from RMR for borehole KFM03A (core sections of 5 m).

Rock unit	Minimum mean UCS	Average mean UCS	Frequent mean UCS	Maximum mean UCS	Standard deviation	Possible min UCS	Possible max UCS
A	32.1	65.7	62.4	121.3	20.8	4.7	203.3
B	32.6	46.2	50.2	56.1	8.5	10.3	103.3
C	32.6	36.6	37.1	38.9	2.4	10.3	1,003.3
D	37.1	52.0	41.1	91.9	22.8	8.8	154.0
Competent rock	32.6	67.4	64.1	121.3	20.5	5.0	203.3
Fractured rock	32.1	48.7	41.5	91.9	15.9	4.7	172.1
Whole borehole	32.1	65.7	62.4	121.3	20.8	4.7	203.3

Summary of the compressive strength of the rock mass derived from RMR for borehole KFM03A (core sections of 30 m).

Rock unit	Minimum mean UCS	Average mean UCS	Frequent mean UCS	Maximum mean UCS	Standard deviation	Possible min UCS	Possible max UCS
A	32.1	65.7	62.4	121.3	20.8	4.7	203.3
B	32.6	46.2	50.2	56.1	8.5	10.3	103.3
C	32.6	60.2	59.3	108.5	18.6	5.7	182.0
D	37.1	50.2	41.3	91.9	20.8	8.8	154.0
Competent rock	32.6	67.4	64.1	121.3	20.5	5.0	203.3
Fractured rock	32.1	48.7	41.5	91.9	15.9	4.7	172.1
Whole borehole	32.1	65.7	62.4	121.3	20.8	4.7	203.3

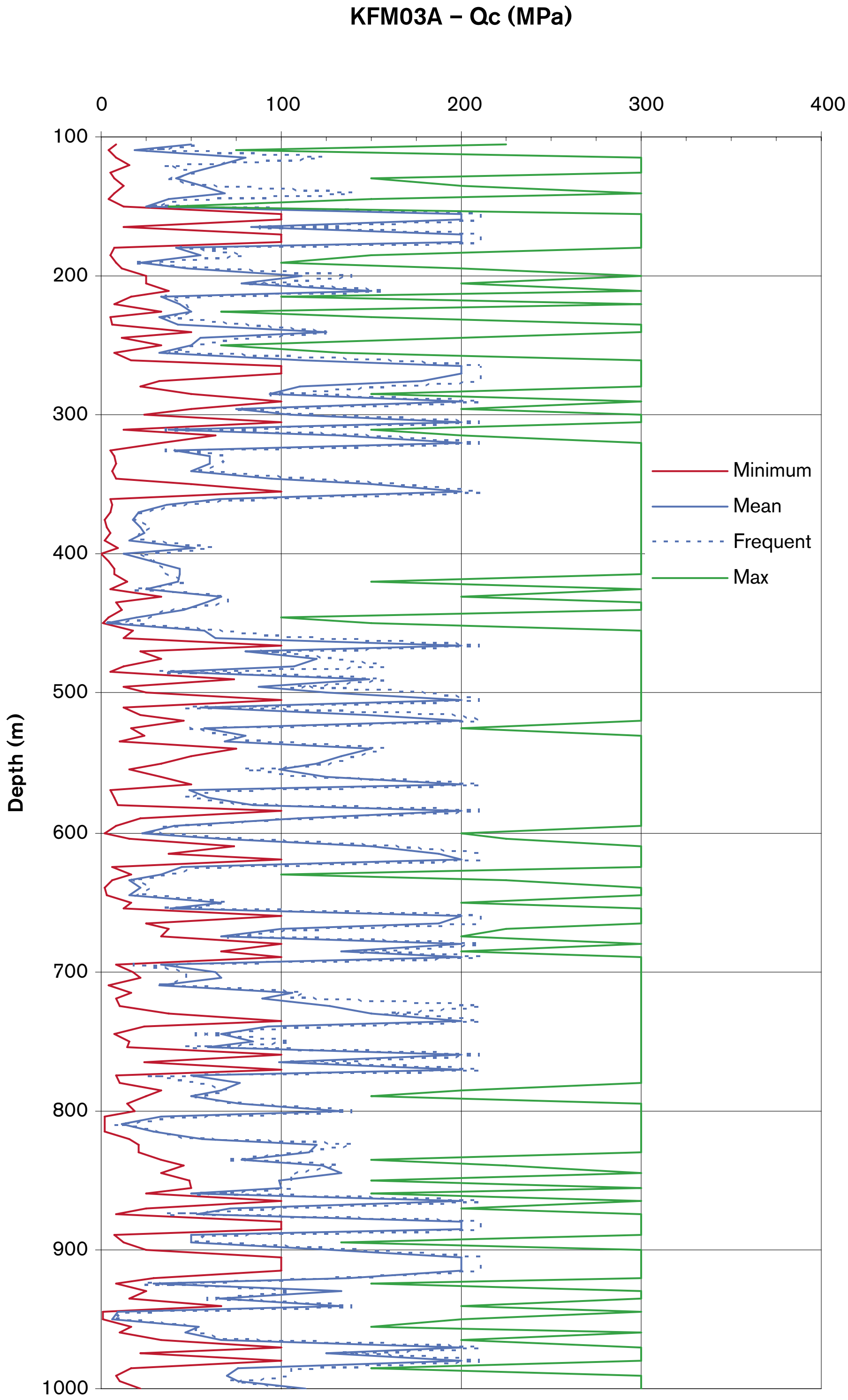


Variation of the uniaxial compressive strength of the rock mass with depth for borehole KFM03A (Hoek & Brown's a = 0.5). The values are given every 5 m.

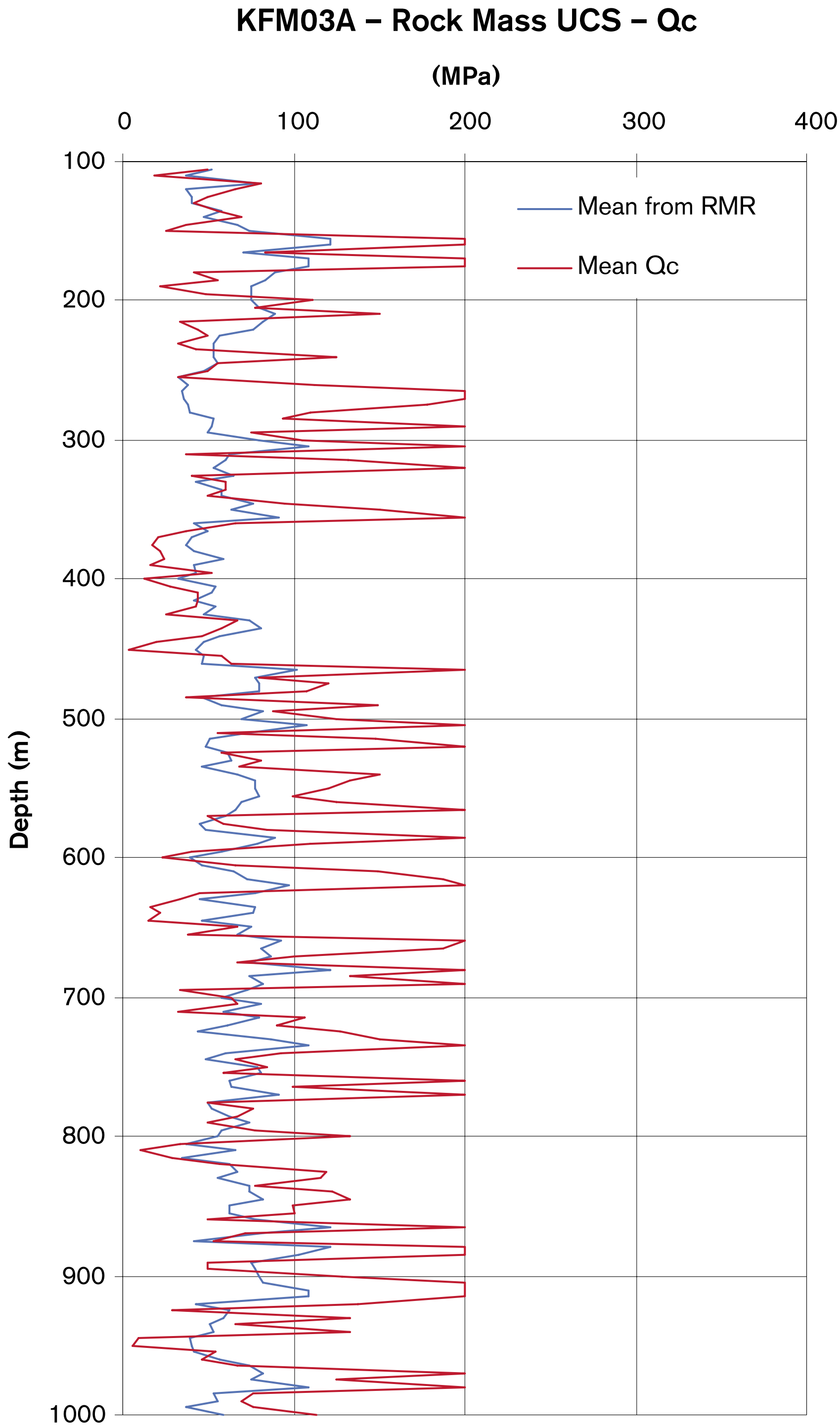
C.2.2 Q

Summary of Qc derived from Q for borehole KFM02A (core sections of 5 m).

Rock unit	Minimum mean Qc	Average mean Qc	Frequent mean Qc	Maximum mean Qc	Standard deviation	Possible min Qc	Possible max QC
A	3.5	93.4	73.2	200.0	61.0	0.2	300.0
B	31.9	103.7	93.8	200.0	63.8	5.6	300.0
C	12.2	82.5	60.5	200.0	62.6	0.2	300.0
D	17.2	60.5	29.5	200.0	70.6	2.4	300.0
Competent rock	3.5	99.4	80.0	200.0	59.4	0.2	300.0
Fractured rock	6.0	36.3	21.6	200.0	45.6	0.2	300.0
Whole borehole	3.5	93.4	73.2	200.0	61.0	0.2	300.0



Variation of Q_c with depth for borehole KFM03A. The values are given every 5 m.



Comparison of the rock mass compressive strength from RMR and Q for borehole KFM03A.

C.3 Friction angle and cohesion and of the rock mass

C.3.1 RMR

Summary of the friction angle (ϕ’) of the rock mass derived from RMR for borehole KFM03A (10–30 MPa) (core sections of 5 m).

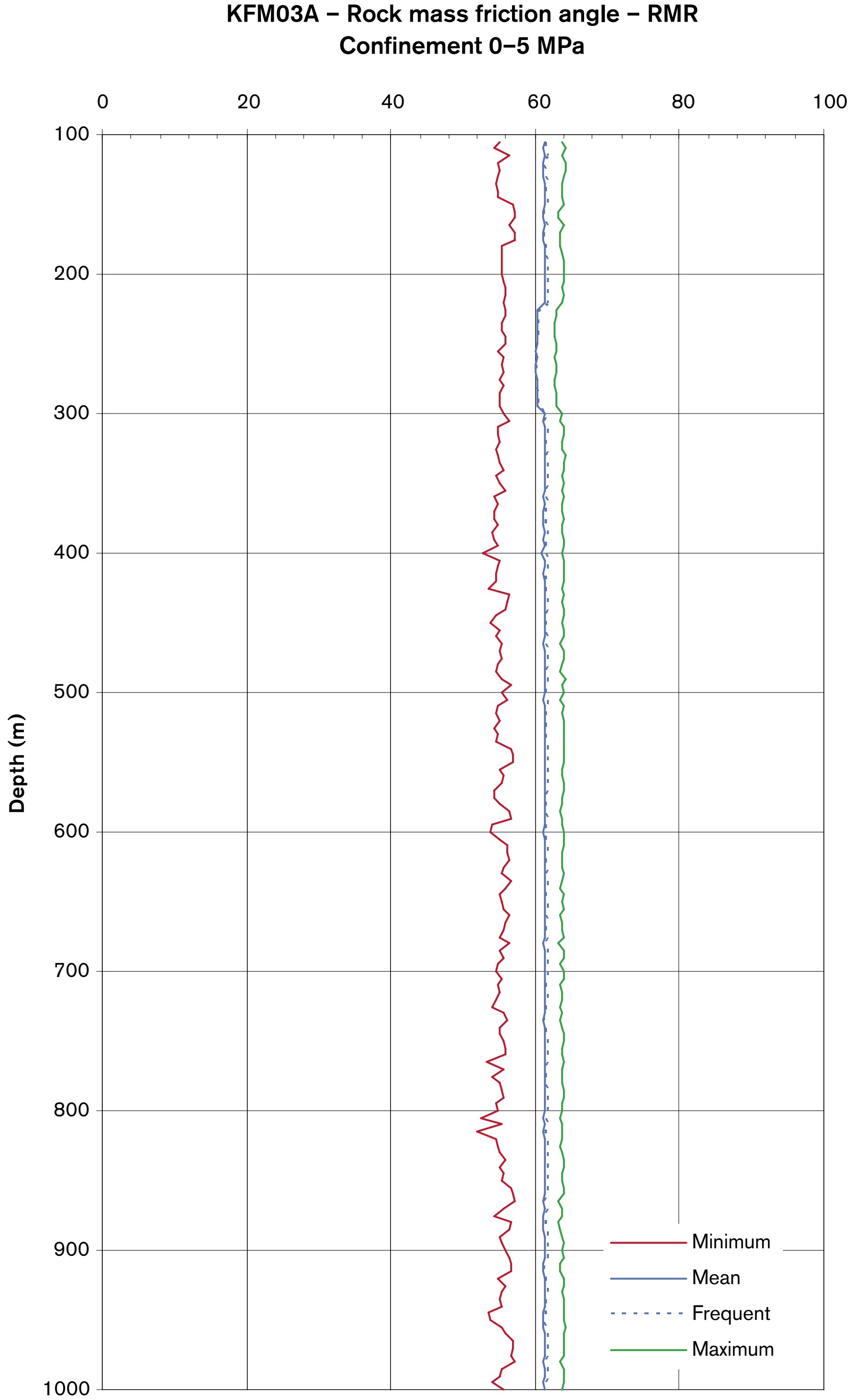
Depth (m)	Minimum mean ϕ’ (°)	Average mean ϕ’ (°)	Frequent mean ϕ’ (°)	Maximum mean ϕ’ (°)	Standard deviation	Possible min ϕ’ (°)	Possible max ϕ’ (°)
100–220	45.9	48.9	49.2	51.0	1.6	34.8	55.3
220–295	44.4	46.0	46.5	47.0	0.9	35.5	51.8
295–350	46.7	48.5	48.5	50.7	1.0	35.2	55.0
350–355	50.0	50.0	50.0	50.0	0	37.8	54.5
355–380	46.0	46.5	46.5	47.4	0.5	34.7	54.5
380–400	45.3	46.6	46.6	48.2	1.2	32.3	54.5
400–450	46.5	47.7	47.7	49.5	1.0	33.6	54.7
450–455	47.2	47.2	47.2	47.2	0	36.2	53.6
455–635	46.3	48.6	48.8	50.6	1.1	34.0	55.0
635–645	47.1	48.2	48.2	49.3	1.6	35.9	54.8
645–805	46.0	48.8	49.1	51.0	1.1	31.7	55.3
805–815	45.7	47.2	47.2	48.6	2.1	31.3	54.6
815–940	46.6	49.0	49.2	51.0	1.2	34.5	55.3
940–950	46.3	46.4	46.4	46.5	0.1	33.5	53.9
950–1,000	45.9	48.3	48.1	50.7	1.4	34.1	55.0

Summary of the friction angle (ϕ’) of the rock mass derived from RMR for borehole KFM03A (10–30 MPa) (core sections of 5 m).

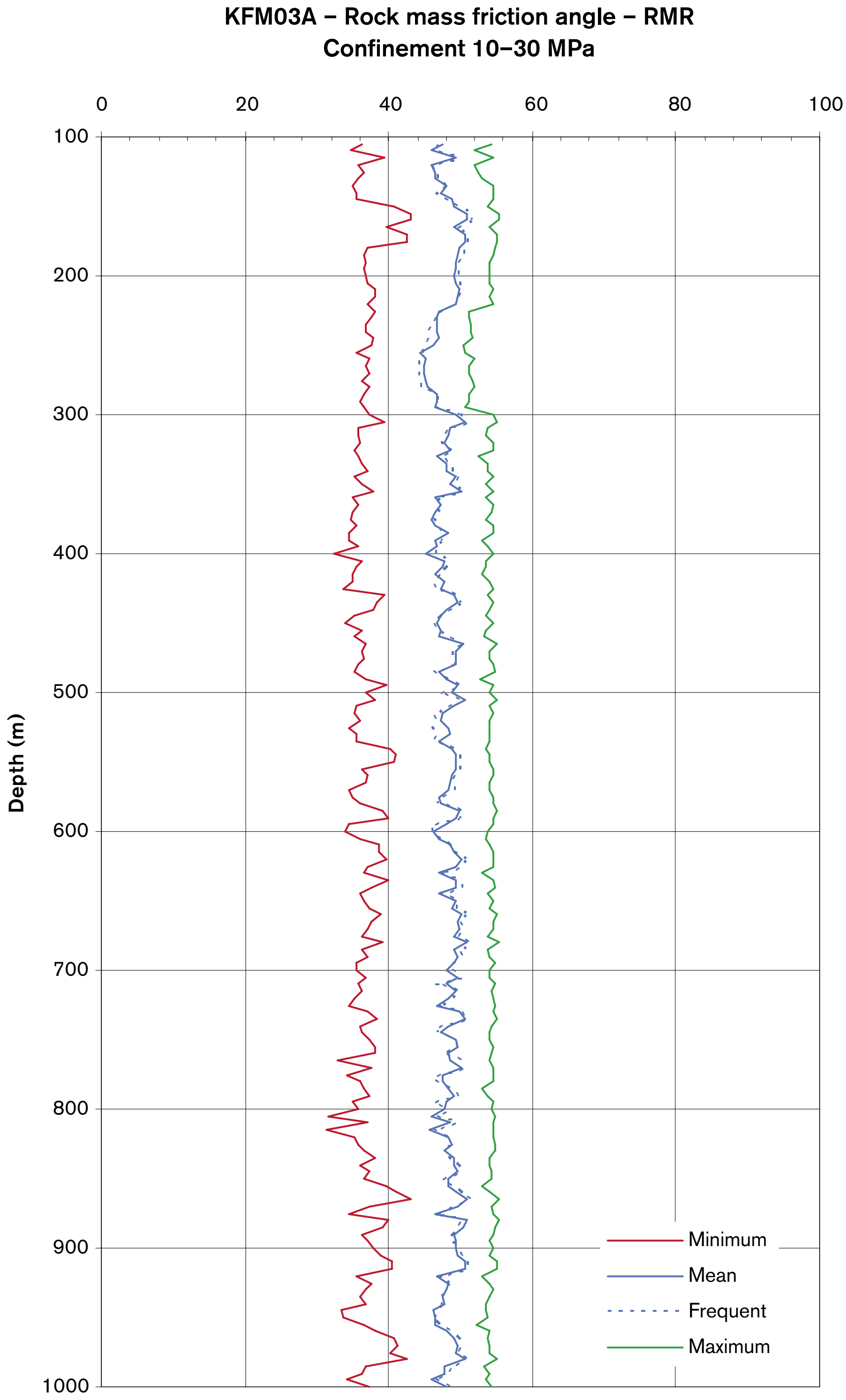
Rock unit	Minimum mean ϕ’ (°)	Average mean ϕ’ (°)	Frequent mean ϕ’ (°)	Maximum mean ϕ’ (°)	Standard deviation ϕ’ (°)	Possible min ϕ’ (°)	Possible max ϕ’ (°)
A	44.4	48.3	48.4	51.0	1.5	31.3	55.3
B	44.4	46.0	46.5	47.0	0.9	35.5	51.8
C	45.3	48.0	48.2	50.7	1.3	32.3	55.0
D	46.0	47.1	46.5	50.0	1.5	34.7	54.5
Competent rock	44.4	48.4	48.5	51.0	1.4	31.7	55.3
Fractured rock	45.3	47.1	46.5	50.0	1.3	31.3	54.8
Whole borehole	44.4	48.3	48.4	51.0	1.5	31.3	55.3

Summary of the friction angle of the rock mass derived from RMR (10–30 MPa) (core sections of 30 m).

Rock unit	Minimum mean ϕ’ (°)	Average mean ϕ’ (°)	Frequent mean ϕ’ (°)	Maximum mean ϕ’ (°)	Standard deviation ϕ’ (°)	Possible min ϕ’ (°)	Possible max ϕ’ (°)
A	47.1	48.3	48.2	49.6	0.7	31.1	55.0
B	44.7	45.8	45.8	46.8	1.5	35.5	51.8
C	46.8	48.1	48.4	49.3	1.3	32.3	54.8
D	47.7	47.7	47.7	47.7	0	33.7	54.8
Competent rock	44.7	48.3	48.4	49.6	1.1	32.5	55.0
Fractured rock	46.8	47.5	47.5	48.2	0.5	31.1	55.0
Whole borehole	44.7	48.1	48.2	49.6	1.0	31.1	55.0



Variation of the rock mass friction angle from RMR for borehole KFM03A under stress confinement 0–5 MPa.



Variation of the rock mass friction angle from RMR for borehole KFM03A under stress confinement 10–30 MPa.

Summary of the cohesion of the rock mass derived from RMR for borehole KFM03A (10–30 MPa) (core sections of 5 m).

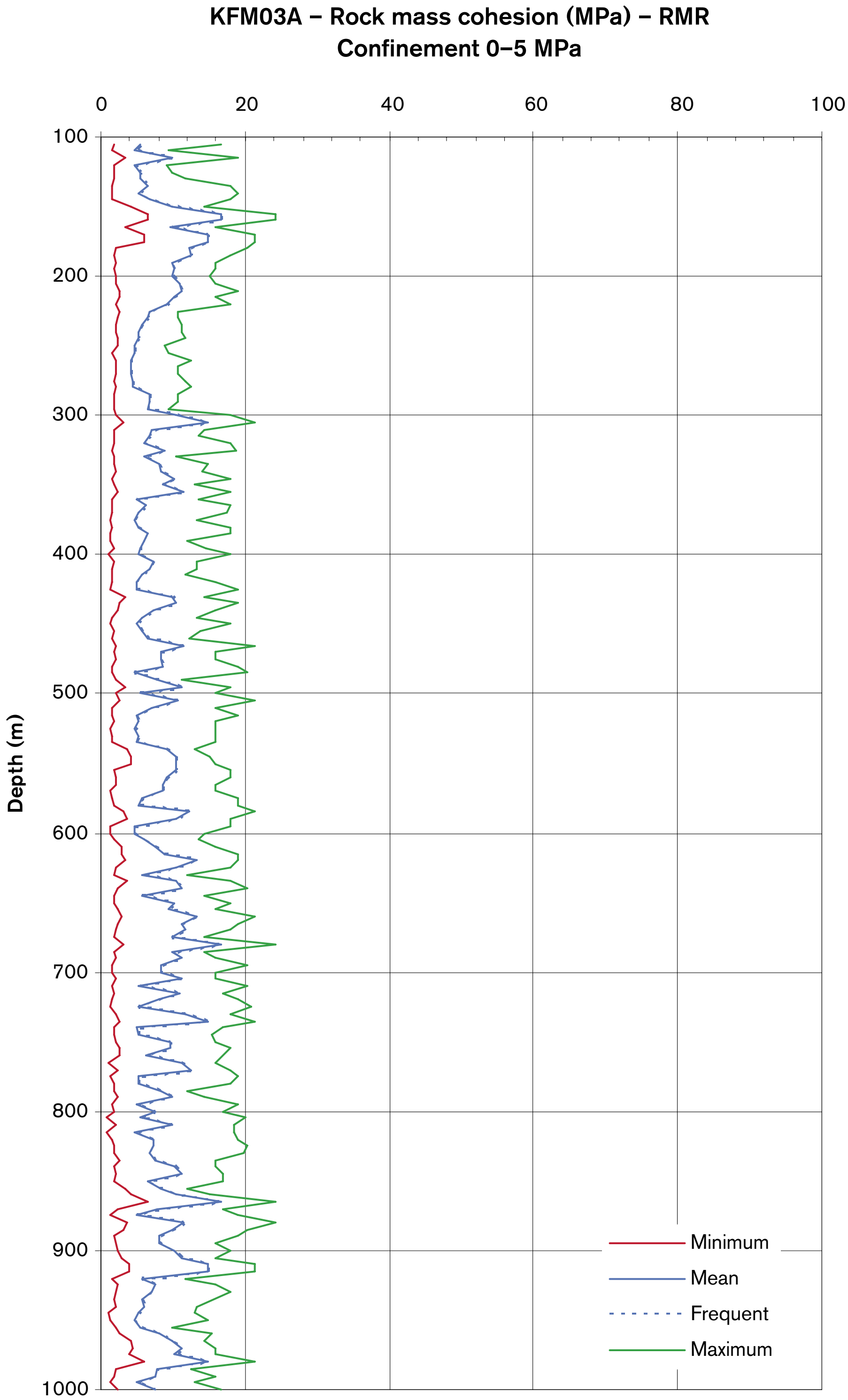
Depth (m)	Minimum mean C'	Average mean C'	Frequent mean C'	Maximum mean C'	Standard deviation	Possible min C'	Possible max C'
100–220	19.3	24.3	24.5	30.3	3.2	12.3	40.4
220–295	18.3	20.3	20.8	21.6	1.2	12.7	28.4
295–350	20.3	23.3	22.9	28.7	2.2	12.5	37.9
350–355	26.6	26.6	26.6	26.6	0	13.9	34.6
355–380	19.4	20.1	20.0	21.2	0.6	12.2	34.6
380–400	18.7	20.3	20.1	22.4	1.6	11.1	34.6
400–450	20.0	21.9	21.6	25.2	1.7	11.7	35.6
450–455	20.9	20.9	20.9	20.9	0	13.0	30.6
455–635	19.8	23.5	23.6	28.6	2.2	11.8	37.9
635–645	20.7	22.6	22.6	24.5	2.7	12.9	36.7
645–805	19.4	23.9	24.2	30.3	2.3	10.8	40.4
805–815	19.1	21.2	21.2	23.3	2.9	10.6	35.2
815–940	20.1	24.5	24.4	30.3	2.9	12.1	40.4
940–950	19.8	19.9	19.9	20.0	0.1	11.6	31.6
950–1,000	19.4	23.0	22.2	28.7	2.7	11.9	37.9

Summary of the cohesion of the rock mass derived from RMR for borehole KFM03A (10–30 MPa) (core sections of 5 m).

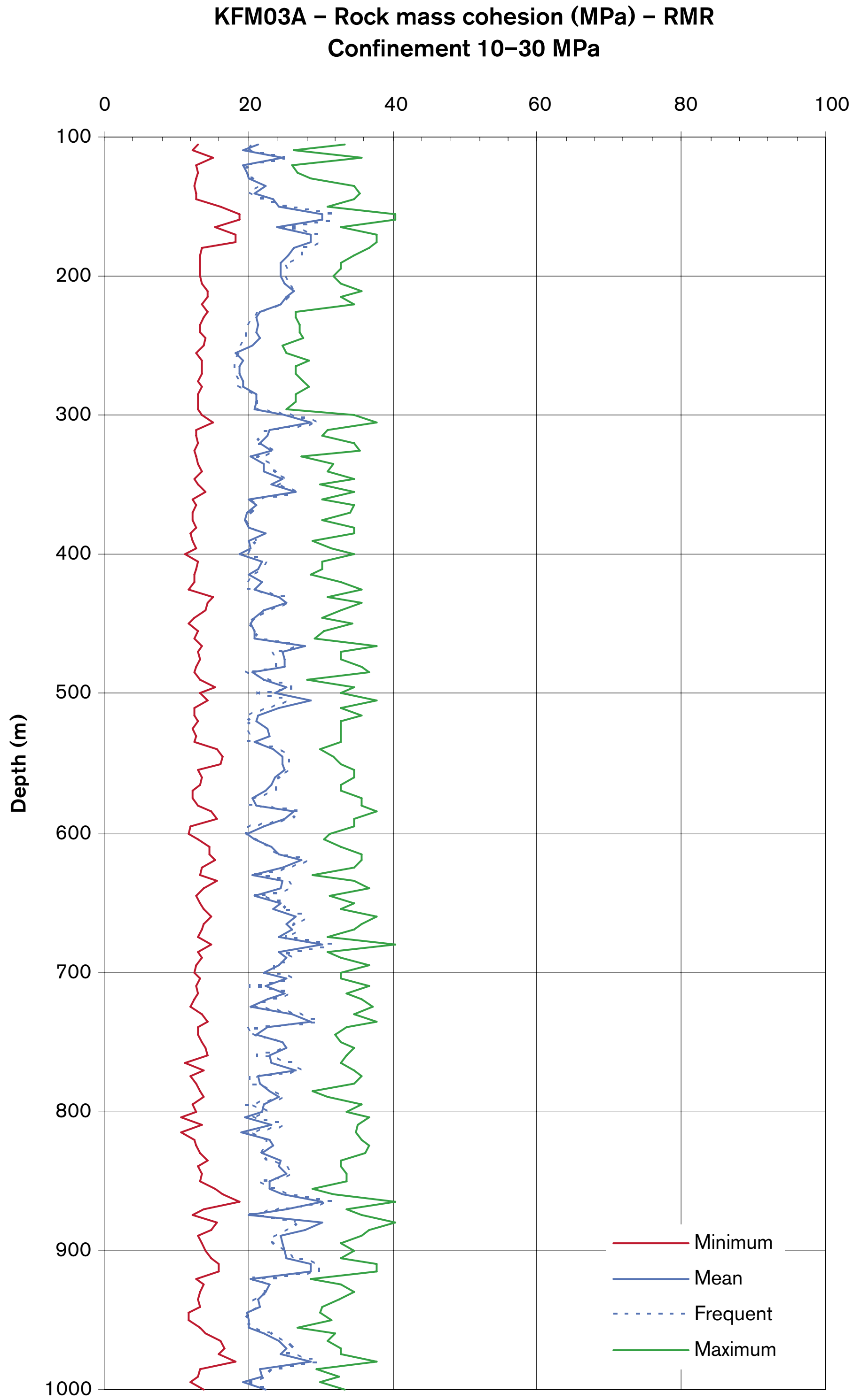
Rock unit	Minimum mean C' (MPa)	Average mean C' (MPa)	Frequent mean C' (MPa)	Maximum mean C' (MPa)	Standard deviation C' (MPa)	Possible min C' (MPa)	Possible max C' (MPa)
A	1.83	23.2	22.8	30.3	2.7	10.6	40.4
B	18.3	20.3	20.8	21.6	1.2	12.7	28.4
C	18.7	22.5	22.4	28.7	2.4	11.1	37.9
D	19.4	21.2	20.0	26.6	2.7	12.2	34.6
Competent rock	1.83	23.4	23.1	30.3	2.7	10.8	40.4
Fractured rock	18.7	21.0	20.1	26.6	2.1	10.6	36.7
Whole borehole	18.3	23.2	22.8	30.3	2.7	10.6	40.4

Summary of the cohesion of the rock mass derived from RMR (10–30 MPa) (core sections of 30 m, Hoek & Brown's a = 0.5).

Rock unit	Minimum mean C' (MPa)	Average mean C' (MPa)	Frequent mean C' (MPa)	Maximum mean C' (MPa)	Standard deviation C' (MPa)	Possible min C' (MPa)	Possible max C' (MPa)
A	20.7	22.8	22.5	25.3	1.4	10.5	37.9
B	18.6	19.9	19.9	21.3	1.9	12.7	28.4
C	20.4	22.6	22.8	24.6	2.1	11.1	36.7
D	21.6	21.6	21.6	21.6	0	11.7	36.7
Competent rock	18.6	22.8	22.8	25.3	1.6	11.2	37.9
Fractured rock	20.4	21.4	21.4	22.4	0.7	10.5	37.9
Whole borehole	18.6	22.5	22.4	25.3	1.6	10.5	37.9



Variation of the rock mass cohesion from RMR for borehole KFM03A under stress confinement 0–5 MPa.



Variation of the rock mass cohesion from RMR for borehole KFM03A under stress confinement 10–30 MPa.

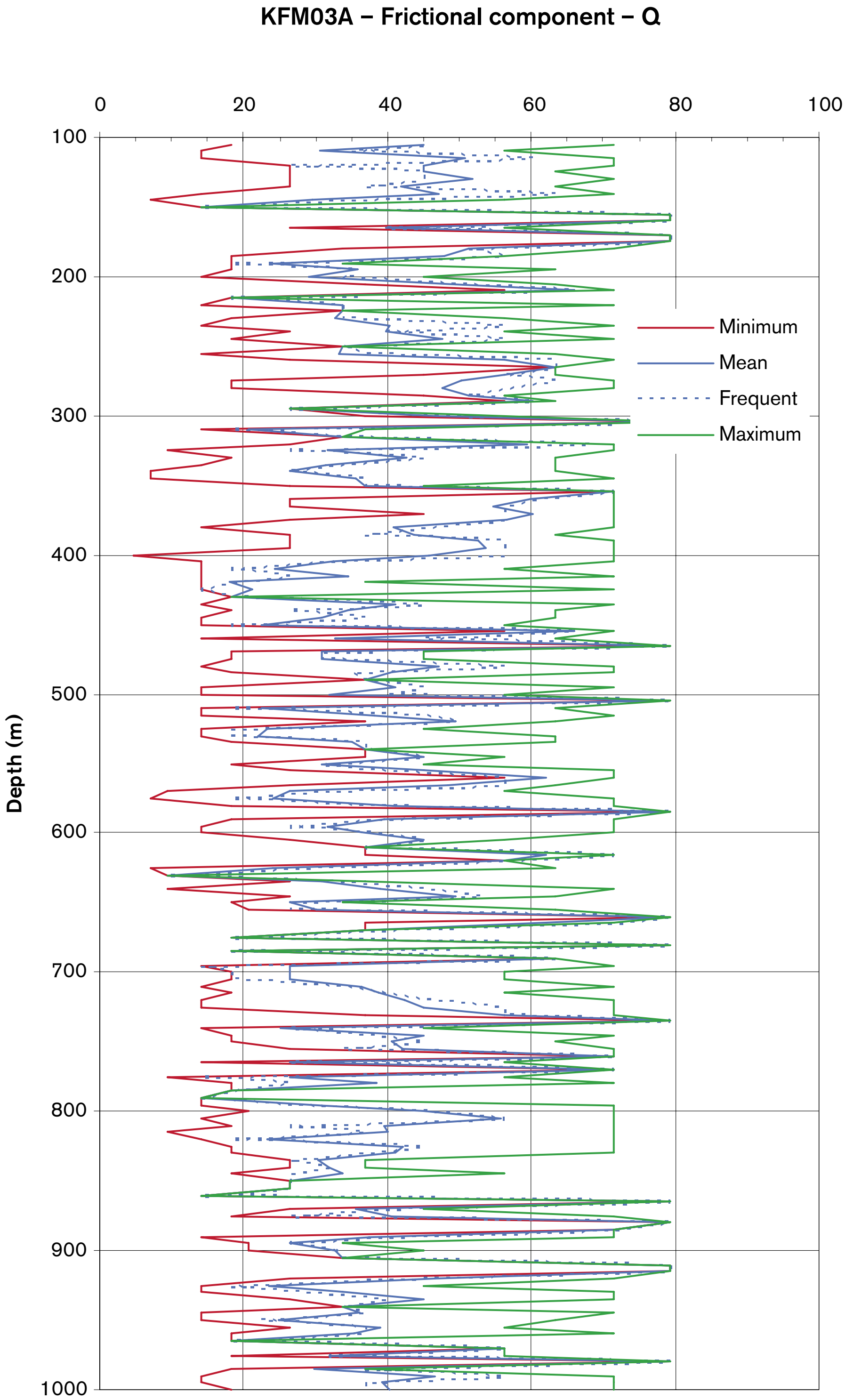
C.3.2 Q

Summary of the frictional component FC of the rock mass derived from Qc for borehole KFM03A (core sections of 5 m).

Rock unit	Minimum mean FC (°)	Average mean FC (°)	Frequent mean FC (°)	Maximum mean FC (°)	Standard deviation FC (°)	Possible min FC (°)	Possible max FC (°)
A	9.5	42.3	39.4	79.4	17.1	4.8	79.4
B	26.6	44.9	47.7	63.4	11.5	14.0	71.6
C	20.6	42.7	42.7	79.4	14.7	4.8	79.4
D	40.9	57.3	58.3	71.6	9.9	14.0	71.6
Competent rock	9.5	41.5	37.5	79.4	17.4	7.1	79.4
Fractured rock	25.0	49.1	49.4	71.6	12.0	4.8	71.6
Whole borehole	9.5	42.3	39.4	79.4	17.1	4.8	79.4

Summary of the frictional component FC of the rock mass derived from Q (core sections of 30 m).

Rock unit	Minimum mean FC (°)	Average mean FC (°)	Frequent mean FC (°)	Maximum mean FC (°)	Standard deviation FC (°)	Possible min FC (°)	Possible max FC (°)
A	9.5	42.3	39.4	79.4	17.1	4.8	79.4
B	26.6	44.9	47.7	63.4	11.5	14.0	71.6
C	20.6	42.7	42.7	779.4	14.7	4.8	79.4
D	40.9	57.3	58.3	71.6	9.9	14.0	71.6
Competent rock	9.5	41.5	37.5	79.4	17.4	7.1	79.4
Fractured rock	25.0	49.1	49.4	71.6	12.0	4.8	71.6
Whole borehole	9.5	42.3	39.4	79.4	17.1	4.8	79.4



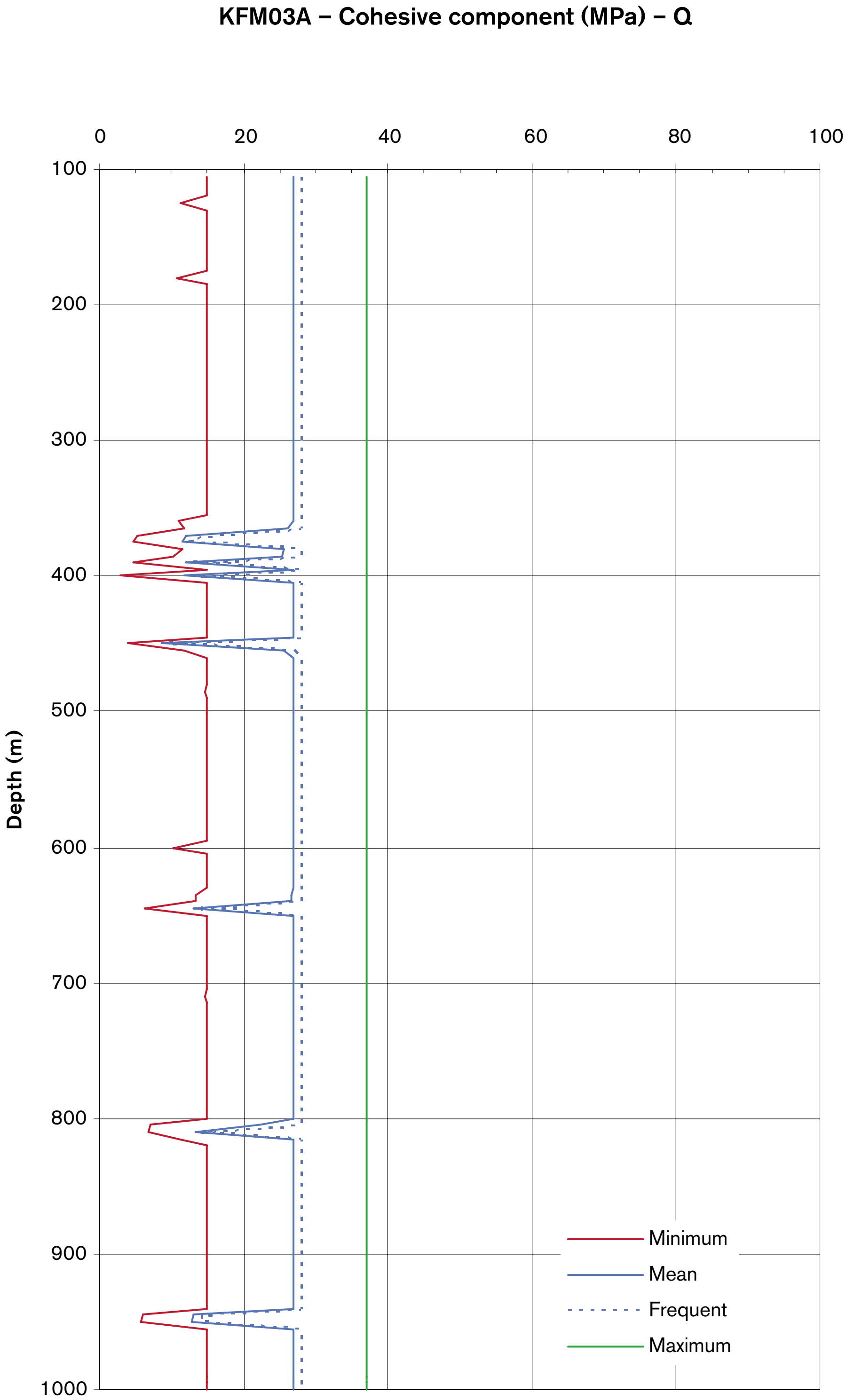
Variation of the frictional component FC from Q for borehole KFM03A.

Summary of the cohesion of the rock mass derived from Qc for borehole KFM03A (core sections of 5 m).

Rock unit	Minimum mean CC (MPa)	Average mean CC (MPa)	Frequent mean CC (MPa)	Maximum mean CC (MPa)	Standard deviation CC (MPa)	Possible min CC (MPa)	Possible max CC (MPa)
A	8.5	26.2	27.0	27.0	3.3	2.9	37.0
B	27.0	27.0	27.0	27.0	0	15.0	37.0
C	11.8	24.9	27.0	27.0	5.3	2.9	37.0
D	11.4	21.5	25.8	27.0	7.6	4.8	37.0
Competent rock	8.5	26.9	27.0	27.0	1.5	4.0	37.0
Fractured rock	11.4	19.8	25.4	27.0	7.2	2.9	37.0
Whole borehole	8.5	26.2	27.0	27.0	3.3	2.9	37.0

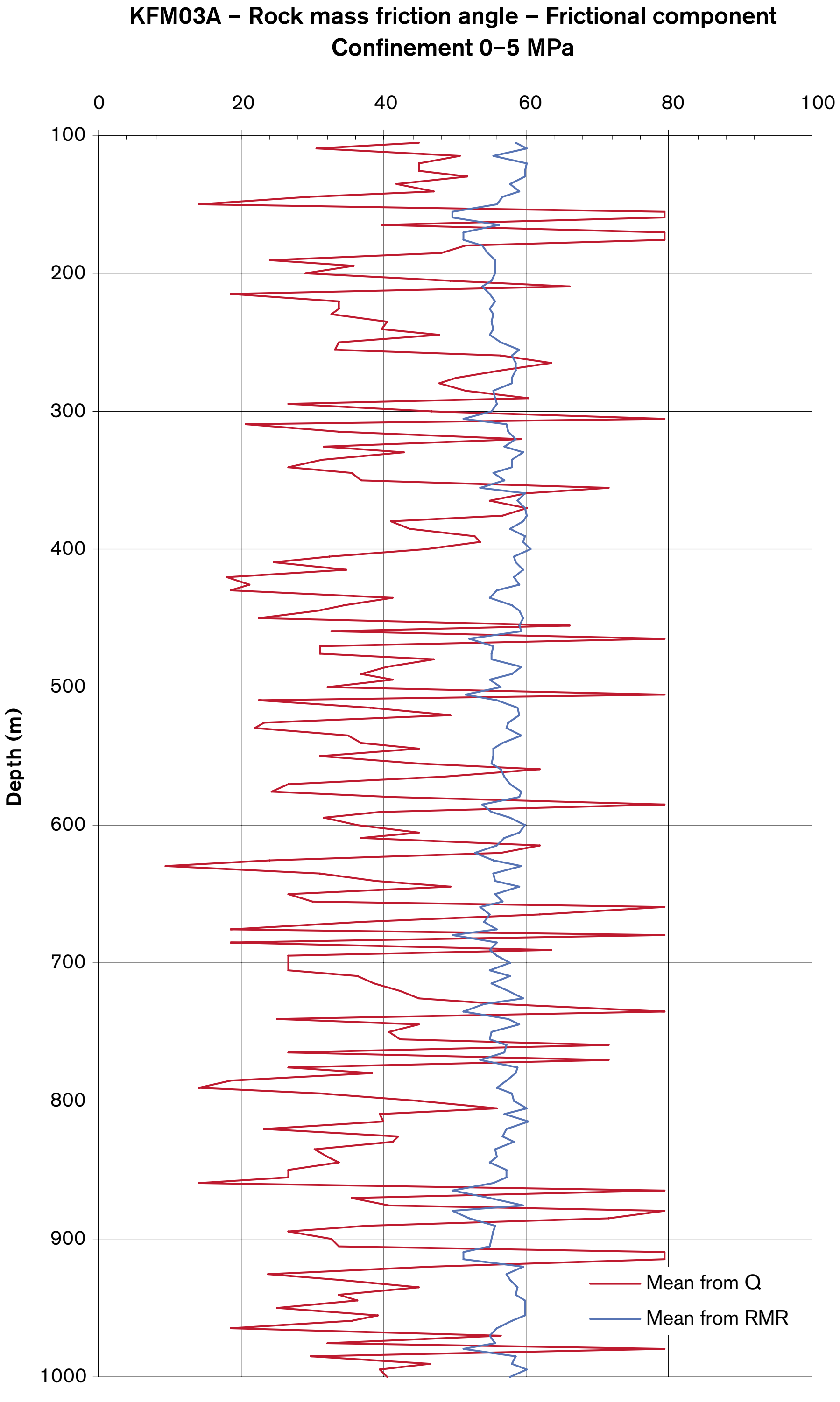
Summary of the cohesion of the rock mass derived from Q (core sections of 30 m).

Rock unit	Minimum mean CC (MPa)	Average mean CC (MPa)	Frequent mean CC (MPa)	Maximum mean CC (MPa)	Standard deviation CC (MPa)	Possible min CC (MPa)	Possible max CC (MPa)
A	8.5	26.2	27.0	27.0	3.3	2.9	37.0
B	27.0	27.0	27.0	27.0	0	15.0	37.0
C	11.8	24.9	27.0	27.0	5.3	2.9	37.0
D	11.4	21.5	25.8	27.0	7.6	4.8	37.0
Competent rock	8.5	26.4	27.0	27.0	1.5	4.0	37.0
Fractured rock	11.4	19.8	25.4	27.0	7.2	2.9	37.0
Whole borehole	8.5	26.2	27.0	27.0	3.3	2.9	37.0

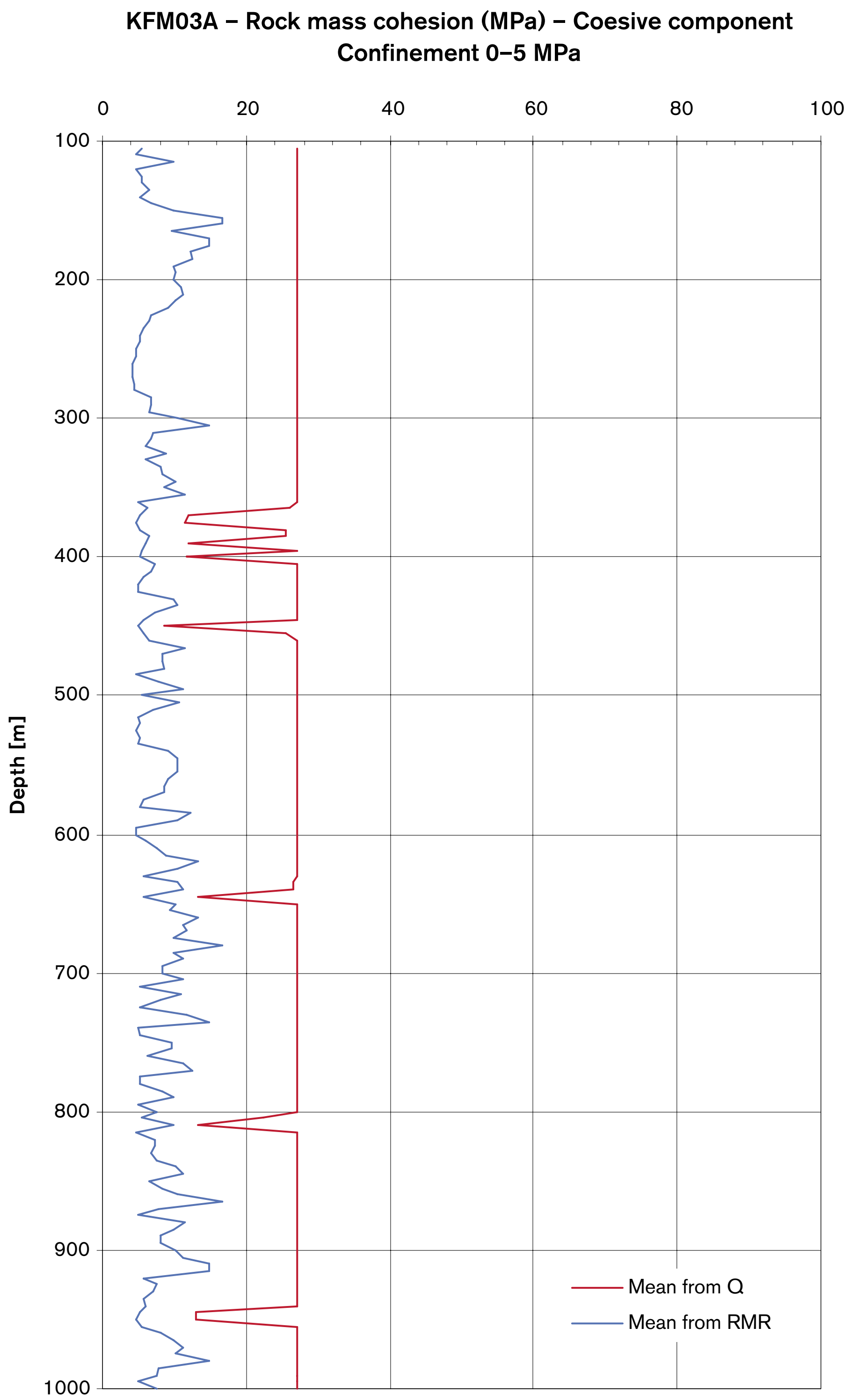


Variation of the cohesive component from Q for borehole KFM03A.

C.3.3 Comparison



Comparison of the rock mass friction angle from RMR and Q for borehole KFM03A under stress confinement 0–5 MPa.



Comparison of the rock mass cohesion from RMR and Q for borehole KFM03A under stress confinement 0–5 MPa.