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Forsmark site investigation

Rock mechanics characterisation of borehole KFM02A

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Abstract

The two independent empirical systems RMR (version 1989) and Q (version 2002) are applied to the rock mass along borehole KFM02A. Geomechanical data are provided from the logging of the core and of the borehole sides. Some sample testing results are also available from earlier studies (intact rock properties) and new tilt tests on fractures. The geological “single-hole” interpretation of the geomechanical data provides the partition of the rock along the borehole in pseudo-homogeneous sections (rock units) and fractured sections (deformation zones). In general, the rock mass along borehole KFM02A is classified as “very good” by both RMR and Q (RMR > 81 and Q > 40). The rock mass in the deformation zones is “good” according to RMR (73 < RMR < 77 with two cases where RMR > 81) but only “fair to good” according to Q (6 < Q < 36).

From the empirical correlations, the deformation modulus, equivalent uniaxial compressive strength, apparent cohesion and friction angle of the rock mass can be evaluated. The deformation modulus of the rock mass is independently obtained from RMR and Q. For the upper 600 m of the borehole, it varies in average between 45 (Q) and 60 GPa (RMR), depending on the method used. The part of the borehole under 600 m presents deformation modulus of the rock mass between 55 and 70 GPa. When only the competent rock is considered, the average varies between 55 and 65 GPa. The deformation modulus of the fractured rock ranges between 30 and 60 GPa. The apparent friction angle and cohesion of the rock mass are obtained as linear interpolation of the Hoek and Brown’s Failure Criterion for confinement stress between 10 and 30 MPa. The resulting friction angle is rather constant along the borehole and its average value is about 48°. The cohesion of the competent rock mass is in average 23 MPa while that of the fractured rock mass is about 20 MPa. The Hoek and Brown’s Failure Criterion also gives the equivalent uniaxial compressive strength of the rock mass. This is about 65 MPa for competent rock and around 48 MPa for the fractured rock, respectively.

Special mention has to be given to the very porous and altered metagranite occurring at depths between 240 and 310 m. Its deformation modulus and the apparent friction angle are very similar to the average values for the rest of the borehole. On the other hand, the strength of the porous metagranite is lower than the rest of the rock mass: the uniaxial compressive strength and the apparent cohesion are 19 MPa and 15 MPa on average, respectively.

Sammanfattning

För borrhål KFM02A har de två oberoende empiriska systemen RMR (version 1989) och Q (version 2002) använts. Den geomekaniska informationen som använts kommer från kärnkartering och loggning av borrhålsväggen. Vissa provresultat från tidigare studier (egenskaperna hos det intakta berget) finns också inkluderade liksom nya tilttests på sprickor. Den geologiska enhålstolkningen användes för att göra en uppdelning i olika bergpartier längs borrhålet. De består av pseudo-homogena sektioner (bergenheter) och sektioner av mycket sprucket berg (sprickzoner). Bergmassan längs borrhål KFM02A klassificeras generellt som ”mycket bra berg” i både RMR- och Q-systemen (RMR > 81 och Q > 40). Sprickzonerna klassificeras som ”bra berg” enligt RMR (73 < RMR > 77 med två fall där RMR > 81) men bara som ”medel till bra berg” enligt Q (6 < Q > 36).

Från de empiriska sambanden kan man utvärdera deformationsmodulen, enaxiella tryckhållfastheten, skenbara kohesionen och friktionsvinkeln. Bergmassans deformationsmodul beräknas separat ur Q och RMR. Beroende av vilken metod man använder varierar medelvärdet mellan 45 (Q) och 60 GPa (RMR) för de översta 600 m av borrhålet, medan under 600 m varierar det mellan 55 och 70 GPa. För kompetent berg varierar medelvärdet mellan 55 och 65 GPa. Deformationsmodulen för sprickzoner varierar mellan 30 och 60 GPa. Bergmassans skenbara friktionsvinkel och kohesion uppskattas genom linjär interpolation av Hoek and Browns brottkriterium mellan 10 och 30 MPa tryck. Friktionsvinkeln är generellt konstant genom hela borrhålet med ett medelvärde på ca 48°. Medelvärdet för det kompetenta bergets kohesion är 23 MPa medan sprickzonerna har ca 20 MPa. Den enaxiella tryckhållfasthet beräknat från Hoek and Browns brottkriterium är ca 65 MPa för kompetent berg och 48 MPa för sprickzoner.

Den mycket porösa metagraniten som förekommer mellan 240–310 m bör få ett speciellt nämnande då den har lägre värden än den resterande bergmassan med avseende på enaxiella tryckhållfastheten (19 MPa) och den skenbara kohesionen (15 MPa). Dock liknar deformationsmodulen och den skenbara friktionsvinkeln för den porösa metagraniten resten av berget i borrhålet.

Contents

1 Introduction

1.1 Background

Borehole KFM02A is centrally situated in the Forsmark Candidate Area. The borehole is about 1,002 m long and is drilled with a bearing angle of 276 and inclination of 85 degrees. The complete core was recovered between 100 and 1,002 m, with a diameter of 51 mm.

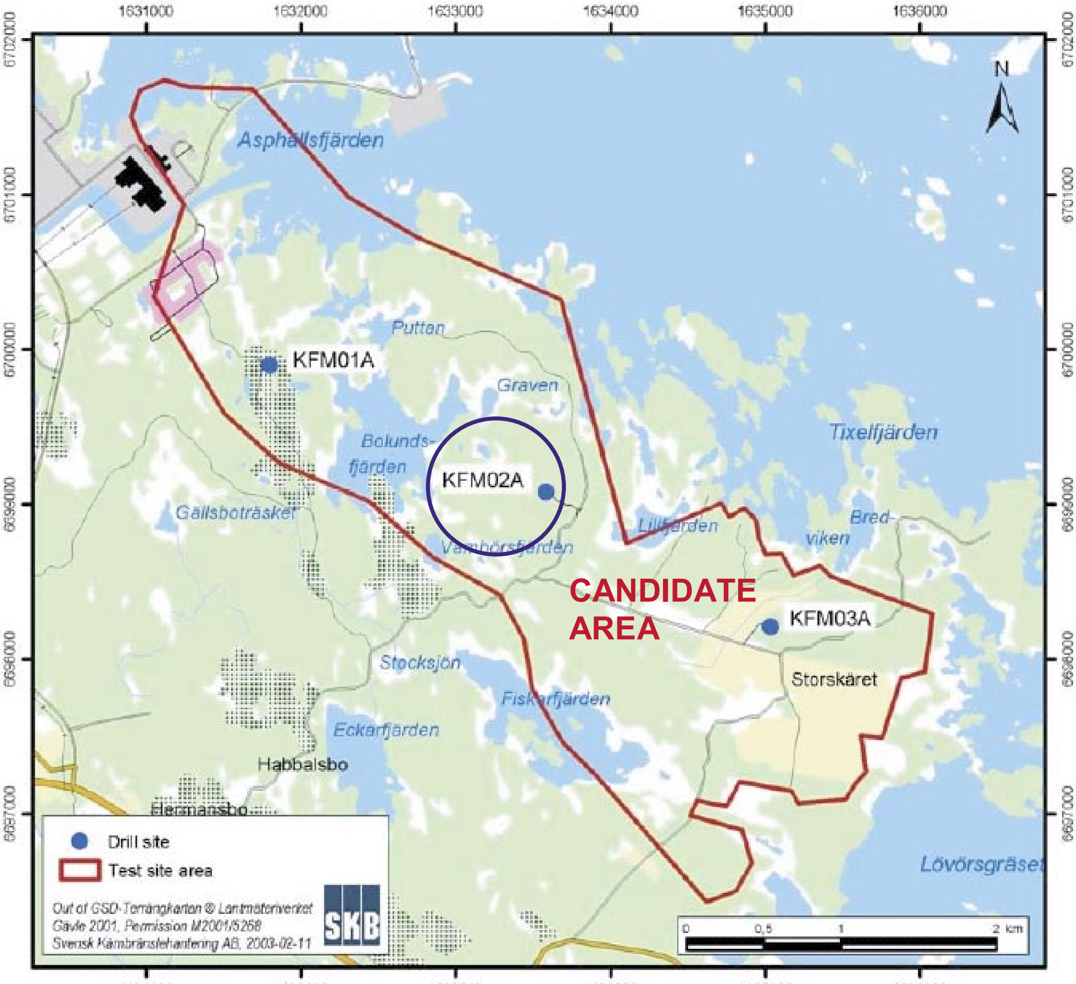

Figure 1-1. *Overview of the Forsmark Site with indication of the Candidate Area and borehole KFM02A.*

1.2 Objectives

The objectives of this study are as follows:

- Summarise all new geological/geotechnical information for the Candiate Area with respect to the already reported information for Borehole KFM02 A (by May, 2004).
- Evaluate the rock mass quality along borehole KFM02A 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 was performed mainly based on data that come directly from the borehole KFM02A (single-hole interpretation). This enables a rock quality determination locally applicable. When comparing the results for different depths, the spatial variation along borehole KFM02A 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 KFM02A (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 derived parameter determination are also treated.
- Discussion of the results.
- Appendices.

2 Boremap data

Borehole KFM02A was mapped by examining the core and the BIPS pictures taken on the borehole wall /Petersson et al. 2003/. The geological parameters obtained and stored in SKB's geological database SICADA 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 among "open" and "closed" ("sealed" or "unbroken"). The rock mechanics characterisation in this report is based on the properties of the "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 (in this report, as it was stored by January, 2004).

For the rock mechanics evaluation of the geological information, additional 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 recognition of the main fracture sets occurring in the rock mass along the borehole was based, not only of the BOREMAP information directly available, but also on the indications from earlier studies: i) for the construction of the Unit 3 of the Nuclear Power Plant; ii) for the SFR Repository for low and intermediate active nuclear waste and iii) for the Site Descriptive Model of the Forsmark Area /SKB, 2004/. 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".

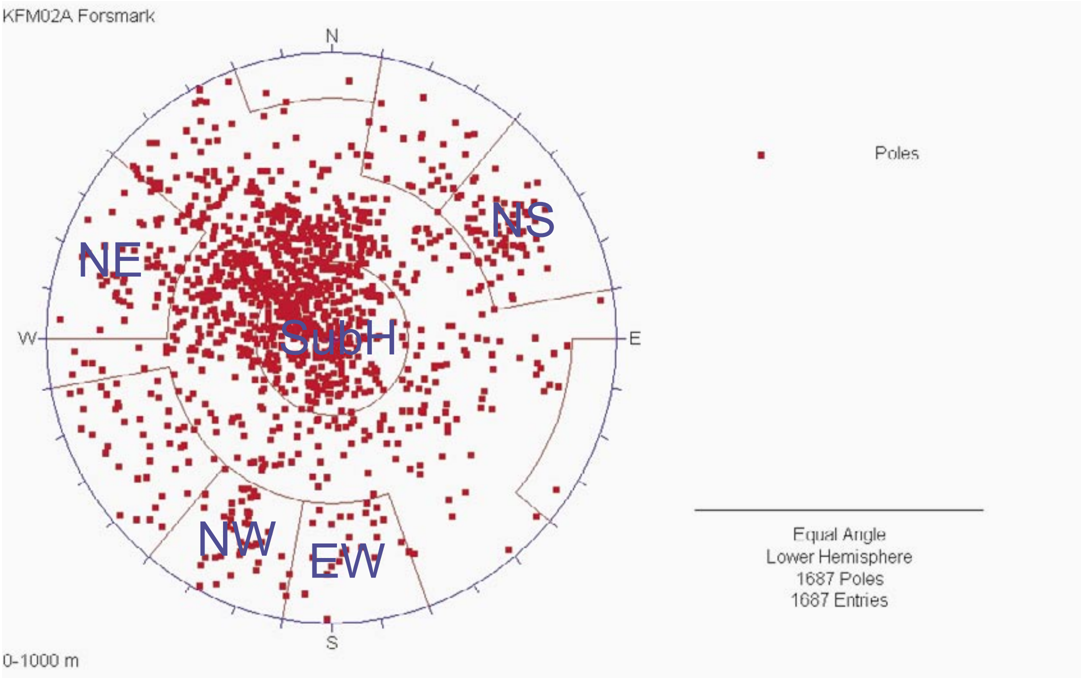

Figure 2-1. *Equiangle pole plot of the fractures logged along borehole KFM02A and indication of the main fracture sets. The borehole orientation is 276/85.*

Once the fracture sets were identified within each rock unit along the borehole, the mean orientation and Fisher's constant were determined (Table 2-1, Table 2-2). Based on the orientation windows shown in Figure 2-1, the fractures were assigned to the different fracture sets. The core was treated in 5 and 30 m sections. In this way, not only the number of fractures of each set occurring could be calculated, but also the frequency and spacing of each fracture set were determined. For the fracture spacing the Terzaghi's weighting was applied to remove the bias due to the linear sampling of the fractures in the rock mass applied by the borehole.

In Figure 2-2, some zones of higher fracture frequency are observed at the depth 120, 170, 300, 400–520 and 900–920 m. When only the frequency of the sub-horizontal fractures is concerned, most of the high-frequency peaks between 400 and 500 m disappear. In general, the fracture frequency is higher for the upper 500 m (between 1 to 10 fractures/m) with respect to the deeper part of the borehole (between 0 and 3 fractures/m).

The Rock Quality Designation, RQD, which gives the sum of the length of core pieces longer than 100 mm for every metre of borehole core, is also given in SICADA and plotted in Figure 2-2. Here, the average values for every 5 m core length are presented. RQD shows values down to 60 at about 120 and 520 m depth. Relative minima occur where the fracture frequency is low.

By counting the number of fracture occurring in each 5 m section of core, the plot of the number of fracture sets contemporarily occurring in Figure 2-2 can be obtained.

Table 2-1. Set identification from the fracture orientation logged for borehole KSH02A (SICADA, 04-01-26). The orientations are given as strike/dip (right-hand rule).

Depth (m)	Number of fractures	EW	NW	NE	NS	SubH
0–79	116		286/85	022/73	149/80	038/05
79–91	35	266/73	111/84	020/80		321/07
91–110	25		288/77			323/03
110–122	69					046/18
122–160	67					068/18
160–184	125		297/69			322/03
184–266	119				338/83	030/06
266–268	7		114/75	040/83		017/15
268–303	80					041/06
303–310	15			037/66		031/08
310–415	132			045/78		035/05
415–520	492		297/74			031/14
520–600	121				147/71	044/03
600–893	164				149/72	037/07
893–905	50				140/78	079/19
905–922	3				143/84	
922–925	21					050/34
925–976	25		128/79			075/34
976–982	11					078/38
982–1,001	10					110/28

Table 2-2. Fisher's constant of the fracture sets identified for borehole KSH02A (SICADA, 04-01-26).

Depth (m)	Number of fractures	EW	NW	NE	NS	SubH
0–79	116		25.70	58.24	17.47	27.48
79–91	35	599.7	10,000	113.27		13.27
91–110	25		15.31			62.14
110–122	69					17.30
122–160	67					17.20
160–184	125		18.41			21.36
184–266	119				24.94	31.27
266–268	7		10,000	10,000		10,000
268–303	80					80.34
303–310	15			35.24		129.13
310–415	132			46.16		137.99
415–520	492		40.71			18.58
520–600	121				52.88	60.89
600–893	164				64.38	133.62
893–905	50				19.47	6.71
905–922	3				10,000	
922–925	21					12.30
925–976	25		220.18			16.11
976–982	11					47.38
982–1,001	10					8.65

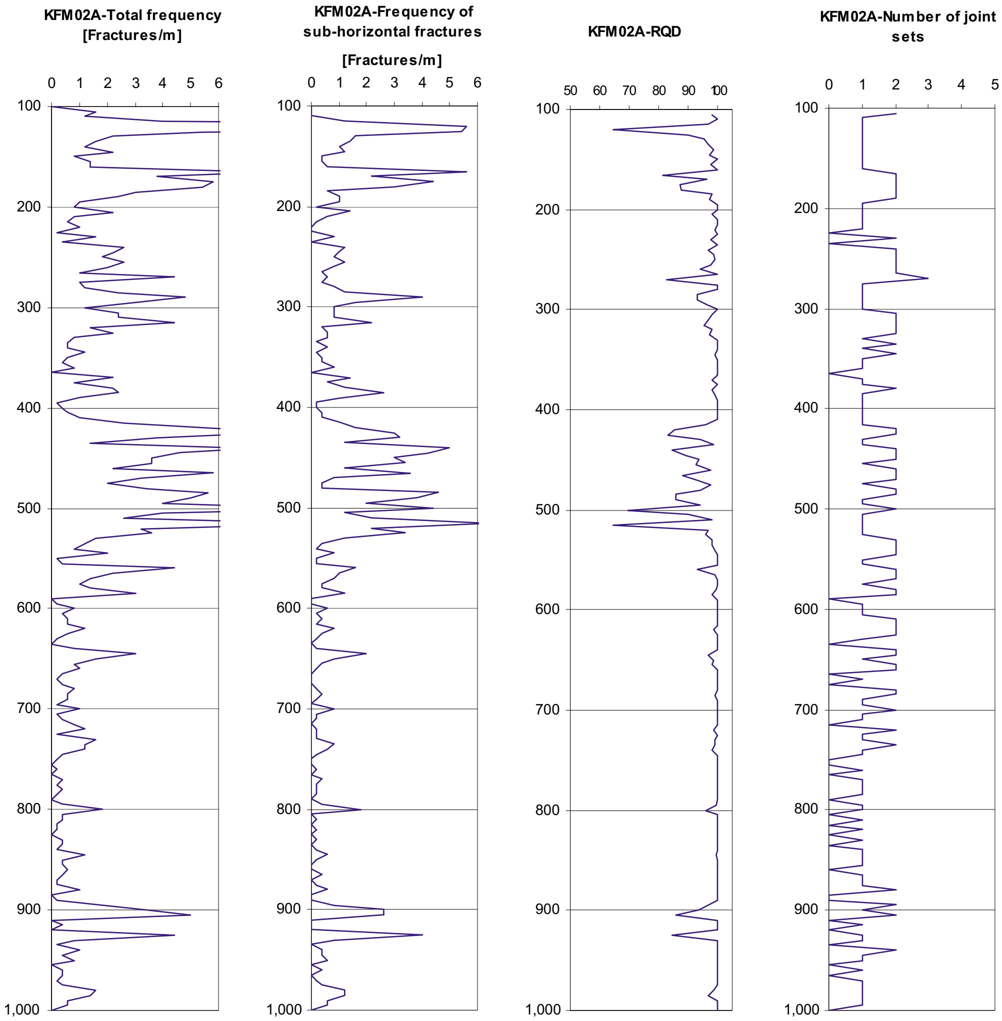

Figure 2-2. *Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM02A. The values are averaged for each 5 m length of borehole.*

In Figure 2-3, the spacing of each of the fracture sets occurring in Borehole KFM02A is shown. While some of the fracture sets has a very low spacing along a rather limited core section (Set EW), the sub-horizontal fracture set (SubH) occurs along the whole borehole. The set NW, NE and NS appear along continuous core sections of length of about 20 to 200 m. Some crushed zones were indicated by the BOREMAP logging at the following depths: 110–119 m, 267 m, 286–299 m, 417–425 m and 483–513 m.

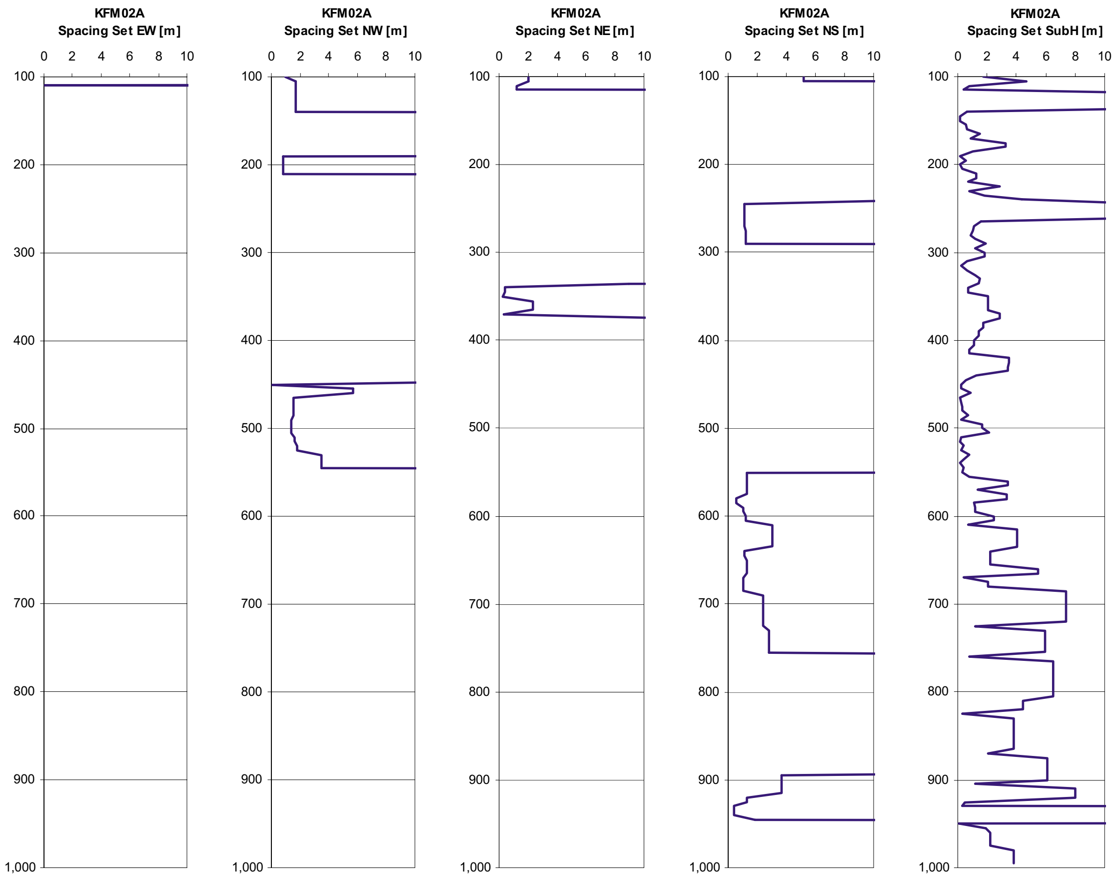

Figure 2-3. *Fracture spacing with depth for the five facture sets in borehole KFM02A. The values are averaged for each 5 m length of borehole.*

3 Mechanical tests

A campaign of laboratory tests is being carried out at the time of compilation of the present report. The results were however not yet available at the time when the analysis contained in this report were carried out. New data has being delivered to SKB's database SICADA on July the 30th, 2004. Those additional data contain:

- Uniaxial and triaxial compressive tests on intact rock.
- Indirect tensile strength tests on intact rock (Brazilian Tests).
- Shear tests on fracture samples.

A series of tilt tests were also conducted on fracture samples from Borehole KFM02A by /Chryssanthakis, 2004/ and the results are summarised in the next sections.

3.1 Intact rock density

To determine the normal load acting on the fractures during tilt testing, the density of the upper half core samples was determined. It resulted in a rock density variation at the wall of the fractures ranging between 2.61 and 2.66 g/cm^3. When the attention is devoted to samples taken at different depths, some differences were observed: 2.65 g/cm^3 to a depth of 420 m, 2.61 g/cm^3 between 420 and 580 m, and 2.66 g/cm^3 to a depth larger than 580 m.

3.2 Intact rock strength

There are no new results from testing of the intact rock yet (by May, 2004). Most of the intact rock is assumed to have the same uniaxial compressive strength, UCS, as in Borehole KFM01A. The minimum, average, most frequet, and maximum UCS are assumed to be 100, 200, 210 and 300 MPa, respectively (Table 3-1). These values are, however, estimations of the strength based on data from the SRF Repository. The Young's modulus of the intact rock is assumed to range between 40 and 90 GPa, with an average value of 75 GPa. The Poisson's ratio of the intact rock is assumed to vary between 0.11 and 0.43, with an average value of about 0.24.

Along borehole KFM02A, a section of very porous altered metagranite ("vuggy metagranite") was observed between about 240 and 310 m. Based on the observations on the core, this rock type should have a low strength comparable with that of quartzitic sandstone (e.g. /Lama and Vutukuri, 1978; Carmichael, 1989/). Because there are no data available, for this rock type the minimum, mean and maximum UCS was estimated to be 50, 85 and 120 MPa, respectively. The Young's modulus of such rock should not differ from that of the intact granite of the rest of the borehole core.

Table 3-1. Estimated uniaxial compressive strength of the intact rock in borehole KFM02A.

Uniaxial compressive strength (MPa)	Minimum	Average	Most frequent	Maximum
Granite to granodiorite	100	200	210	300
Porous altered metagranite	50	85	85	120

3.3 Rock fracture properties

It was rather difficult to find suitable samples along the core due to the small core diameter and the presence of many drilling breaks according to /Chryssanthakis, 2004/. The recurrent kinds of coatings of the fractures are calcite and chlorite, but sometimes pyrite, epidotite and laumontite also occur. 40 samples were finally chosen at depths between 200 and 840 m.

The mean JRC of the samples is about 6, the joint wall compressive strength about 80 MPa, while the basic and residual friction angles are about 31 and 27 degrees, respectively.

/Chryssanthakis, 2004/ classified the samples according to their inclination with respect to the borehole axis, which does not mirror the fracture sets identified in section. 2. For this reason, the data is here reorganised according to the orientations in Table 2-1 and summarised in Table 3-2. In Appendix A, various plots against depth and correlation diagrams of the fracture parameters are given.

Although the fracture samples exhibit rather uniform mechanical properties, fractures from Set NE present slightly lower JRC, JCS, basic friction angle, and marked lower residual friction angle than the others. These samples were all collected at about 310 m depth.

Table 3-2. Summary of the results of tilt tests performed on rock joints from borehole KFM02A /Chryssanthakis, 2004/.

Fracture set	Number of samples	Basic friction angle**	JRC(100)**	JCS(100)**	Residual friction angle**
Set EW	–	–	–	–	–
Set NW	4	31–33	4–9	66–88	24–31
Set NE	2	26–32	4–7	59–60	19–25
Set NS	9	26–34	3–9	67–103	21–30
Set SubH	9	28–33	4–7	65–116	25–30
Random	15	27–35	2–8	35–132	22–33
All fractures	40*	31 (2)	6 (2)	80 (20)	27 (3)

* 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 (between brackets) of the parameters are listed.

4 Characterisation of the rock mass along the borehole

According to the methodology for rock mass characterisation /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 (see KFM01A). 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 of concern.

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 (Table 4-1). The basic equation for the RMR /Bieniawski, 1989/ is:

$$RMR = RMR_{strength} + RMR_{RQD} + RMR_{spacing} + RMR_{conditions} + \\ + RMR_{water} + RMR_{orientation} \qquad (1)$$

where the subscripts *strength, RQD, spacing, conditions, water, orientation* refer to the strength of the intact rock, the Rock Quality Designation, the conditions and spacing of the fracture, the groundwater conditions and the orientation of the fractures 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:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \qquad (2)$$

where, besides RQD, J_n depends on the number of fracture sets, J_r and J_a on the roughness and alteration of the fractures, J_w on the groundwater conditions and the Stress Reduction Factor, SRF, which takes into account the stresses in the rock mass. These parameters are also described and tabulated in the source.

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	III	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 units

The geological single-hole interpretation /Carlsten et al. 2004/ provides a partitioning of the borehole into pseudo-homogeneous sections that apply also for the rock mechanics analysis. Four different rock type groups were recognised in borehole KFM02A together with 10 fractured or "deformation" zones.

The rock type groups can be shortly described as:

- Medium-grained metagranite to granodiorite with occurrences of amphibolite.
- Vuggy metagranite (low density, high porosity) subjected to strong alteration.
- Predominately fine-grained metagranitoid.
- Tonalitic fine-grained metagranite.

For Rock Mechanics purposes, the partitioning according to rock type groups was kept to investigate possible differences in the rock quality between the different rock types. 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 fractured zones in borehole KFM02A for Rock Mechanics are reported.

Table 4-2. Partitioning of borehole KFM02A: rock units, rock types and fractured zones.

Rock units/ depth (m)	Rock type	Depth (m)	Fractured zones
100–155	RU1	79–91	Extensive crushed zone – RQD about 60
155–205	RU3	110–122	Considered as competent rock for Rock Mechanics
205–240	RU1	160–184	51 cm crushed zone
240–310	RU2*	266–267	Several crushed zones
310–485	RU1	303–310	Grouped with the former crushed zone
485–520	RU3	415–520	Crushed zones at 423–425, 480–483, 496–499, 513 m
520–540	RU1	520–600	Considered as competent rock for Rock Mechanics
540–575	RU3	893–905	Fractured rock
575–600	RU1	922–925	Fractured rock
600–635	RU3	976–982	Considered as competent rock for Rock Mechanics
635–835	RU1		
835–867	RU3		
867–903	RU1		
903–938	RU4		
938–1,001	RU1		

* "Vuggy metagranite" dominates.

4.3 Characterisation with RMR

For each 5 and 30 m long sections of borehole, the geomechanical parameters from borehole logging were scrutinized (see also Appendix B). The minimum, average, most frequent and maximum rating for RMR was determined for each borehole section, sometimes through an averaging process. The maximum and minimum possible values that the rock quality can assume for a certain borehole section are also reported. The possible minimum and maximum RMR values are obtained by combining the RMR ratings in the most favourable and unfavourable way, respectively. These take into account the uncertainty of the empirical methods, that of the geomechanical parameters and the uncertainty that depend on the operator performing the characterisation.

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 in the same figure, for 5 m and 30 m, respectively. The ratings for tunnel orientation and water pressure were assumed for "fair conditions" ($RMR_{orientation}$ = 0) and for a "completely dry" borehole (RMR_{water} = 15), as prescribed for rock mass characterisation.

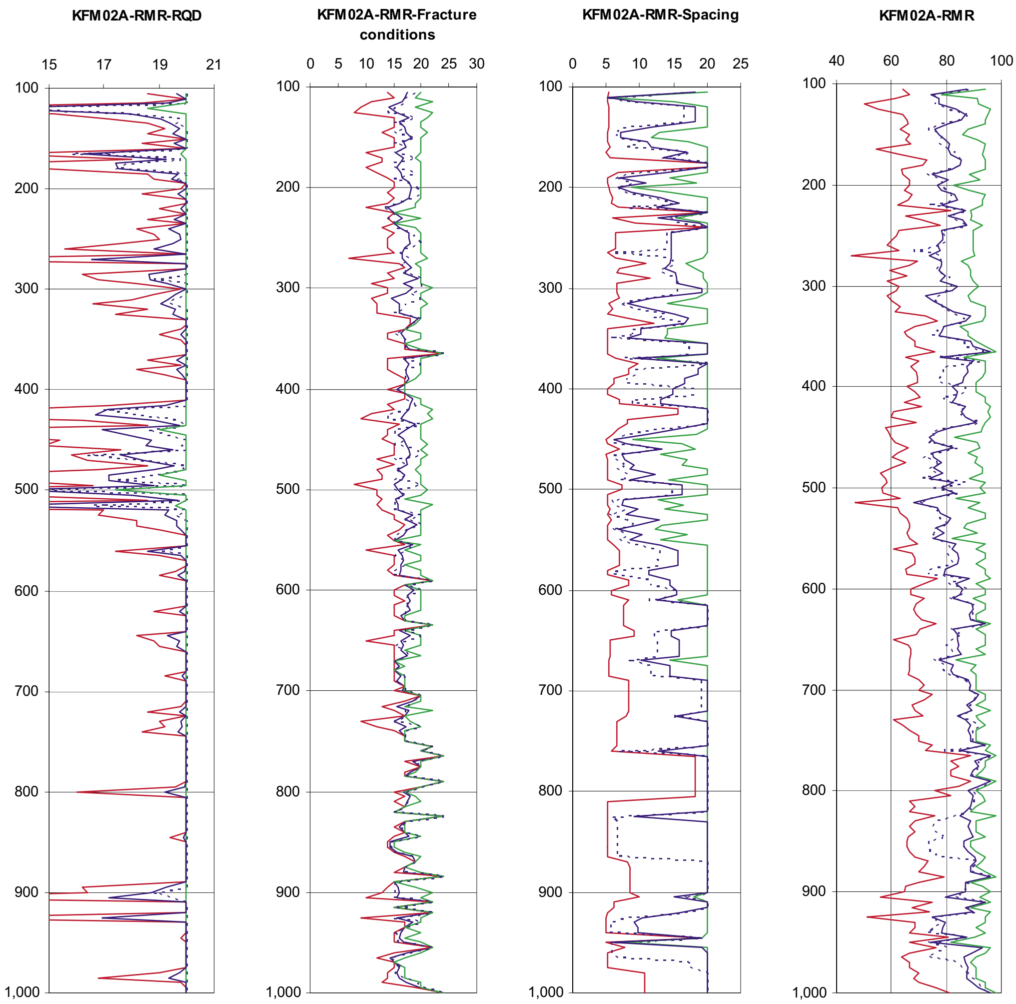

Figure 4-1. *Ratings for RMR characterisation and resulting RMR values for borehole KFM02A. The ratings for RQD, fracture conditions, fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every 5 m long core section, respectively.*

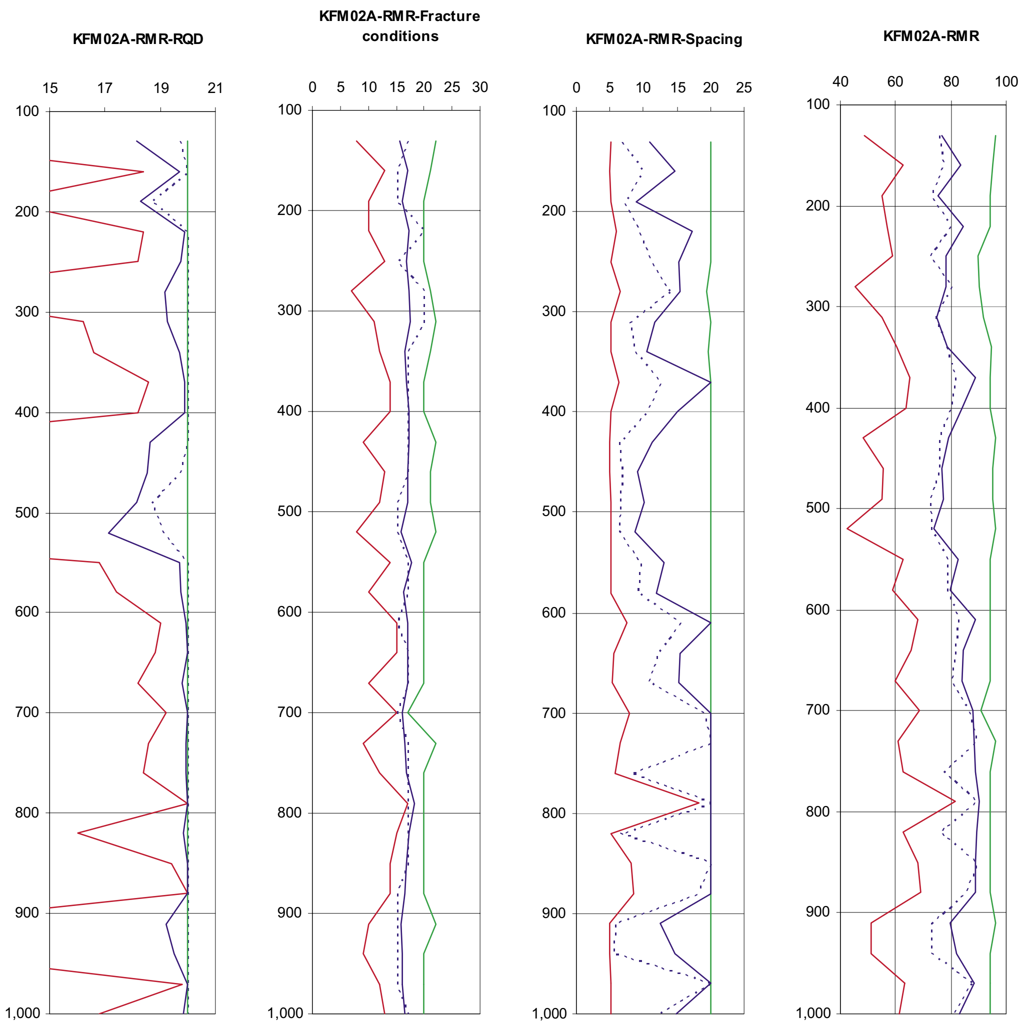

__Figure 4-2.__ RMR and RMR ratings as a function of depth for borehole KFM02A. Minimum, average, most frequent and maximum values are plotted in red, blue, dashed blue and green respectively. Core sections of 30 m are considered.

The RMR values were also summarised for each rock type, for competent rock and fractures zones as shown in Table 4-3. When referring to the rock quality classes in Table 4-1, the rock mass along borehole KFM02A can be described as "very good", even thought toward the lower range of this class. There are not remarkable differences between the rock type groups in rock unit RU1, RU3 and RU4, while group in RU2 show a lower rock quality in the upper range of the rock class "good rock".

The variation of RMR for the rock units is also shown in a graphical form in Figure 4-3 where two different core section lengths 5 and 30 m are analysed. No apparent scale-effect can be noted on the results from the RMR determination. The results generally coincide along the entire borehole length. This is probably due to the homogeneity of the fracture properties along the borehole with respect to their orientation. The low fracture frequency can also imply a limited scale dependency.

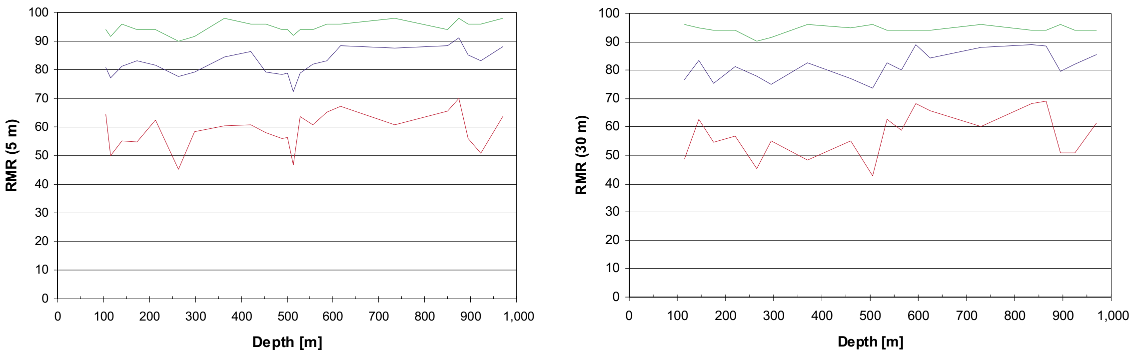

Figure 4-3. *Variations of RMR with depth for the two different length of core section of 5 (left) and 30 m (right). Minimum possible, average, most frequent and maximum possible values are plotted in red, blue, dashed blue and green, respectively.*

Table 4-3. Summary of RMR values for borehole KFM02A (core sections of 5 m).

Rock unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Minimum possible RMR	Maximum possible RMR
A	73.7	84.8	86.0	96.0	5.5	50.0	98.0
B	72.4	78.1	78.1	83.9	2.9	45.2	91.7
C	68.1	83.4	83.9	94.0	5.6	46.6	96.0
D	74.8	83.1	79.7	94.0	7.1	50.9	96.0
Competent rock	73.7	84.4	84.9	96.0	5.6	45.2	98.0
Fractured rock	68.1	80.9	81.7	87.0	5.1	46.6	96.0
Whole borehole	68.1	83.9	84.1	96.0	5.7	45.2	98.0

4.4 Characterisation with Q

The input numbers for the Q system and the resulting rock quality index are plotted in Figure 4-4 and Figure 4-5 for 5 m and 30 m borehole sections, respectively. Like for RMR, the Q numbers are obtained through the choice of the average, most frequent, possible minimum and maximum values of the geomechanical parameters logged along the borehole and combined with each others to mirror the intrinsic uncertainty of the method and of the input parameters. The possible minimum and maximum Q values are obtained by combining the indices in the most favourable and unfavourable way, respectively.

The fracture set (J_n), roughness (J_r) and alteration (J_a) numbers are obtained for each borehole sections of 5 and 30 m (see also Appendix B). SRF is assigned to the fractured zones based on information of 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. The fractured zones listed in Table 4-2 and the whole “vuggy metagranite” in rock unit B were assigned an SRF of 2.5. The Q-number for water (J_w) was assumed equal to 1 for a dry borehole, as it is usually done for rock mass characterisation.

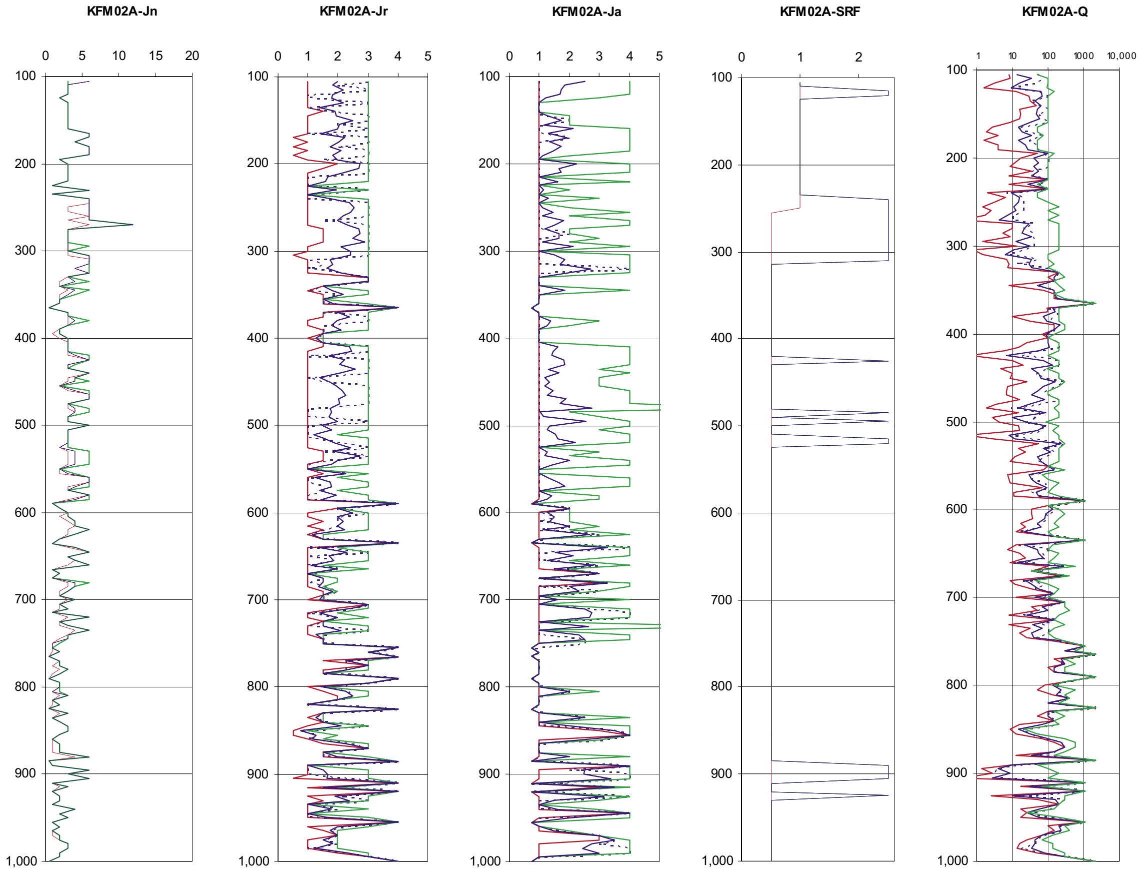

Figure 4-4. *Numbers for Q characterisation and resulting Q values for borehole KFM02A. The number for fracture set number, fracture roughness; fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every 5 m long core section, respectively.*

The variation of Q with depth for the two different lengths of core section of 5 and 30 m are shown in Figure 4-6. The plots show that Q is rather sensitive to the change of scale. In fact, the maximum possible values diminish when the core section length goes from 5 to 30 m. On the other hand, the mean value does not seem to be much affected by scale. This is probably due to the fact that longer core sections tend to sample a larger variability of fracture properties. Furthermore, the probability that a larger number fracture sets are encountered by a long borehole section increases, and thus Q tends to decrease.

The Q values were also summarised for each rock type, for competent rock and fractures zones as shown in Table 4-4. According to the Q system, the rock in borehole KFM02A can generally be classified as "very good rock". The rock types grouped as units RU1, RU3 and RU4 show higher quality than RU2 (vuggy metagranite) that is classified as "good rock". In average, the fractured zones can also be classified as "good rock" with some exceptions in the "poor rock" class.

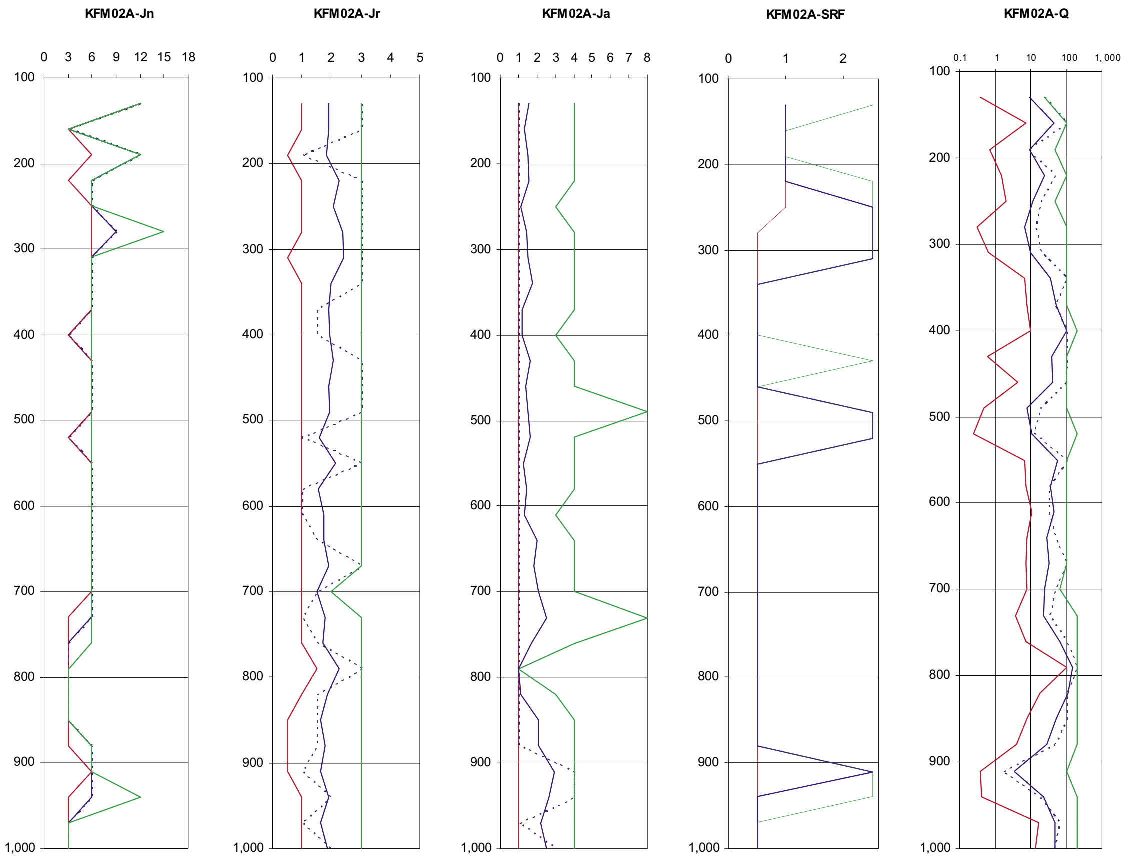

Figure 4-5. *Q and Q numbers as a function of depth for borehole KFM02A. Minimum, average, most frequent and maximum values are plotted in red, blue, dashed blue and green, respectively. Core sections of 30 m are considered.*

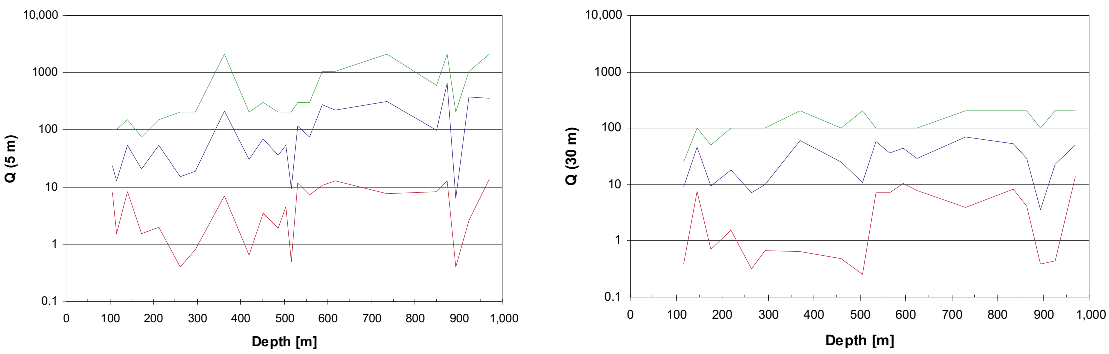

Figure 4-6. *Variations of Q with depth for the two different core section lengths 5 and 30 m. Minimum, average, most frequent and maximum values are plotted in red, blue, dashed blue and green, respectively.*

Table 4-4. Summary of the Q values for borehole KFM02A (core sections of 5 m).

Rock Unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Confidence min Q	Confidence max Q
A	2.8	218.5	71.4	2,133.3	0.4	2,133.3
B	4.3	16.5	13.9	33.3	0.4	200.0
C	7.9	91.7	50.0	1,066.7	0.5	1,066.7
D	10.3	369.5	158.3	1,066.7	2.6	1,066.7
Competent rock	4.3	209.8	71.2	2,133.3	0.4	2,133.3
Fractured rock	2.8	19.0	12.7	84.8	0.4	200.0
Whole borehole	2.8	185.4	62.3	2,133.3	0.4	2,133.3

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 of a single parameter can widely vary depending on the acquisition technique, subjective interpretation or size of the sample population. But uncertainty can also be derived 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. To take into account the spatial variability, the differences between maximum and mean value, and minimum and mean value are evaluated at 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 of the mean $\Delta_{conf\ mean}$ is obtained as:

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

where σ is the standard deviation of the population and n is the number of values of the sample. The number of values on which the mean can be calculated on average for each rock unit. In KFM02A, there are in average 11 borehole sections of 5 m in competent rock and 3 sections in fractured rock. 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:

$$\Delta P_{+conf\ mean} = \frac{P_{MAX} - P_{MEAN}}{\sqrt{n}}$$
$$\Delta P_{-conf\ mean} = \frac{P_{MEAN} - P_{MIN}}{\sqrt{n}} \qquad (4)$$

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. 5) 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 KFM02A. It can be noticed that although RMR shows a total variation span of about 9% around the RMR mean value, Q spans over an interval correspondent to 76% of the mean Q value. This is due to the fact that the Q value can span from 40 to 2,000 within the classes of "very good", "extremely good" and "exceptionally good" occurring along borehole KFM02A. For the fractured rock this effect is even more accentuated because some borehole sections with very good rock are alternated with rock with poor quality making the range of Q values going from about 1 to about 100. However, these confidence intervals should be 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) the values composing the characterisation results for a certain rock unit are in general reduced to one fourth.

Table 4-5. Uncertainty of the mean values of RMR and Q for borehole KFM02A with borehole sections of 5 m.

	Competent rock		Fractured rock	
	Lower confidence of the mean	Upper confidence of the mean	Lower confidence of the mean	Upper confidence of the mean
RMR	–6%	+3%	–14%	+8%
Q	–14%	+62*%	–45*%	+663*%

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

Table 4-6. Uncertainty of the mean values of RMR and Q for borehole KFM02A with borehole sections of 30 m.

	Competent rock		Fractured rock	
	Lower confidence of the mean	Upper confidence of the mean	Lower confidence of the mean	Upper confidence of the mean
RMR	–18%	+8%	–34%	+23%
Q	–56%	+196*%	–94*%	+1,010*%

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

It can be observed that the scale of RMR determination does only marginally affect the confidence of the characterisation results. Differences could be observed for the deepest rock domains. The confidence span of Q, on the other hand, seems to be very sensitive to the scale of the determination. Besides the effect of scale on the mean values, the uncertainty spans are significantly increasing when passing from core section lengths of 5 m to lengths of 30 m. 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 do not change when the length of borehole section is increased. Among these, the ratings estimated based on expert judgement are also included due to the lack of data.

5 Mechanical properties of the rock mass

5.1 Deformation modulus of the rock mass

By means of empirical formulas /Serafim and Pereira, 1983; Barton, 2002/, it is possible to obtain an estimation of the equivalent deformation modulus E_m of the rock mass seen as a continuum. 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 average, most probable possible minimum and maximum expected deformation modulus are given. Comparing the mean values obtained independently by means of RMR and Q_c, a very good agreement can be observed in Figure 5-1 (right). Larger differences are found for the vuggy metagranite (rock type group B) due to the choice of the SRF=2.5 factor for Q_c for this borehole section.

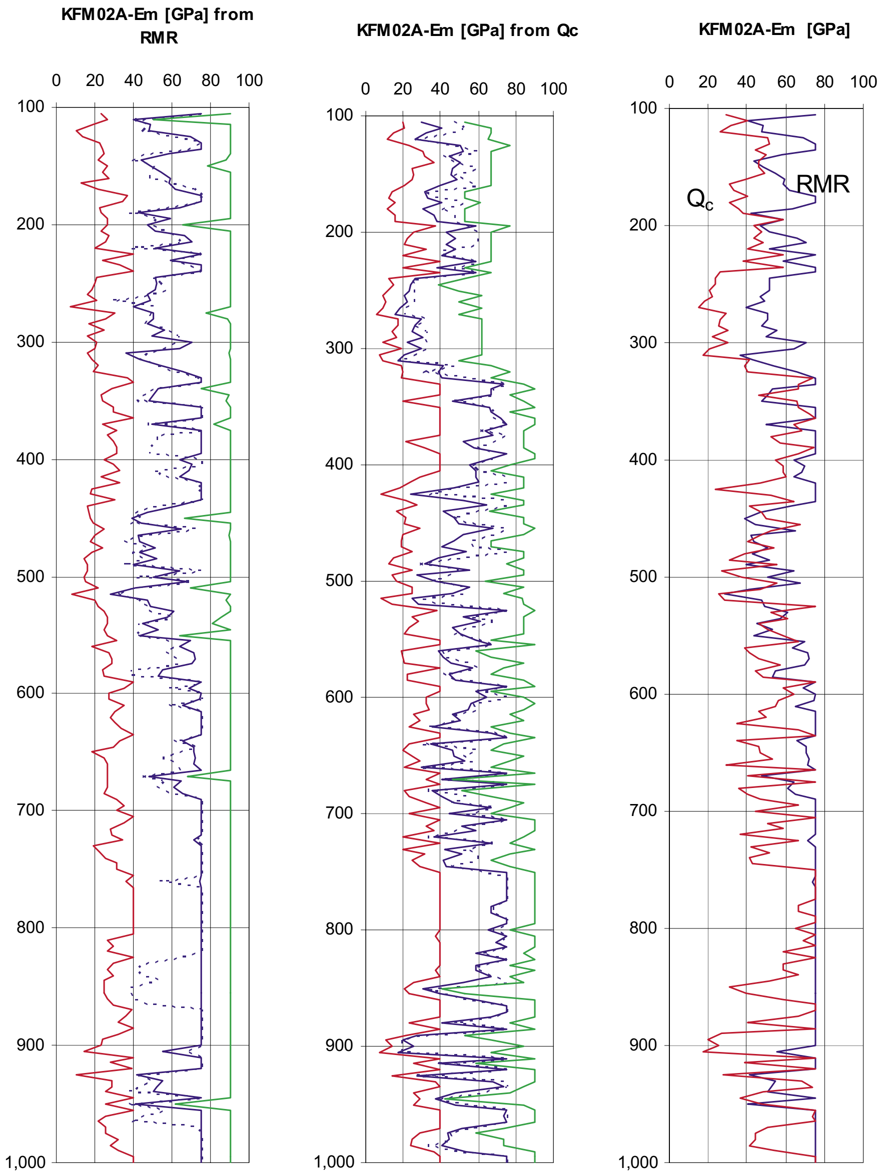

Figure 5-1. *Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m for borehole KFM02A. A comparison of the mean values along the borehole is given in the graph on the right.*

In general, Q_c produces deformation moduli lower than RMR (Table 5-1). By combining the two results, the mean deformation modulus for the competent rock varies in the range 54–66 GPa, with extreme values between 40 and 75 GPa. It is worth to notice that a cut-off value of the mean deformation modulus of 75 GPa has been applied due to the physical limit represented by the deformation modulus of the intact rock. For the fractured rock, the mean deformation modulus should vary between 30 and 60 GPa. The relatively high values can be explained by the fact that the fractured zones often concern rocks with relatively good rock mass quality.

In Figure 5-2 and Figure 5-3, the histograms of the deformation modulus of the rock mass obtained by means of RMR and Q_c for each rock unit are shown for the purpose of comparison. It can be noticed that the distribution of E_m obtained from RMR exhibits a sudden peak when applying a cut-off limit of 75 GPa. However, the shape of the distributions are rather similar to the values of the deformation modulus from Q_c, except for the fractured rock, where the influence of the SRF factor leads to lower values of the deformation modulus from Q_c.

An independent Q determination was carried out on the core of borehole KFM02A by /Barton, 2003/. As shown in Figure 5-4, the two results agree very well. Some differences can be observed for the worse rock quality because the logging by Barton was applied to core sections of variable length, while the single-hole interpretation in this report was carried out every 5 m. Due to averaging processes, some of the extreme peaks can only be observed in the results from Barton's investigations.

Table 5-1. Summary of the deformation modulus E_m derived from RMR and Q for borehole KFM02A (core sections of 5 m).

Rock unit	Average mean E_m from RMR (GPa)	Average mean E_m from Q_c (GPa)
A	66.5	54.3
B	51.1	23.3
C	64.7	46.8
D	60.6	58.0
Competent rock	65.5	53.7
Fractured rock	59.5	29.5
Whole borehole	64.7	50.6

A physical threshold of 75 GPa is used for the rock mass deformation modulus. Thus threshold coincides with the mean Young's modulus of the intact rock.

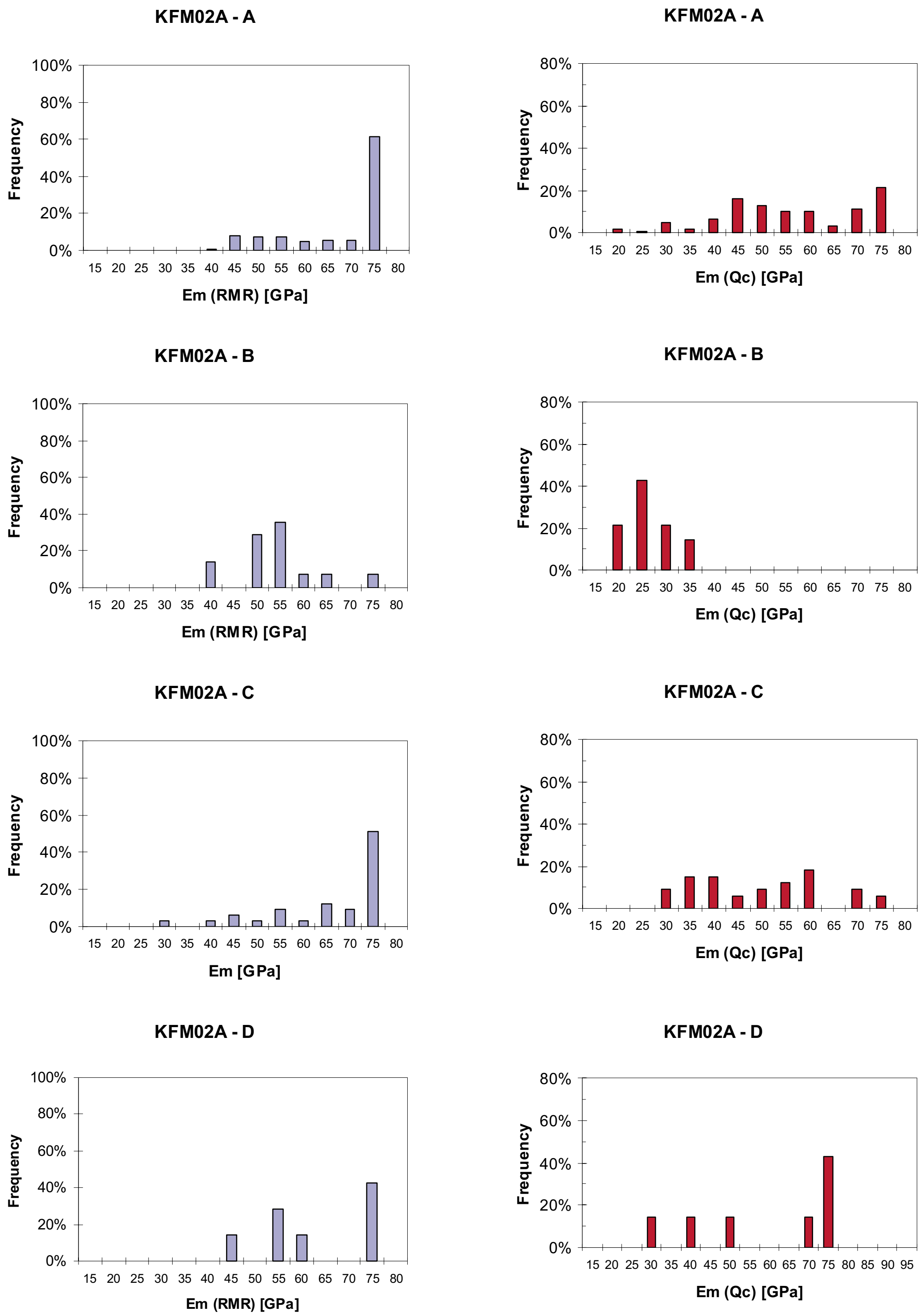

Figure 5-2. *Histograms of the deformation modulus of the rock mass E_m derived from RMR and Q (core sections of 5 m) for the four rock type groups in borehole KFM02A.*

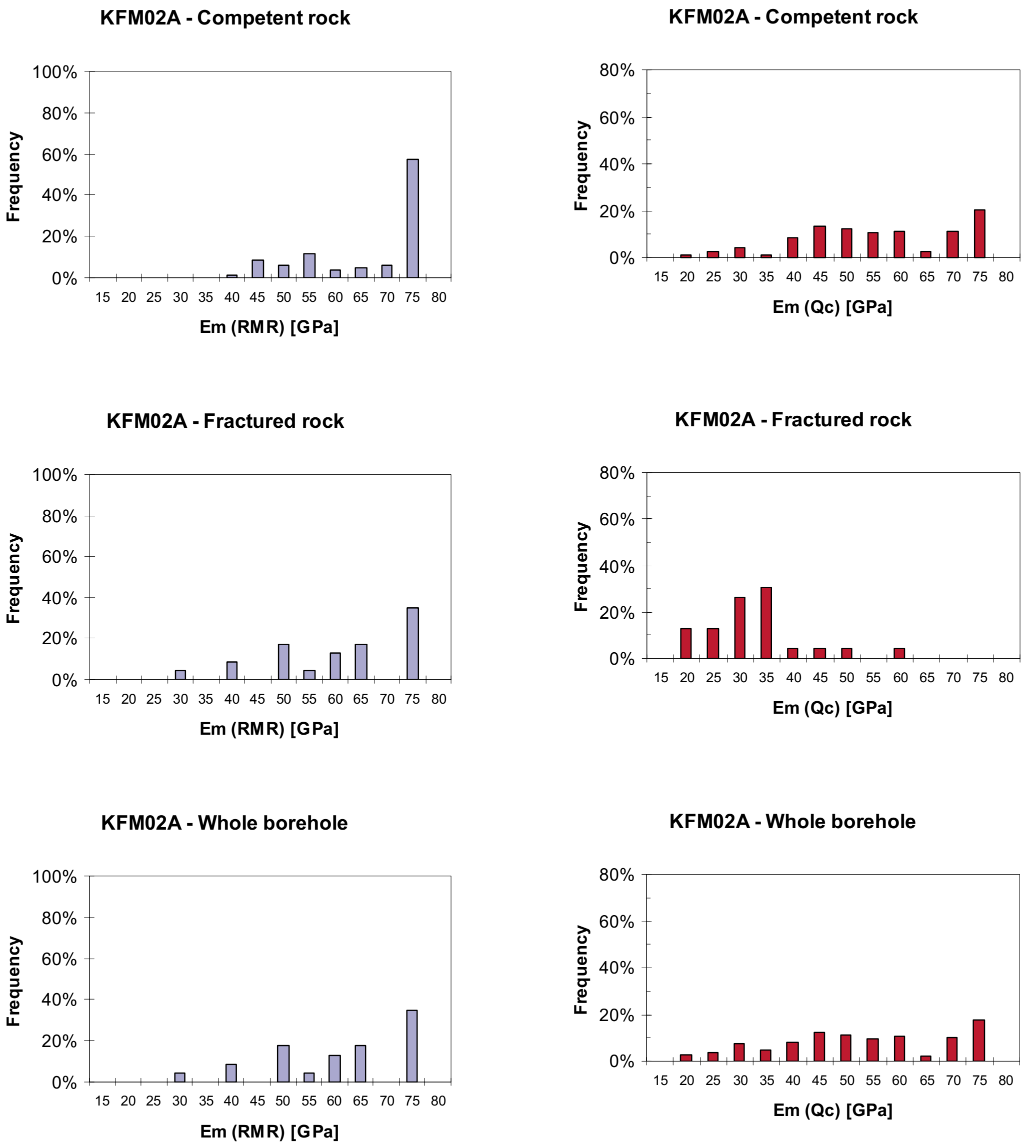

Figure 5-3. *Histograms of the deformation modulus E_m derived from RMR and Q (core sections of 5 m) for competent and fractured rock, and for the whole borehole KFM02A.*

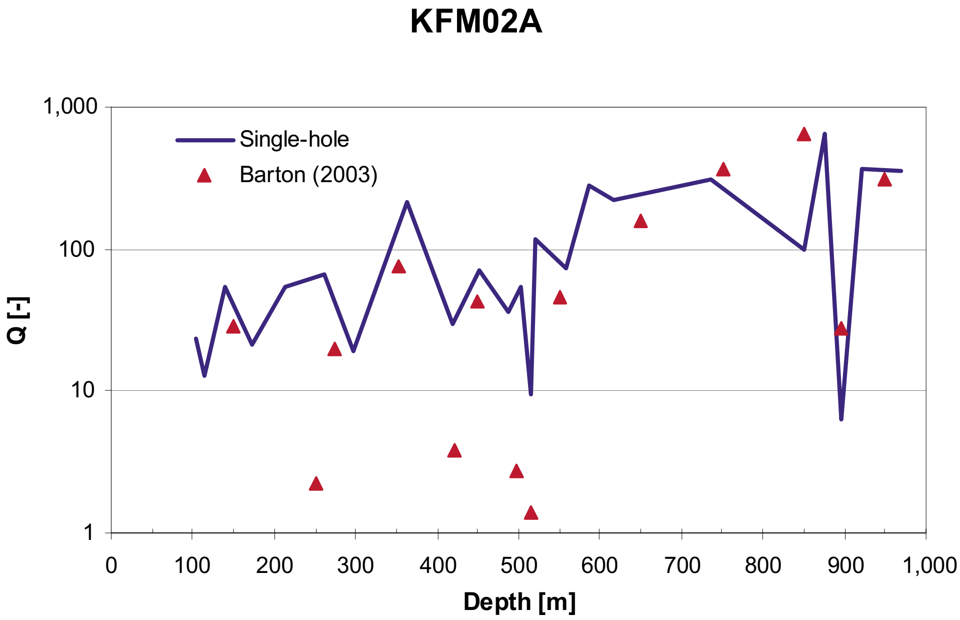

Figure 5-4. *Comparison of the average Q from sigle-hole interpretation with the results obtained by /Barton, 2003/ from the logging of the core of borehole KFM02A.*

5.1.1 Uncertainty

The confidence intervals for the mean deformation modulus calculated from Q_c are smaller than those calculated from RMR (Table 5-2). The upper confidence is almost the same because both methods tend to give the maximum deformation modulus physically possible for this rock mass (90 GPa). Even if the deformation modulus from RMR is in general larger than that from Q_c, the minimum possible deformation modulus obtained from RMR is approximately as large as that obtained from Q_c. This explains why the lower confidence interval on the mean deformation modulus from RMR is larger than that from Q_c. This also means that RMR is more sensitive to effects of the uncertainty on the indexes and ratings than Q_c.

In consequence of the large confidence interval of RMR and Q_c, also the confidence intervals for the deformation modulus are relatively large. This also depends on the fact that the rock mass appear as an alternation of better and poorer rock inside the same rock unit. This is also indicated by the tight alternation of short the rock units along borehole KFM02A (see also Table 4-2).

Table 5-2. Confidence of the mean values of the deformation modulus E_m from RMR and Q_c for borehole KFM02A and borehole sections of 5 m.

Deformation modulus (GPa)	Competent rock		Fractured rock	
	Lower confidence of the mean	Upper confidence of the mean	Lower confidence of the mean	Upper confidence of the mean
E_m (RMR)	–17%	+12%	–34%	+36%
E_m (Q_c)	–14%	+13%	–32%	+72%

5.2 Poisson's ratio of the rock mass

The Poisson's ratio of the rock mass is often determined as a fraction of that 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 KFM02A, the Poisson's ratio of the competent rock is estimated to be about 0.19 on average, while that of the fractured rock could be about 0.14. The range of variation of the possible Poisson's ratio of the rock mass along borehole KFM02A are shown in Table 5-3.

Table 5-3. Estimation of the minimum and maximum Poisson's ratio of the rock mass at different depths.

ν (–)	Minimum	Maximum
100–200	0.13	0.33
200–400	0.11	0.33
400–1,000	0.14	0.34

5.2.1 Uncertainty

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

$$\nu_m = \nu \times \frac{E_m}{E} \qquad (5)$$

where E and ν are the Young's modulus and the Poisson's ratio of the intact rock.

5.3 Uniaxial compressive strength of the rock mass

As shown in Table 5-4, the uniaxial compressive strength obtained by means of RMR agrees very well with that determined by means of Q. However, the strength of the fractured zones estimated by Q_c is much lower than that estimated by RMR. The mean uniaxial compressive strength of the competent rock mass should vary between 60 and 70 MPa, with the exception of the vuggy metagranite that should have a UCS of about 19 MPa, while that of the fracture zones have a UCS between 14 and 74 MPa. The results in Figure 5-5 show the uniaxial compressive strength obtained accoding to the Hoek and Brown's criterion /Hoek et al. 2002/ with parameters derived from RMR through the Geological Strength Index, GSI.

Table 5-4. Summary of the uniaxial compressive strength of the rock mass derived from RMR (Hoek and Brown's criterion) and Q_c (core sections of 5 m) for borehole KFM02A.

Rock unit	Average mean UCS (MPa)	Average mean Q_c (MPa)
A	68.0	136.9
B	19.3	14.0
C	62.9	108.1
D	63.7	141.5
Competent rock	65.3	135.3
Fractured rock	48.1	33.3
Whole borehole	63.1	122.2

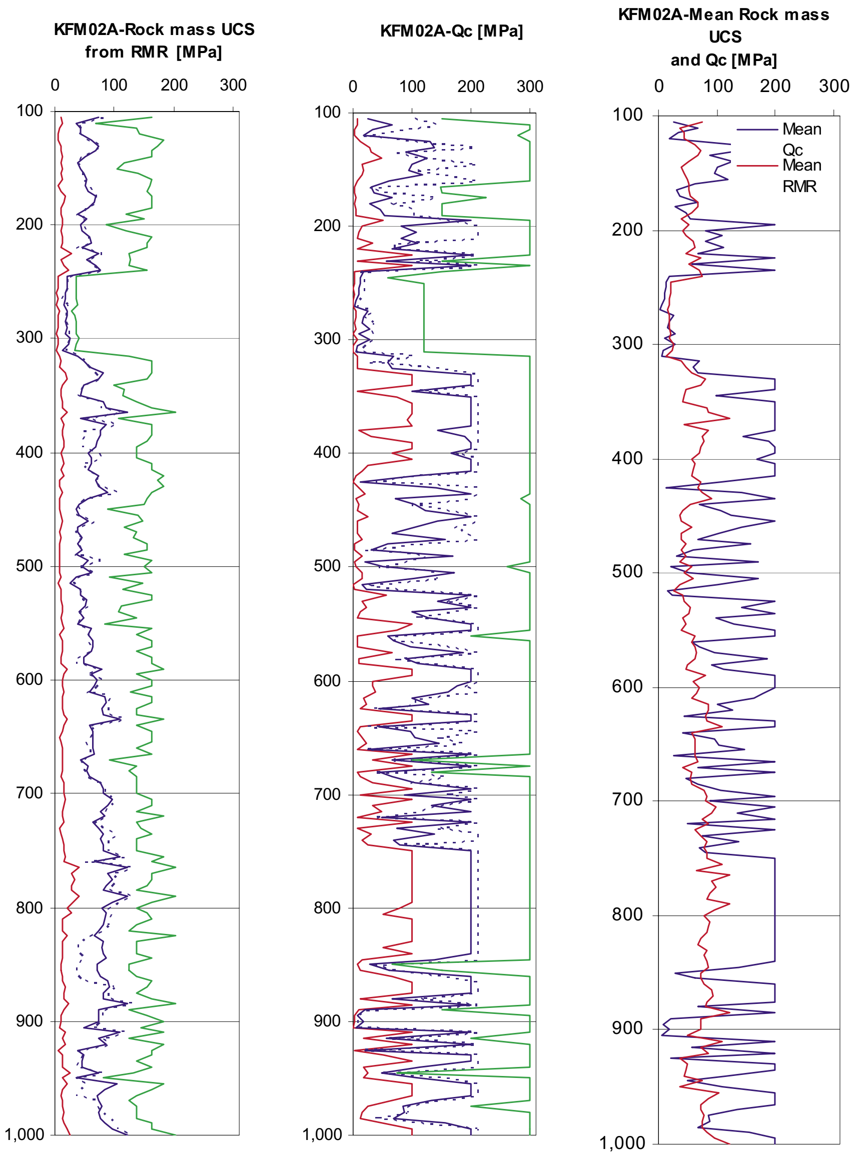

Figure 5-5. *Variation of the rock mass compressive strength from RMR and Q_c for borehole KFM02A.*

5.4 Cohesion and friction angle of the rock mass

In Figure 5-6, the strength of the rock mass is summarised in terms of equivalent cohesion and friction angle obtained by approximating the Hoek and Brown's failure criterion with a linear Coulomb's criterion for low confinement stress (0–5 MPa) and 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, the cohesion of the rock mass varies between 7 and 9 MPa, with a minimum value for the "vuggy metagranite" (about 3 MPa). The friction angle of the rock mass should vary between 57 and 61 degrees for all rock units.

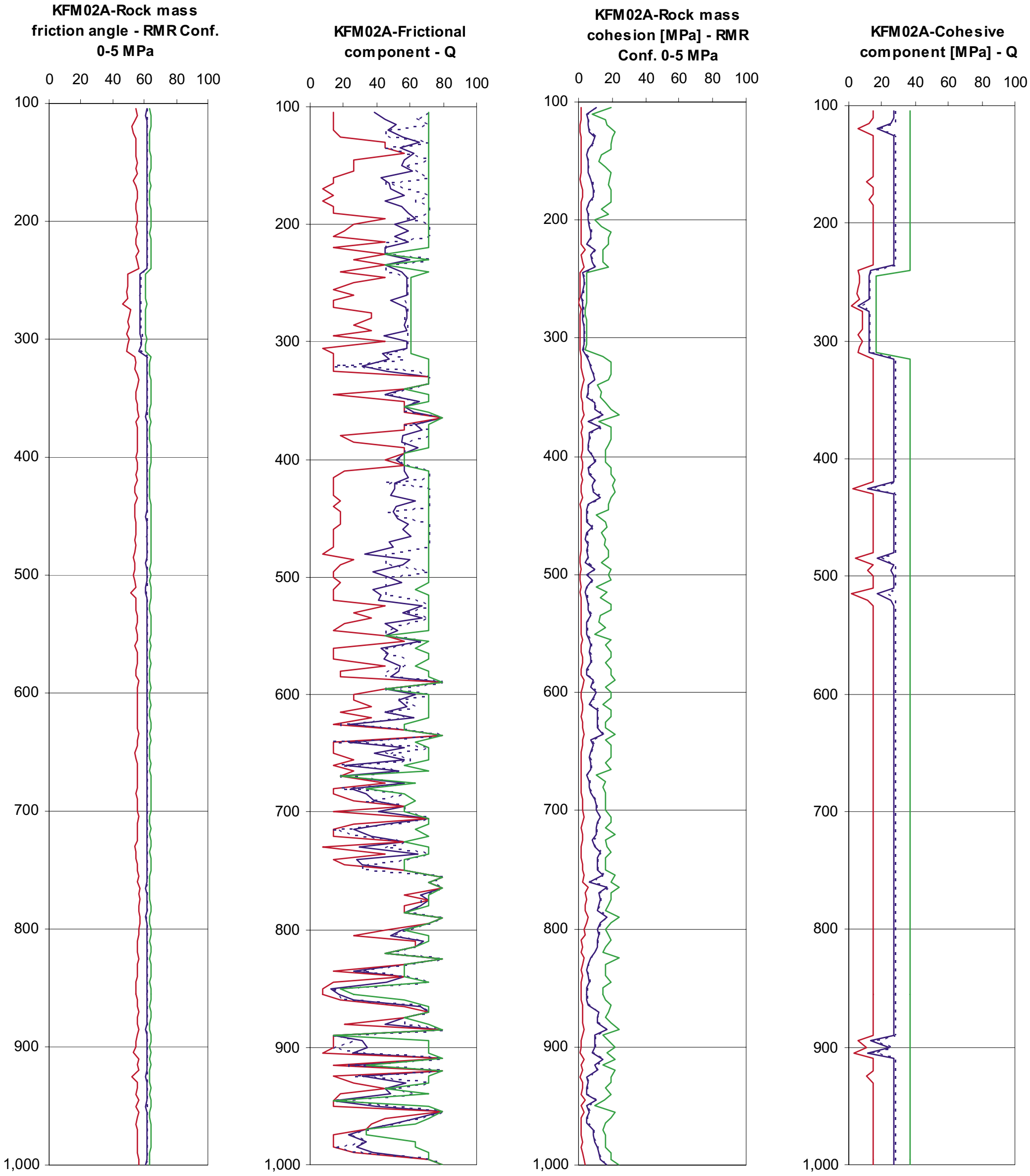

***Figure 5-6.** Variation of the rock mass friction angle and cohesion from RMR and Q for borehole KFM02A under stress confinement between 0 and 5 MPa (core length of 5 m).*

Table 5-5 and Table 5-6 contain the summary of the equivalent Mohr-Coulomb parameters for high confinement stress (10–30 MPa). These parameters are compared with the correspondent parameters obtained by means of the Q system. The equivalent friction angle for high stress confinement is on average about 48°, ranging between 40° (for rock unit B) and 48.5° (for rock unit A). The equivalent cohesion for high confinement stress ranges between 16 (for rock unit B) and 23.5 MPa (for rock unit A), with an average value of 23 MPa. In Figure 5-7, the plots of the equivalent friction angle and cohesion of the rock mass with depth are given for high confinement stress. The values are rather constant except for the sharp trough related to the rock unit B.

Table 5-5. Summary of the friction angle of the rock mass derived from RMR and Q for borehole KFM02A (core sections of 5 m). The confinement stress is between 10 and 30 MPa.

Rock unit	Average mean ϕ' (deg)	Average mean FC (deg)
A	48.5	53.2
B	39.9	55.1
C	47.9	46.3
D	48.1	52.1
Competent rock	48.1	52.6
Fractured rock	46.1	46.0
Whole borehole	47.8	51.8

Table 5-6. Summary of the cohesion of the rock mass derived from RMR and Q for borehole KFM02A (core sections of 5 m). The confinement stress is between 10 and 30 MPa.

Rock unit	Average mean C' (MPa)	Average mean CC (MPa)
A	23.5	26.7
B	15.2	11.5
C	22.3	26.1
D	22.9	27.0
Competent rock	23.1	26.1
Fractured rock	20.5	20.2
Whole borehole	22.7	25.3

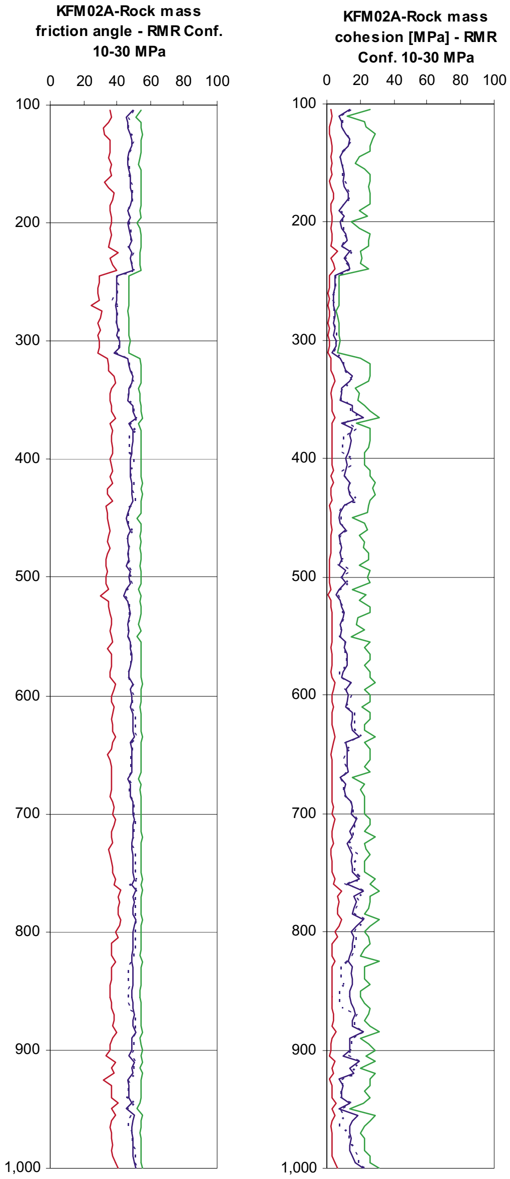

Figure 5-7. *Variation of the rock mass friction angle and cohesion from RMR and Q for borehole KFM02A under stress confinement between 10 and 30 MPa (core length of 5 m).*

5.4.1 Uncertainty

The confidence on the mean values of the equivalent friction angle, cohesion and uniaxial compressive strength $UCS_{m\ (M\text{-}C)}$ of the rock mass obtained by linear approximation of the Hoek and 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 change more widely and can be combined in various ways depending on the operator performing the characterisation.

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

	Competent rock		Fractured rock	
	Lower confidence of the mean	Upper confidence of the mean	Lower confidence of the mean	Upper confidence of the mean
ϕ'	–7%	+4%	–16%	+8%
c'	–13%	+13%	–25%	+32%
$UCS_{m\ (H\ and\ B)}$	–24%	+40%	–48%	+109%

6 P-wave velocity along the borehole

P-wave velocity measurements were carried out on 74 samples taken from the core of borehole KFM02A 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 (e.g relative orientation). By treating the tensor of the velocity, the principal velocity directions relatively to the foliation, and the anisotropy ratio could be determined. In Figure 6-1, the principal P-wave velocities along the borehole are shown. It can be observed that the P-wave velocity has a rather drastic drop at about 300 m where the dip angle of the foliation also significantly changes. Between 300 and 500 m the average velocity is rather constant. For depths larger than 700 m, the velocity starts to diminish almost linearly down to the bottom of the hole and reaches the lowest values along the borehole. The difference between the maximum and minimum principal velocity is small down to 300 m. For larger depths, the difference increases and the anisotropy ratio generally exceeds 1.1.

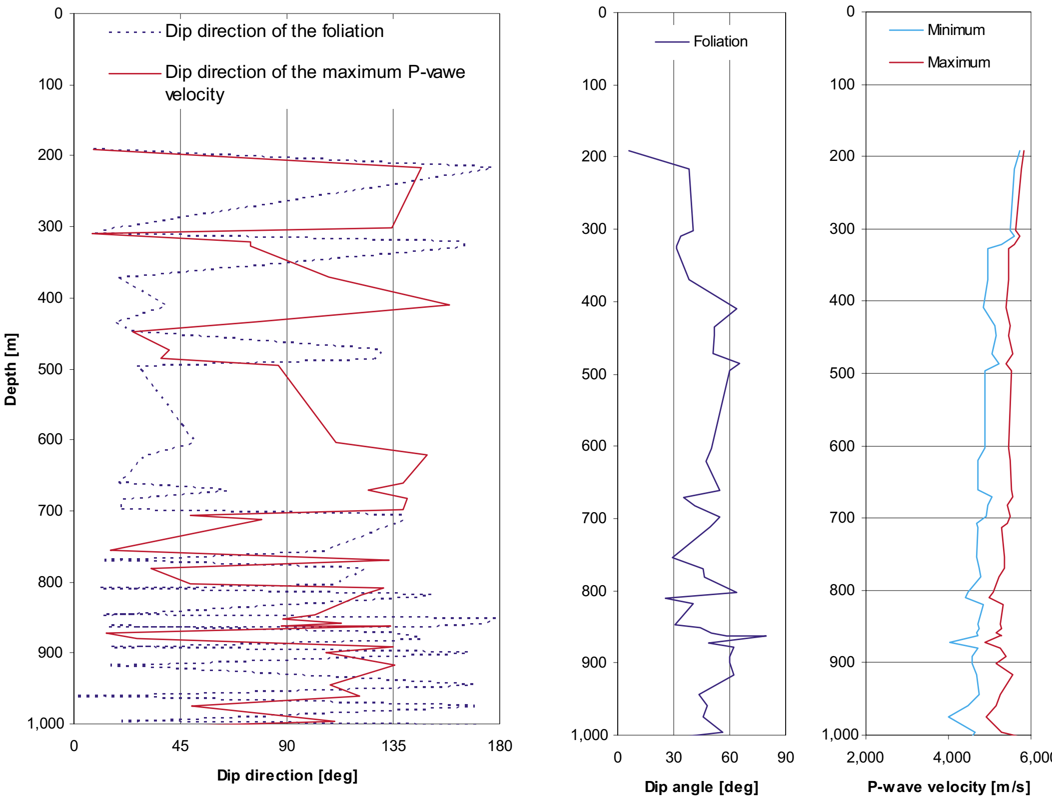

Figure 6-1. *Dip direction of the maximum P-wave compared with the dip direction of the foliation for borehole KFM02A. The dip angle of the foliation and the values of the maximum and minimum P-wave velocities are also shown.*

The absolute orientation of the rock foliation is reported in the BOREMAP data. Thus, the absolute principal velocity orientation is obtained, with some approximations, by combining the information from the two sources. The orientation of the maximum velocity is typically 10–30 or 160–170 degrees from the foliation direction, measured clockwise looking down-hole. Roughly, the dip direction of the maximum P-wave velocity follows the orientation of the dip direction of the foliation. However, the difference in orientation can be between 10 and 30 degrees and can locally be larger.

7 Discussion

In this report, the two independent systems for rock mass quality determination RMR and Q are applied for characterisation of the rock mass along borehole KFM02A. Their results cannot be quantitatively compared since RMR and Q have different ranges of variation. However, the values of RMR and Q for each analysed borehole section can be set into a diagram that makes it possible to assess the consistency between the rock mass quality systems and the results previously published in the literature. In Figure 7-1, the characterisation results for KFM02A are compared with several other empirical relations between RMR and Q obtained for the purpose of tunnel design. 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, for which RMR and Q systems are usually applied. It is worth noticing that the version of the Q-system adopted here (e.g. modified for the characterisation of the rock mass /Barton, 2002/) also considers the increase of stress confinement with depth by means of a favourable SRF factor. This produces higher values of Q than the original Q-system (see relations from the literature in Figure 7-1 and 7-2). Considering that the empirical relations apply on average, however, the characterisation results can be considered satisfactory. The linear regression of the data shown in Figure 7-1 and Figure 7-2 for core sections of 5 and 30 m, respectively, can also be expressed in mathematical terms as:

$$RMR_{(5\,m)} = 2.49 \cdot \ln(Q) + 73.46 \quad (R^2{=}0.33) \qquad (6)$$

$$RMR_{(30\,m)} = 3.93 \cdot \ln(Q) + 69.67 \quad (R^2{=}0.36) \qquad (7)$$

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

As demonstrated in section. 5.1, the scale of evaluation, or the length of the core sections (5 and 30 m), affects the result of the characterisation (e.g. the deformation modulus in Figure 7-3). The analysis of longer core sections applies an averaging process that smoothen all the extreme values of most of the geological input parameters. This averaging process affects RMR and Q in different ways. For core sections of 30 m, the interval of RMR values stays the same as for core sections of 5 m ($75 < RMR < 95$), while that of Q tend to move toward lower Q values (around 10). This probably depends, for example, on the Joint Set Number J_n that tends to diminish as soon as longer core sections are considered. Also the fact that the SRF factor of 2.5 is applied to the fractured zones contributes to this drop. In fact, this factor is sometimes applied to a whole core section of 30 m although not all the rock in the section consists of much fractured rock.

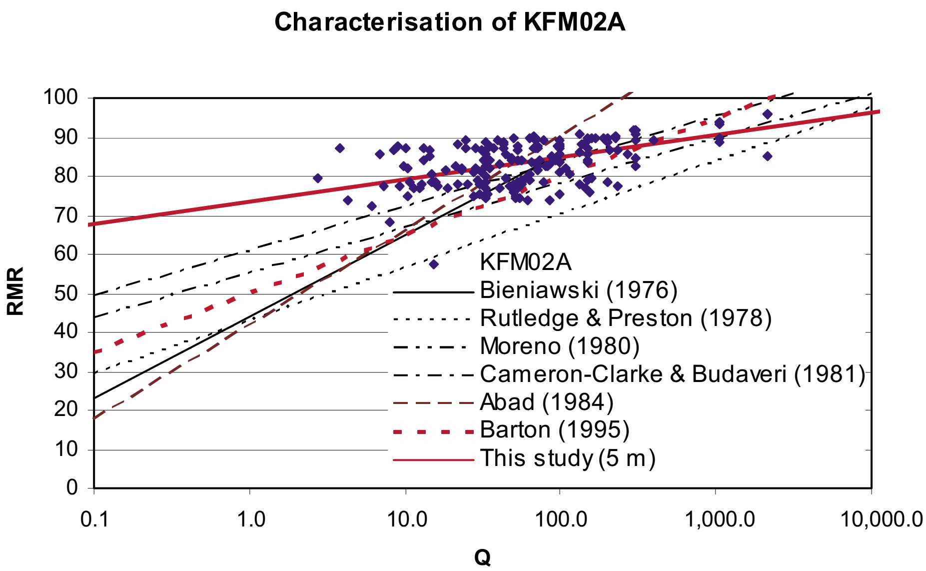

Figure 7-1. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM02A (core sections of 5 m). The characterisation results are compared with some design relations from the literature.*

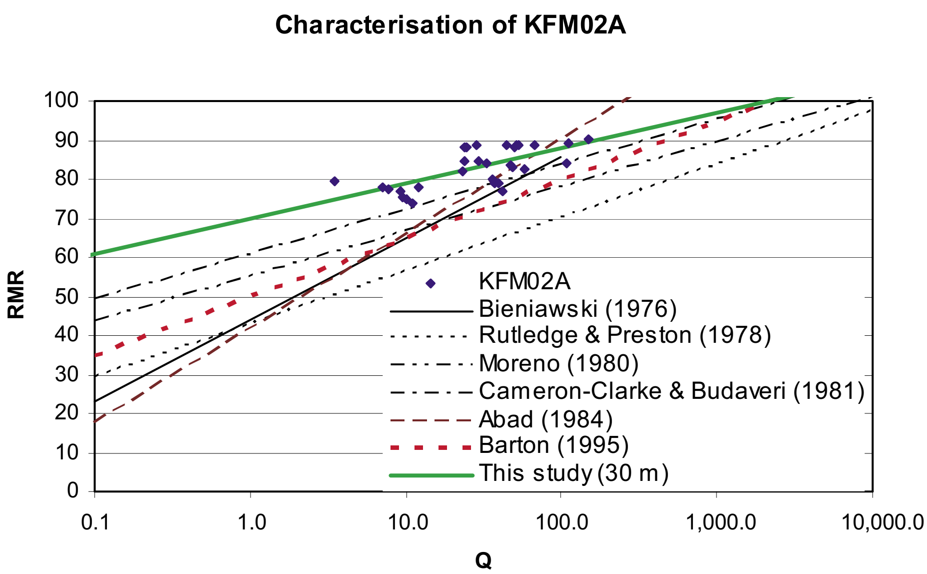

Figure 7-2. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KFM02A (core sections of 30 m). The characterisation results are compared with some design relations from the literature.*

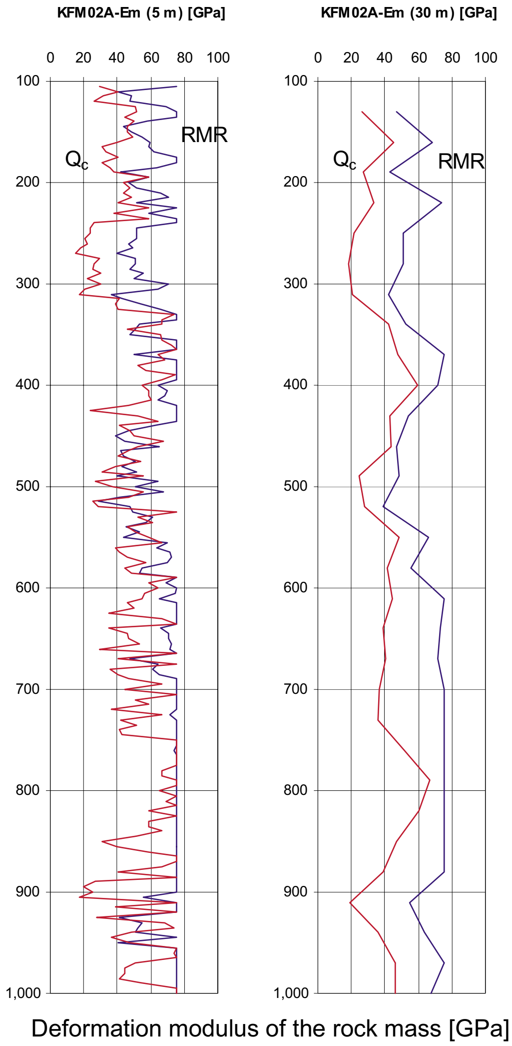

Figure 7-3. *Scale effect on the deformation modulus of the rock mass obtained from RMR and Q for core sections of 5 and 30 m, respectively.*

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 and Brown's failure criteria of the rock mass are provided for the "competent rock" and the "fractured rock". The values are given in average for the whole borehole.

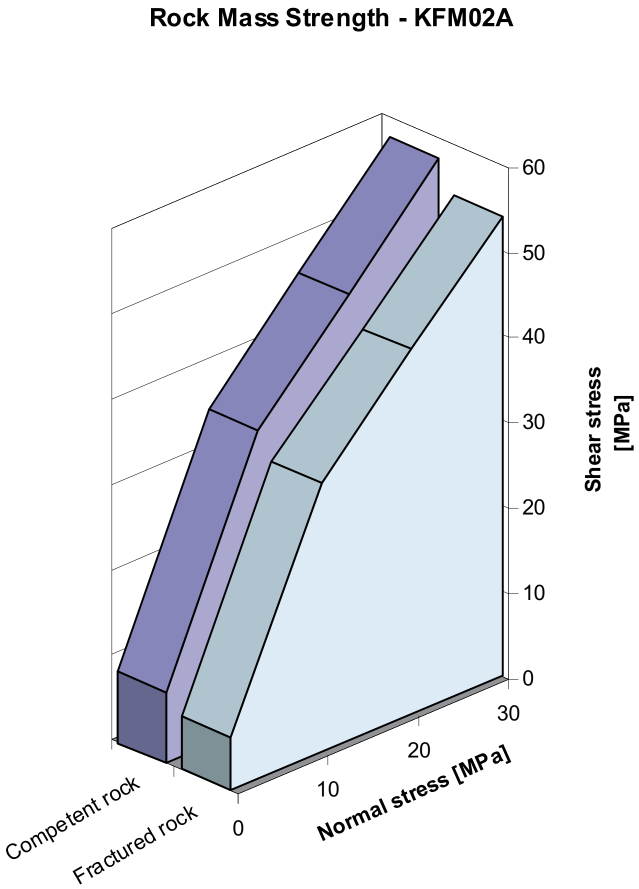

Figure 7-4. *Approximated Hoek and Brown's failure criteria for the "competent rock" and "fractured rock" along borehole KFM02A.*

8 Conclusions

The geological logging of borehole KFM02A was completed by this Rock Mechanics characterisation. The purpose of the characterisation was to determine the rock mass quality and derive mechanical properties by means of empirical methods. The RMR and Q systems were applied here according to SKB's methodology, previously developed /Andersson et al. 2002/.

The data from the borehole, in digital format, were analysed in sections of 5 and 30 m to highlight possible scale effects. It was observed that, while RMR does not seem to be affected by scale, Q tends to diminish when applied to longer borehole sections. This is due to the fact that longer core section intercepts a larger amount of fractures, thus the number of fracture sets occurring in the section can easily increase one or two units. This implies evaluated worse rock conditions.

The application of two independent empirical systems to the characterisation of the rock mass provides a mutual restriction of the range of possible and expected values of the rock mass quality and derived mechanical properties. Some differences between the two methods arise particularly for what concerning the fractured zones. This is probably due to the Q factor called SRF representing the ratio between rock stresses and uniaxial compressive strength of the intact rock. Due to the stepwise structure of the tables providing the values of SRF for the Q system /Barton, 2002/, it is possible that the quality of the fractured zone is slightly underestimated.

The rock quality along borehole KFM02A varies between "good" and "very good", despite the fractured zones. The equivalent deformation modulus of the rock mass was estimated to range between 54–66 GPa, with some possible extreme values between 40 and 75 GPa. The average Poisson's ratio estimated for the rock mass may vary between 0.19 and 0.14, the lower the poorer the rock quality. The total fracture frequency is seldom larger than 6 fractures/m, thus the identified fractured zones are at most classed as "poor rock". This is particularly true at the depths of 510–520 m and 885–905 m. A poorer section of rock is observed between 415 and 520 m, where rather fractured rock is alternated with very good rock.

The equivalent uniaxial compressive strength of the rock mass seem to be over 100 MPa for the competent rock, while it could be as small as about 30 MPa for the fractured zones and the vuggy metagranite. Less marked differences were observed for the equivalent cohesion and friction angle for stress confinement between 10 and 30 MPa. The cohesion of the rock mass varies around 20 MPa for all rock types and rock mass conditions, except for the "vuggy metagranite", where it drops down to about 10 MPa. According to the collected information, this metagranite is highly porous and could be assimilated to quartzitic sandstone. The friction angle of the rock mass should vary between 40 and 50 degrees for all rock type groups.

The results of this single-hole characterisation and those obtained by /Barton, 2003/ agree very well. Only the characterisation of the core of some fracture zones differs, probably due to the sometimes very local determinations performed during direct core logging /Barton, 2003/. The single-hole interpretation is applied to fixed length of borehole (5 m and 30 m), and cannot identify details at scales smaller than the considered borehole length.

Some P-wave velocity measurements are analysed with respect to the orientation of the foliation. The maximum velocity and the dip direction of the foliation seem to be somewhat coherent.

The data contained in the Appendices are delivered and inputted into SKB's database SICADA to complete the single-hole interpretation. This report also contains data that quantify the confidence level of the obtained results. The confidence ranges given are a measure of the spatial variability and uncertainty of the results in each rock unit, rock type group and for the whole borehole.

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" in SICADA. For each borehole, data are given for the pseudo-homogenous sections (rock units) of drillcore/borehole identified by the geological "single-hole" interpretation. For each rock unit, six values resulting from the characterisation are delivered to the database: the minimum, average 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, one 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 delivered data.

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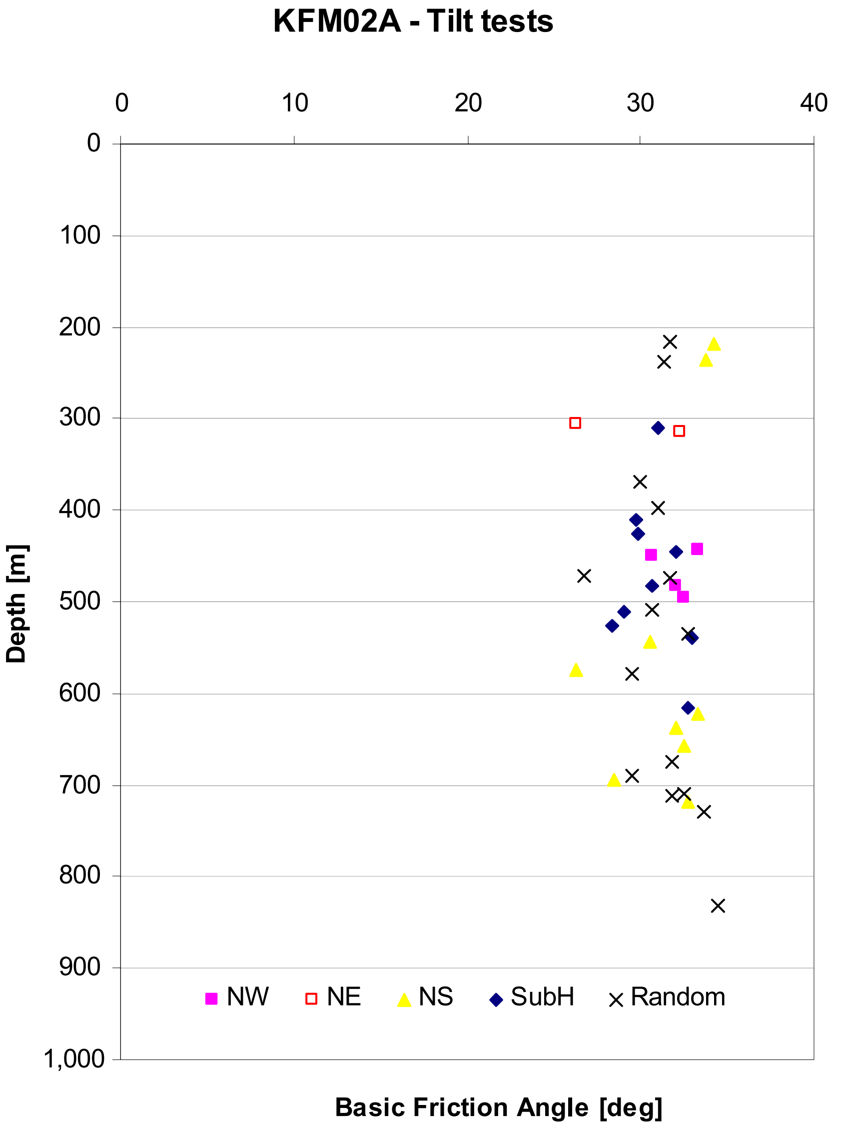
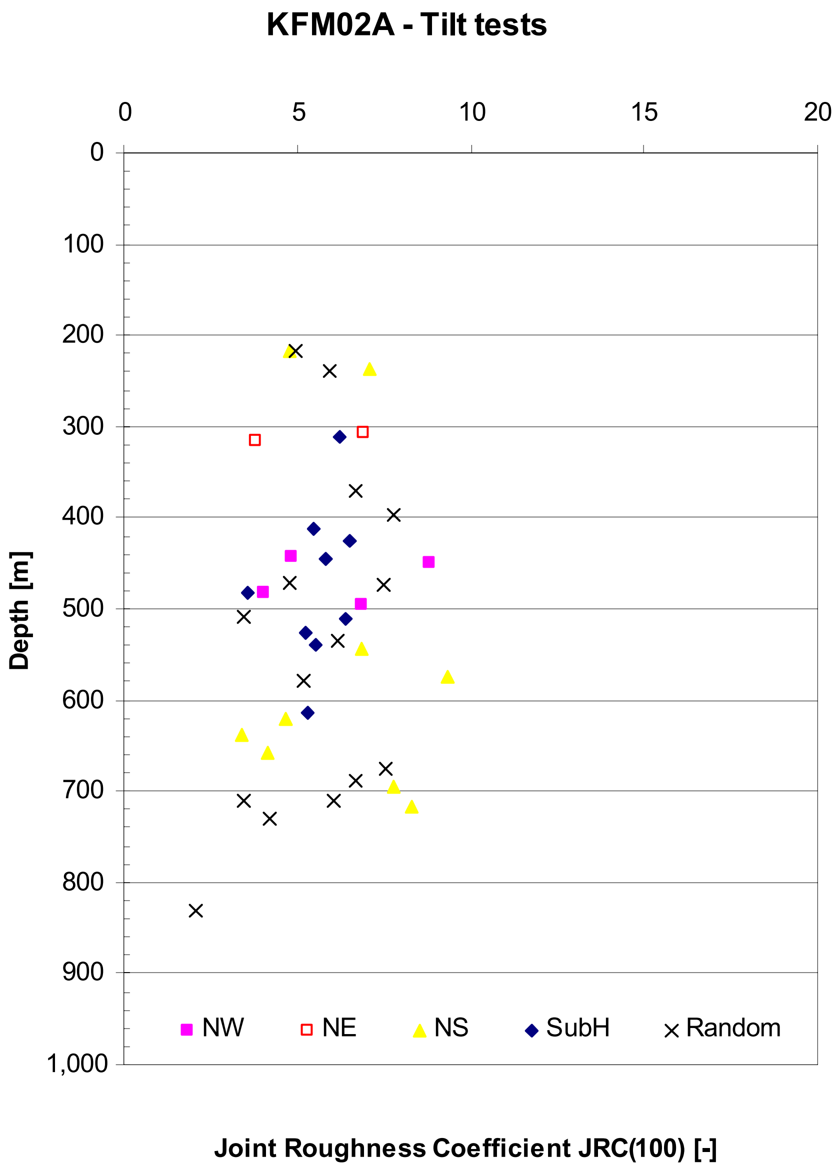
Rock fracture properties

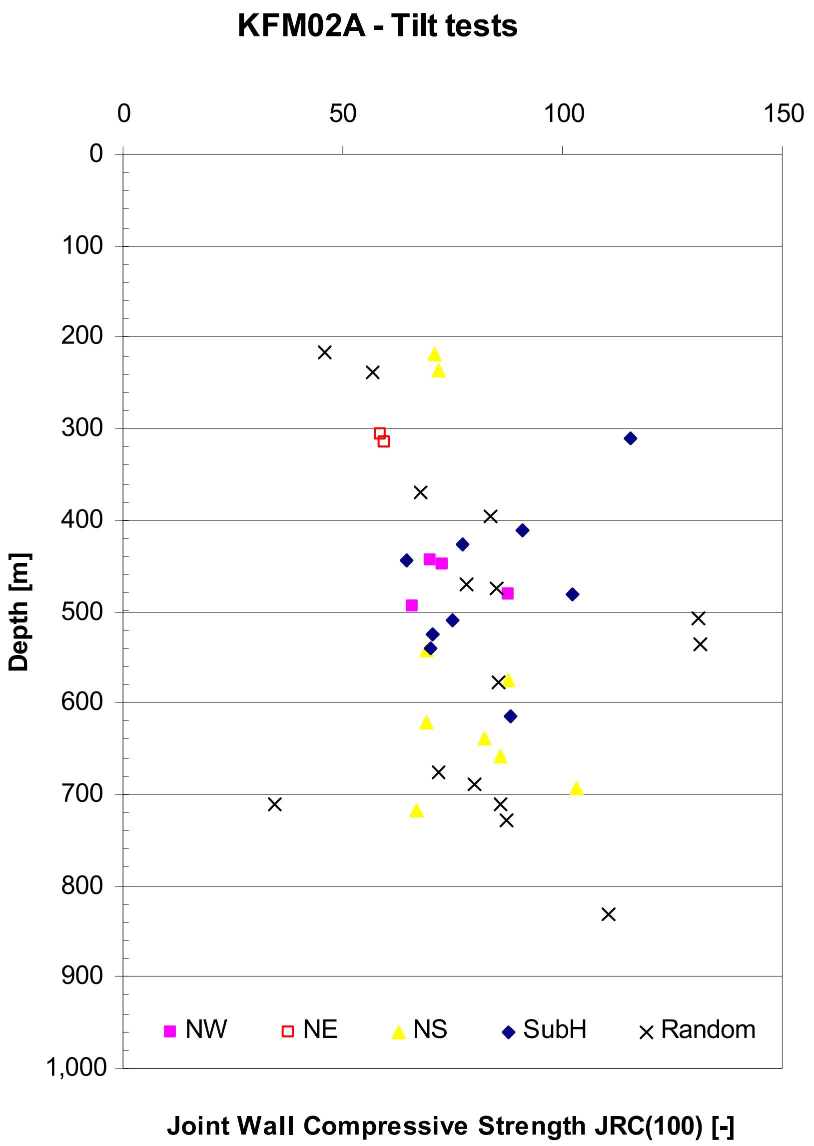
A.1 Tilt test results



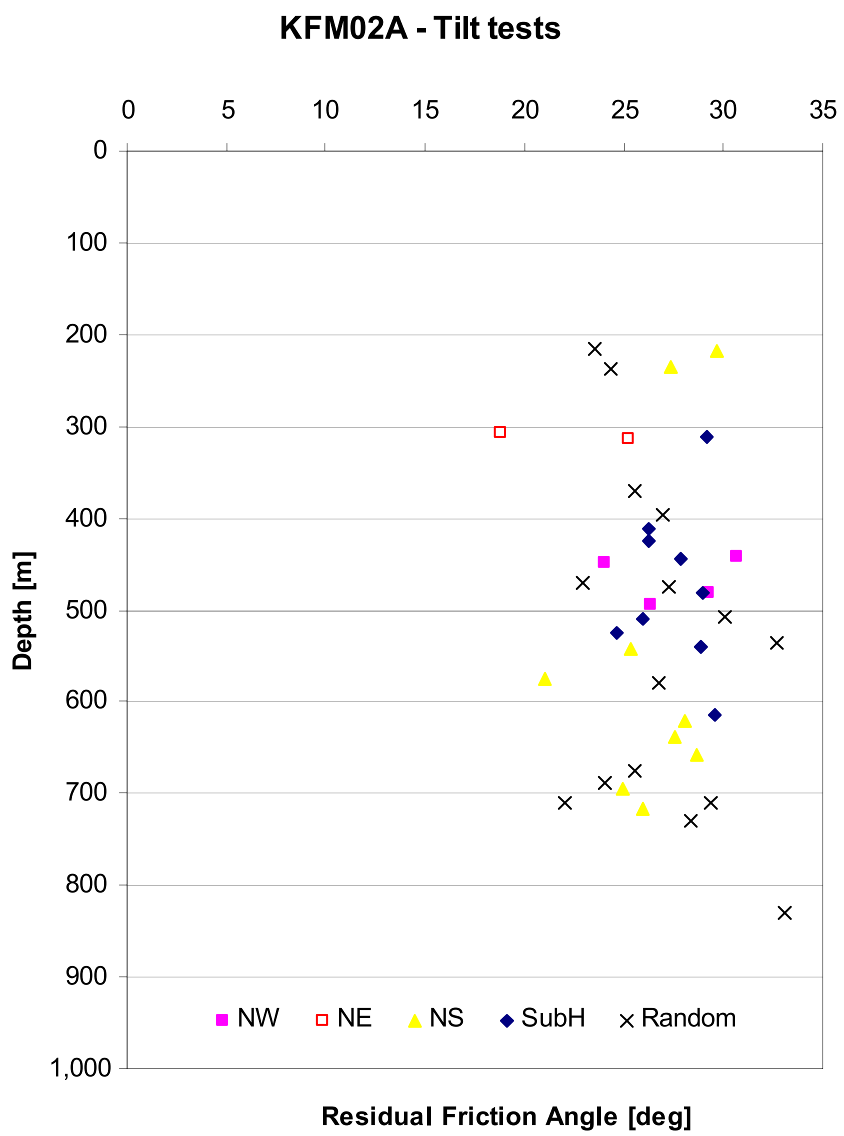
Variation of the basic friction angle of the tested fractures from KFM02A.



Variation of the Joint Roughness Coefficient JRC of the tested fractures from KFM02A.

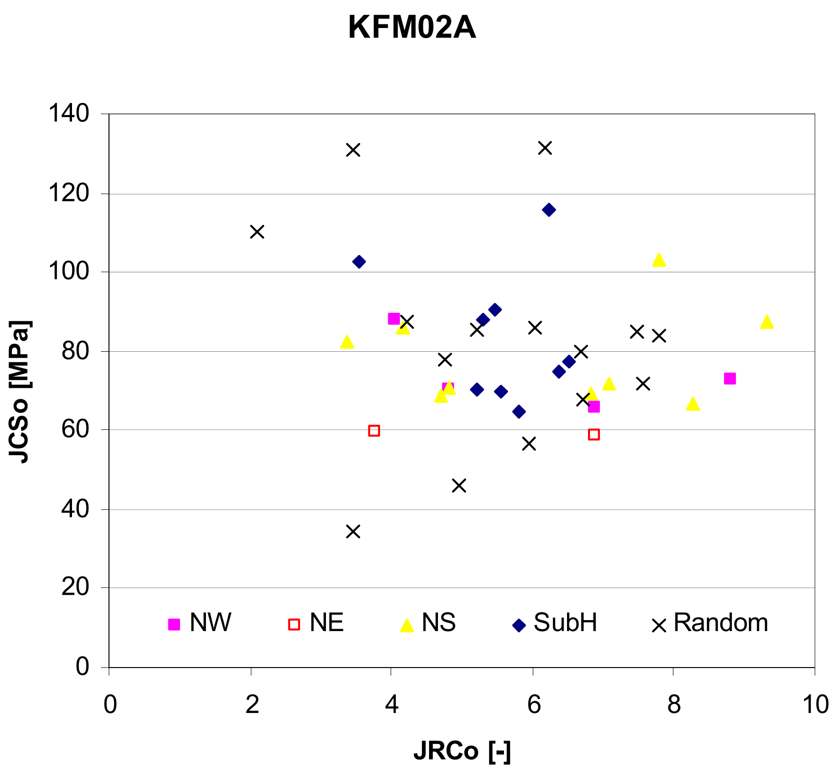


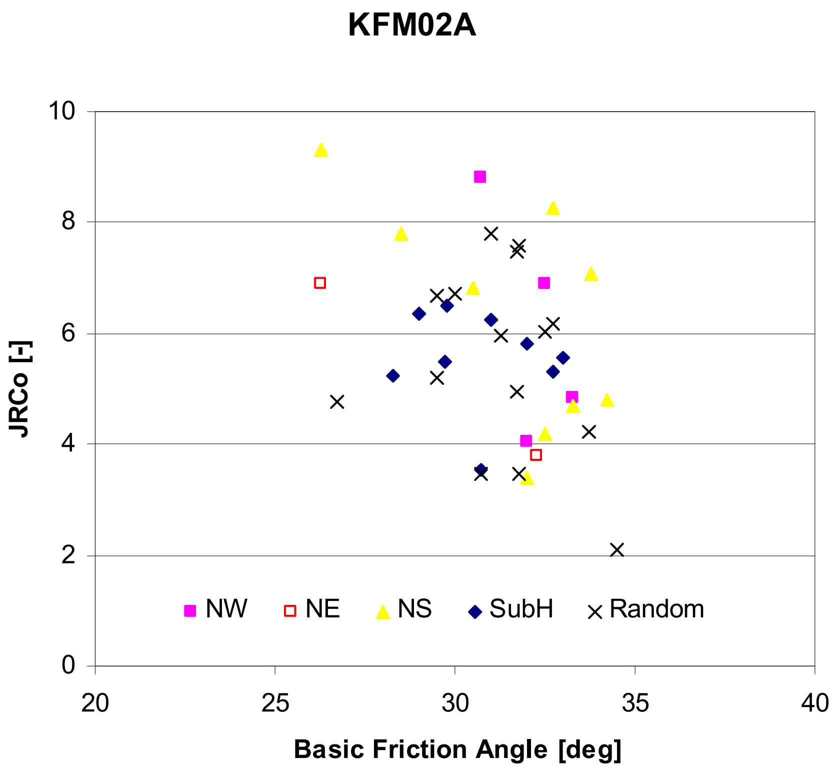
Variation of the Joint Wall Compressive Strength JCS of the tested fractures from KFM02A.

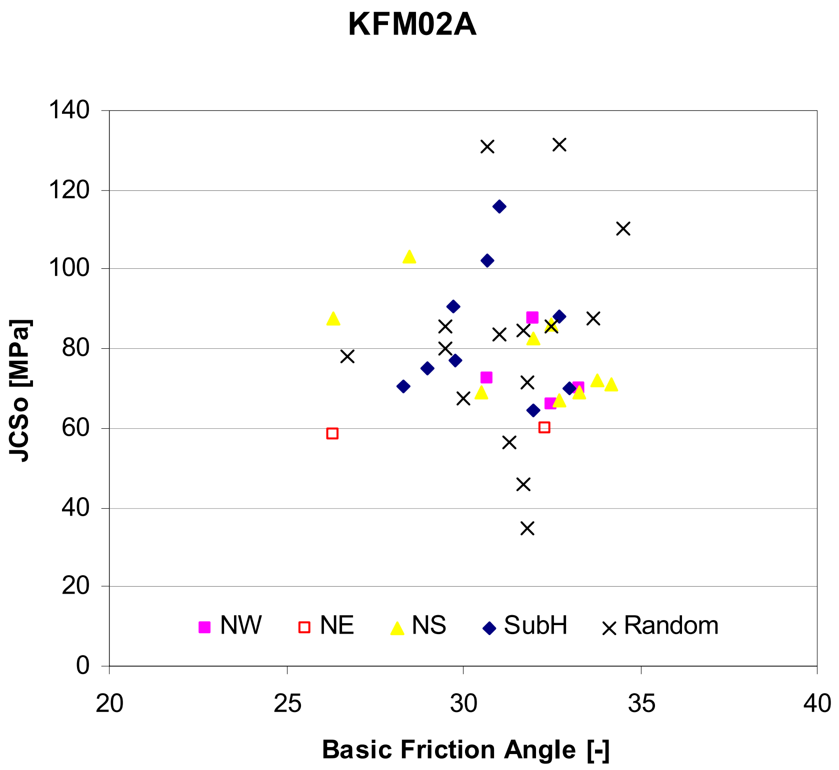


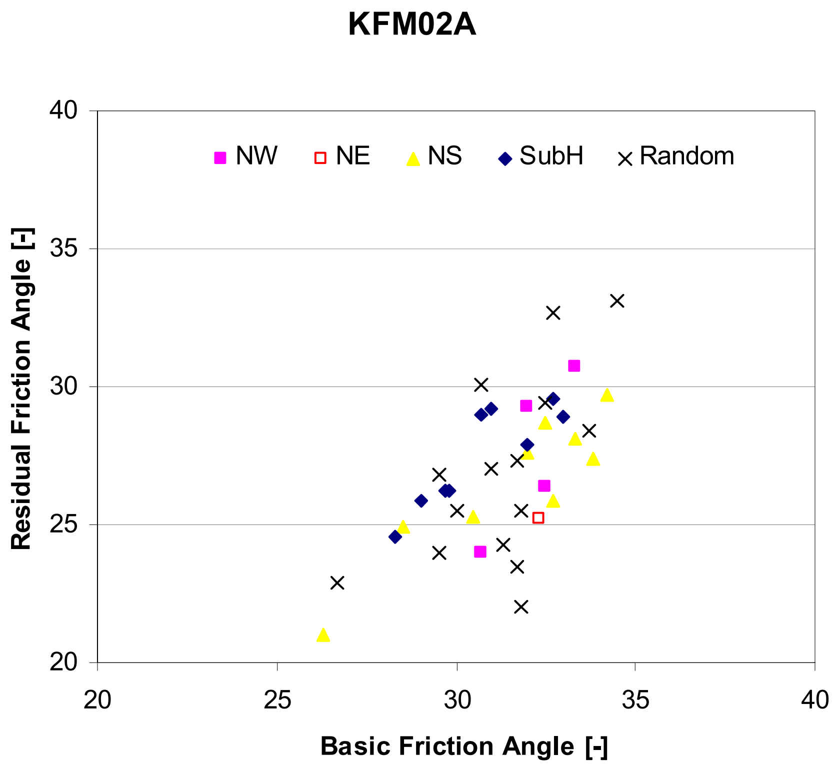
Variation of the residual friction angle of the tested fractures from KFM02A.

A.2 Correlations






KFM02A
JCSo [MPa]
140
120
100
80
60
40
20
0
20
25
30
35
40
Basic Friction Angle [-]
NW
NE
NS
SubH
Random


KFM02A
Residual Friction Angle [-]
40
35
30
25
20
20
25
30
35
40
Basic Friction Angle [-]
NW
NE
NS
SubH
Random

Appendix B

Characterisation of the rock mass

B.1 Summary of the RMR values

RMR values along borehole KFM02A (core sections of 5 m).

Rock Unit	Depth (m)	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation	Min possible RMR	Max possible RMR
RU1	100–110	74.2	80.7	80.7	87.3	9.3	64.4	94.0
DZ2	110–120	77.2	77.3	77.3	77.5	0.2	50.0	91.6
RU1	120–160	75.7	81.3	80.8	87.0	3.9	55.0	96.0
DZ3	160–185	80.7	83.1	82.2	85.6	2.2	54.7	94.0
RU1	185–240	75.1	81.6	80.9	87.4	4.2	62.2	94.0
RU2	240–285	74.0	77.5	78.1	78.5	1.4	45.2	90.1
DZ5	285–310	72.4	79.3	79.8	83.9	4.5	58.3	91.7
RU1	310–415	75.4	84.2	83.8	96.0	5.2	60.5	98.0
DZ6	415–425	85.7	86.3	86.3	86.9	0.9	60.8	96.0
RU1	425–480	73.7	79.3	76.8	90.6	5.5	58.0	96.0
DZ6	480–495	74.1	78.3	78.6	82.3	4.1	56.1	94.0
RU3	495–510	74.5	78.6	78.1	83.3	4.4	56.4	94.0
DZ7	510–520	68.1	72.6	72.6	77.0	6.3	46.6	92.2
RU1	520–540	76.1	78.9	79.0	81.5	2.5	63.4	94.0
RU3	540–575	75.5	81.8	83.7	84.4	3.3	60.8	94.0
RU1	575–600	79.0	83.4	83.5	88.5	4.1	65.2	96.0
RU3	600–635	82.6	88.3	89.0	94.0	3.7	67.2	96.0
RU1	635–835	77.1	87.7	88.3	96.0	3.9	60.8	98.0
RU3	835–865	86.5	88.3	88.3	90.5	1.7	65.6	94.0
RU1	865–885	88.8	91.2	90.0	96.0	3.4	70.1	98.0
DZ8	885–905	79.7	85.2	86.9	87.0	3.6	55.9	96.0
RU4	905–940	74.8	83.1	79.7	94.0	7.1	50.9	96.0
RU1	940–1,000	74.4	88.1	87.7	96.0	5.2	63.6	98.0

The shading in yellow indicates the location of the potential deformation zones identified in Borehole KFM02A.

RMR values for the Rock Units for borehole KFM02A (core sections of 5 m).

Rock Unit	Depth (m)	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation RMR	Min possible RMR	Max possible RMR
RU1	100–160	74.2	80.6	80.0	87.3	4.5	50.0	96.0
RU3	160–240	75.1	82.0	81.9	87.4	3.7	54.7	94.0
RU2	240–310	72.4	78.1	78.1	83.9	2.9	45.2	91.7
RU1	310–480	73.7	82.8	82.6	96.0	5.7	58.0	98.0
RU3	480–520	68.1	77.0	77.6	83.3	4.9	46.6	94.0
RU1	520–540	76.1	78.9	79.0	81.5	2.5	63.4	94.0
RU3	540–575	75.5	81.8	83.7	84.4	3.3	60.8	94.0
RU1	575–600	79.0	83.4	83.5	88.5	4.1	65.2	96.0
RU3	600–635	82.6	88.3	89.0	94.0	3.7	67.2	96.0
RU1	635–835	77.1	87.7	88.3	96.0	3.9	60.8	98.0
RU3	835–865	86.5	88.3	88.3	90.5	1.7	65.6	94.0
RU1	865–905	79.7	88.2	87.9	96.0	4.6	55.9	98.0
RU4	905–940	74.8	83.1	79.7	94.0	7.1	50.9	96.0
RU1	940–1,000	74.4	88.1	87.7	96.0	5.2	63.6	98.0

Summary of RMR values for borehole KFM02A (core sections of 5 m).

Rock Unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation RMR	Min possible RMR	Max possible RMR
RU1	73.7	84.8	86.0	96.0	5.5	50.0	98.0
RU2	72.4	78.1	78.1	83.9	2.9	45.2	91.7
RU3	68.1	83.4	83.9	94.0	5.6	46.6	96.0
RU4	74.8	83.1	79.7	94.0	7.1	50.9	96.0
Competent rock	73.7	84.4	84.9	96.0	5.6	45.2	98.0
Fractured rock	68.1	80.9	81.7	87.0	5.1	46.6	96.0
Whole borehole	68.1	83.9	84.1	96.0	5.7	45.2	98.0

Summary of RMR values for borehole KFM02A (core sections of 30 m).

Rock Unit	Minimum mean RMR	Average mean RMR	Frequent mean RMR	Maximum mean RMR	Standard deviation RMR	Min possible RMR	Max possible RMR
RU1	76.7	83.7	84.1	90.3	4.7	48.1	96.0
RU2	74.8	76.5	76.5	78.1	2.3	45.4	91.7
RU3	73.7	81.9	82.2	89.1	6.7	42.6	96.0
RU4	82.2	–	–	82.2	–	50.9	94.0
Competent rock	76.8	85.5	88.0	90.3	4.0	55.3	96.0
Fractured rock	73.7	78.1	77.3	84.7	3.6	42.6	96.0
Whole borehole	73.7	82.8	83.2	90.3	5.2	42.6	96.0

B.2 Summary of the Q values

Q values along borehole KFM02A (core sections of 5 m).

Rock Unit	Depth (m)	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Min possible Q	Max possible Q
RU1	100–110	13.1	23.2	23.2	33.3	7.8	100.0
DZ2	110–120	9.1	12.7	12.7	16.2	1.5	100.0
RU1	120–160	31.1	53.7	54.5	69.4	8.3	150.0
DZ3	160–185	14.6	20.9	18.2	33.0	1.5	75.0
RU1	185–240	9.1	53.5	40.7	100.0	2.0	150.0
RU2	240–285	4.3	15.2	15.2	30.0	0.4	200.0
DZ5	285–310	6.1	19.0	12.7	33.3	0.8	200.0
RU1	310–415	29.7	212.8	130.9	2,133.3	6.9	2,133.3
DZ6	415–425	6.8	29.7	29.7	52.5	0.6	200.0
RU1	425–480	30.1	70.2	61.4	154.3	3.5	300.0
DZ6	480–495	9.9	36.5	15.0	84.8	1.9	200.0
RU3	495–510	25.3	53.8	50.8	85.2	4.4	200.0
DZ7	510–520	7.9	9.6	9.6	11.2	0.5	200.0
RU1	520–540	49.5	117.1	93.5	232.0	11.9	300.0
RU3	540–575	28.9	74.2	64.3	150.0	7.3	300.0
RU1	575–600	44.8	280.1	100.0	1,066.7	10.6	1,066.7
RU3	600–635	21.9	217.5	81.3	1,066.7	12.5	1,066.7
RU1	635–835	13.1	308.9	119.3	2,133.3	7.6	2,133.3
RU3	835–865	14.3	98.3	84.5	225.0	8.3	600.0
RU1	865–885	33.3	654.2	225.0	2,133.3	12.5	2,133.3
DZ8	885–905	2.8	6.3	6.2	10.0	0.4	200.0
RU4	905–940	10.3	369.5	158.3	1,066.7	2.6	1,066.7
RU1	940–1,000	25.0	356.4	72.1	2,133.3	14.0	2,133.3

The shading in yellow indicates the location of the potential deformation zones identified in Borehole KFM02A.

Q values for the Rock Units for borehole KFM02A (core sections of 5 m).

Rock Unit	Depth (m)	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Min possible Q	Max possible Q
RU1	100–160	9.1	41.8	46.0	69.4	1.5	150.0
RU3	160–240	9.1	43.3	33.0	100.0	1.5	150.0
RU2	240–310	4.3	16.5	13.9	33.3	0.4	200.0
RU1	310–480	6.8	155.9	89.1	2,133.3	0.6	2,133.3
RU3	480–520	7.9	36.3	20.1	85.2	0.5	200.0
RU1	520–540	49.5	117.1	93.5	232.0	11.9	300.0
RU3	540–575	28.9	74.2	64.3	150.0	7.3	300.0
RU1	575–600	44.8	280.1	100.0	1,066.7	10.6	1,066.7
RU3	600–635	21.9	217.5	81.3	1,066.7	12.5	1,066.7
RU1	635–835	13.1	308.9	119.3	2,133.3	7.6	2,133.3
RU3	835–905	2.8	230.8	51.2	2,133.3	0.4	2,133.3
RU4	905–940	10.3	369.5	158.3	1,066.7	2.6	1,066.7
RU1	940–1,000	25.0	356.4	72.1	2,133.3	14.0	2,133.3

Summary of Q values for borehole KFM02A (core sections of 5 m).

Rock Unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Min possible Q	Max possible Q
RU1	2.8	218.5	71.4	2,133.3	0.4	2,133.3
RU2	4.3	16.5	13.9	33.3	0.4	200.0
RU3	7.9	91.7	50.0	1,066.7	0.5	1,066.7
RU4	10.3	369.5	158.3	1,066.7	2.6	1,066.7
Competent rock	4.3	209.8	71.2	2,133.3	0.4	2,133.3
Fractured rock	2.8	19.0	12.7	84.8	0.4	200.0
Whole borehole	2.8	185.4	62.3	2,133.3	0.4	2,133.3

Summary of Q values for borehole KFM02A (core section of 30 m).

Rock Unit	Minimum mean Q	Average mean Q	Frequent mean Q	Maximum mean Q	Min possible Q	Max possible Q
RU1	3.5	43.3	39.6	150.0	0.4	200.0
RU2	7.1	8.6	8.6	10.1	0.3	100.0
RU3	9.4	41.2	32.5	109.7	0.3	200.0
RU4	23.0	–	–	23.0	0.4	200.0
Competent rock	23.5	54.8	46.7	150.0	3.9	200.0
Fractured rock	3.5	15.3	10.1	39.6	0.3	200.0
Whole borehole	3.5	39.9	34.6	150.0	0.3	200.0

Appendix C

Rock mass properties

C.1 Deformation modulus

C.1.1 RMR

Deformation modulus E_m derived from RMR along borehole KFM02A (core sections of 5 m).

Rock Units	Depth (m)	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max possible E_m (GPa)
RU1	100–110	40.2	57.6	57.6	75.0	24.6	22.9	90.0
DZ2	110–120	47.9	48.3	48.3	48.6	0.5	10.0	90.0
RU1	120–160	44.0	60.5	58.8	75.0	11.7	13.3	90.0
DZ3	160–185	58.4	66.8	63.7	75.0	7.7	13.1	90.0
RU1	185–240	42.3	61.1	59.1	75.0	12.0	20.2	90.0
RU2	240–285	39.7	48.7	50.4	51.7	3.8	7.6	90.0
DZ5	285–310	36.2	55.3	55.7	70.5	13.3	16.1	90.0
RU1	310–415	43.2	65.8	70.0	75.0	11.2	18.3	90.0
DZ6	415–425	75.0	75.0	75.0	75.0	0.0	18.7	90.0
RU1	425–480	39.1	53.3	46.9	75.0	13.5	15.9	90.0
DZ6	480–495	40.0	52.1	51.9	64.4	12.2	14.2	90.0
RU3	495–510	41.0	53.1	50.5	67.8	13.6	14.5	90.0
DZ7	510–520	28.4	37.9	37.9	47.3	13.4	8.2	90.0
RU1	520–540	44.9	53.1	53.1	61.2	7.5	21.6	90.0
RU3	540–575	43.4	63.3	69.5	72.3	11.0	18.7	90.0
RU1	575–600	53.2	65.4	68.8	75.0	10.7	24.0	90.0
RU3	600–635	65.3	73.6	75.0	75.0	3.7	26.9	90.0
RU1	635–835	47.6	72.7	75.0	75.0	5.3	18.6	90.0
RU3	835–865	75.0	75.0	75.0	75.0	0.0	24.6	90.0
RU1	865–885	75.0	75.0	75.0	75.0	0.0	31.8	90.0
DZ8	885–905	55.4	70.1	75.0	75.0	9.8	14.0	90.0
RU4	905–940	41.6	60.6	55.1	75.0	14.1	10.5	90.0
RU1	940–1,000	40.8	72.1	75.0	75.0	9.9	21.9	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 E_m derived from RMR for borehole KFM02A (core sections of 5 m).

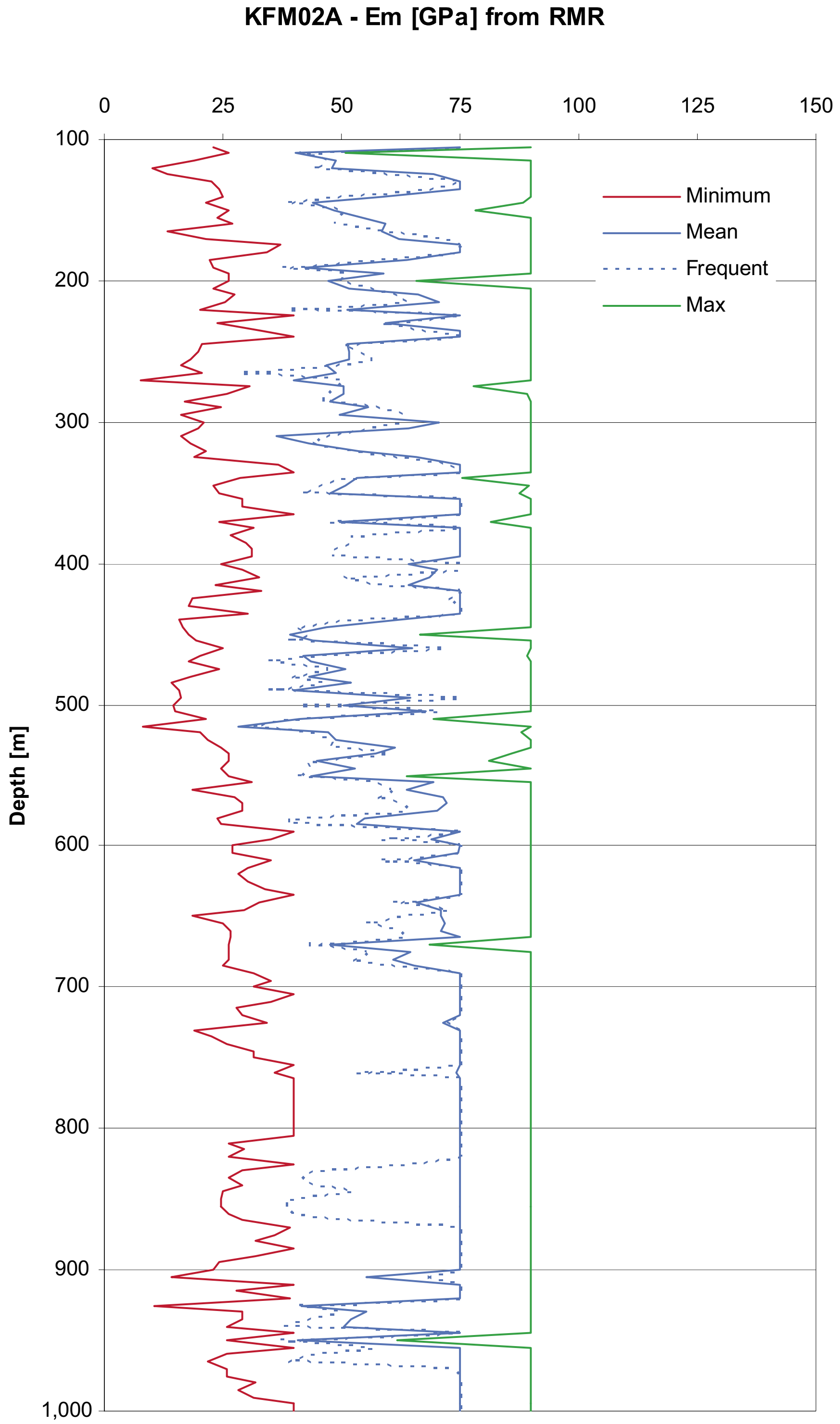
Rock Unit	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max possible E_m (GPa)
RU1	39.1	66.5	75.0	75.0	11.6	10.0	90.0
RU2	36.2	51.1	50.4	70.5	8.6	7.6	90.0
RU3	28.4	64.7	70.2	75.0	13.0	8.2	90.0
RU4	41.6	60.6	55.1	75.0	14.1	10.5	90.0
Competent rock	39.1	65.5	74.7	75.0	12.0	7.6	90.0
Fractured rock	28.4	59.5	61.9	75.0	14.1	8.2	90.0
Whole borehole	28.4	64.7	71.4	75.0	12.4	7.6	90.0

The maximum mean E_m 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 E_m derived from RMR for borehole KFM02A (core sections of 30 m).

Rock Unit	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max possible E_m (GPa)
RU1	46.5	65.2	71.1	75.0	11.2	9.0	90.0
RU2	41.7	46.1	46.1	50.5	6.2	7.7	90.0
RU3	39.2	60.1	64.3	75.0	16.5	6.5	90.0
RU4	63.8	–	–	63.8	–	10.5	90.0
Competent rock	46.6	69.6	75.0	75.0	8.6	13.6	90.0
Fractured rock	39.2	51.5	48.1	73.6	11.2	6.5	90.0
Whole borehole	39.2	62.9	67.8	75.0	12.7	6.5	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 E_m of the rock mass obtained from RMR with depth for borehole KFM02A. The values are given every 5 m.

C.1.2 Q

Deformation modulus E_m derived from Q along borehole KFM02A (core sections of 5 m).

Rock Unit	Depth (m)	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max pos-sible E_m (GPa)
RU1	100–110	29.7	35.1	35.1	40.5	7.7	19.8	66.9
DZ2	110–120	26.3	29.1	29.1	31.9	3.9	11.5	66.9
RU1	120–160	39.6	47.3	47.7	51.8	4.0	20.3	76.6
DZ3	160–185	30.8	34.3	33.2	40.4	4.0	11.6	60.8
RU1	185–240	26.3	45.5	43.3	58.5	10.1	12.6	76.6
RU2	240–285	15.4	22.8	23.5	29.4	4.2	5.8	62.1
DZ5	285–310	17.4	24.2	22.1	30.5	5.9	7.3	62.1
RU1	310–415	39.0	60.5	64.0	75.0	11.3	19.1	90.0
DZ6	415–425	23.9	35.5	35.5	47.2	16.4	8.6	84.3
RU1	425–480	39.2	50.5	39.2	67.6	9.1	15.2	90.0
DZ6	480–495	27.0	37.8	31.1	55.4	15.3	12.4	84.3
RU3	495–510	37.0	46.4	46.7	55.4	9.2	16.4	84.3
DZ7	510–520	25.1	26.6	26.6	28.2	2.2	7.9	84.3
RU1	520–540	46.3	58.7	56.8	75.0	12.5	22.8	90.0
RU3	540–575	38.6	51.2	50.5	66.9	10.2	19.4	90.0
RU1	575–600	44.8	58.1	58.5	75.0	12.3	21.9	90.0
RU3	600–635	35.2	55.0	54.6	75.0	13.1	23.2	90.0
RU1	635–835	29.7	59.3	61.8	75.0	15.0	19.6	90.0
RU3	835–865	30.6	53.7	58.5	75.0	16.7	20.3	90.0
RU1	865–885	40.5	64.4	71.0	75.0	16.3	23.2	90.0
DZ8	885–905	17.7	22.6	22.7	27.1	4.6	7.3	84.3
RU4	905–940	27.4	58.0	68.2	75.0	19.7	13.8	90.0
RU1	940–1,000	36.8	57.7	52.4	75.0	15.7	24.1	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 E_m derived from Q for borehole KFM02A (core sections of 5 m).

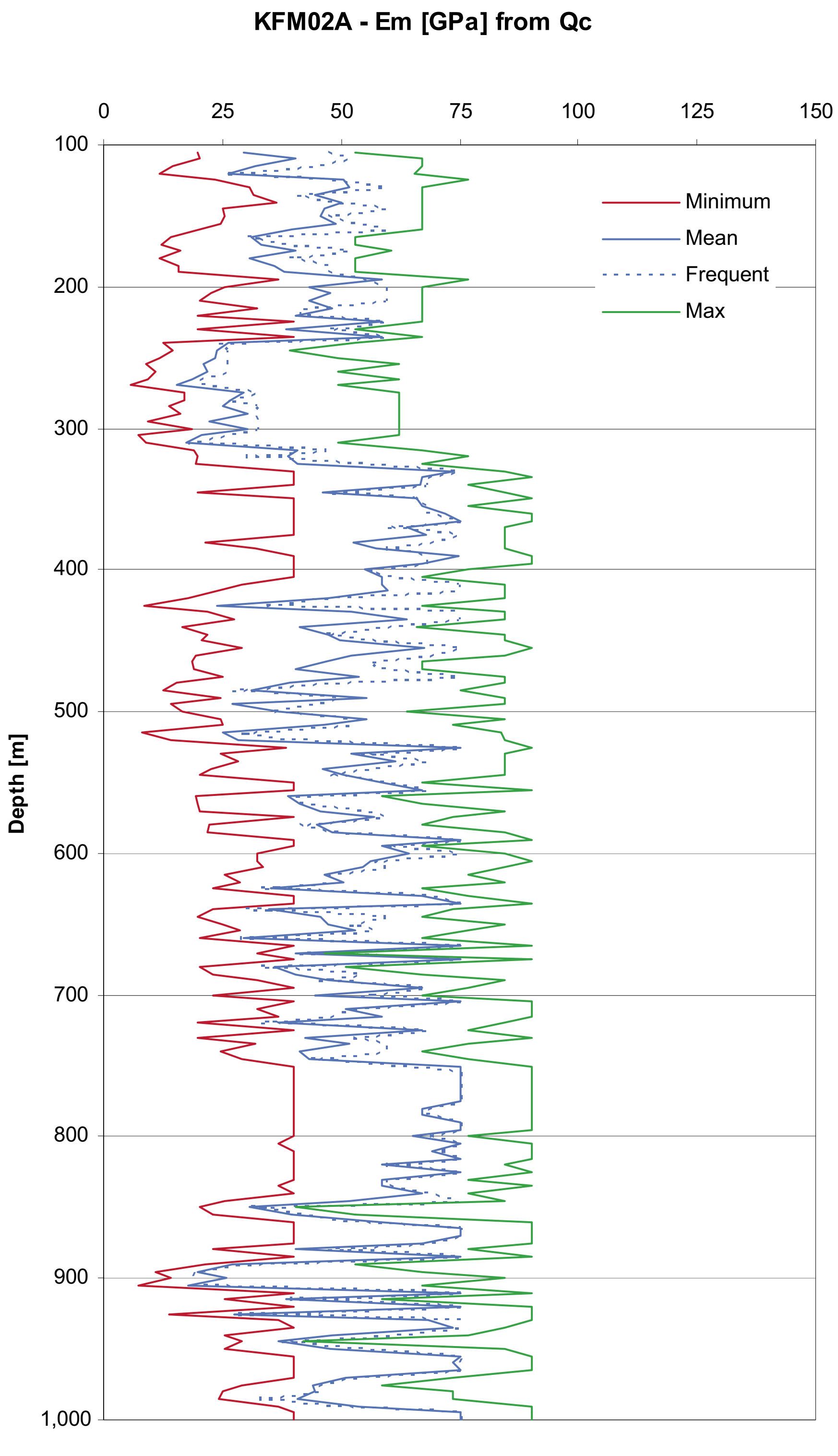
Rock Unit	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max possible E_m (GPa)
RU1	17.7	54.3	52.3	75.0	15.2	7.3	90.0
RU2	15.4	23.3	22.8	30.5	4.7	5.8	62.1
RU3	25.1	46.8	46.4	75.0	14.2	7.9	90.0
RU4	27.4	58.0	68.2	75.0	19.7	13.8	90.0
Competent rock	15.4	53.7	52.2	75.0	15.5	5.8	90.0
Fractured rock	17.4	29.5	28.2	55.4	9.0	7.3	84.3
Whole borehole	15.4	50.6	49.9	75.0	16.9	5.8	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 E_m derived from Q for borehole KFM02A (core sections of 30 m).

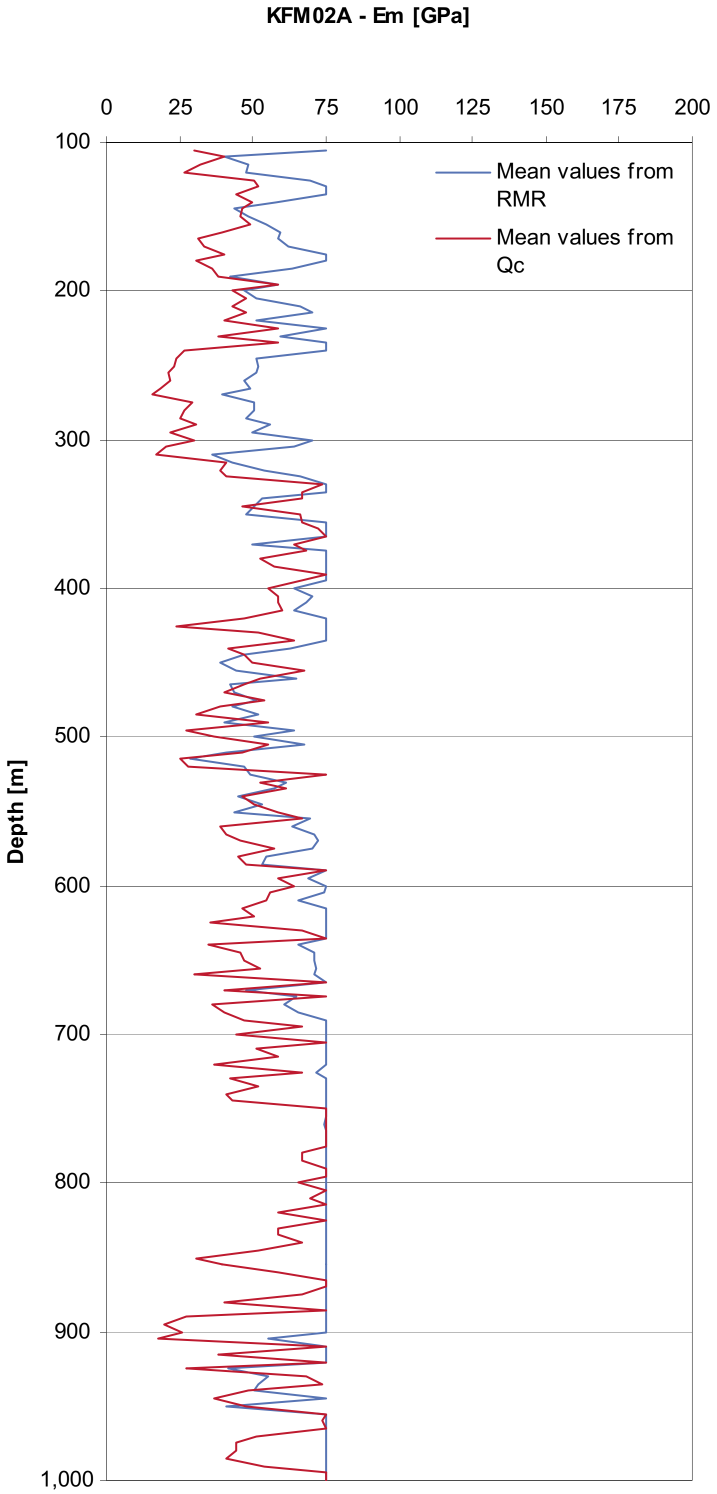
Rock Unit	Minimum mean E_m (GPa)	Average mean E_m (GPa)	Frequent mean E_m (GPa)	Maximum mean E_m (GPa)	Standard deviation E_m (GPa)	Min possible E_m (GPa)	Max possible E_m (GPa)
RU1	19.1	41.1	42.9	66.9	11.8	7.3	84.3
RU2	18.2	19.3	19.3	20.5	1.6	5.4	49.3
RU3	26.6	40.7	41.5	60.3	14.0	6.3	84.3
RU4	35.8	–	–	35.8	–	7.6	84.3
Competent rock	36.1	46.4	45.4	66.9	8.3	15.7	84.3
Fractured rock	19.1	28.6	26.6	42.9	7.5	6.3	84.3
Whole borehole	18.2	39.3	41.0	66.9	12.4	5.4	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 KFM02A. 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 KFM02A.

C.2 Uniaxial compressive strength

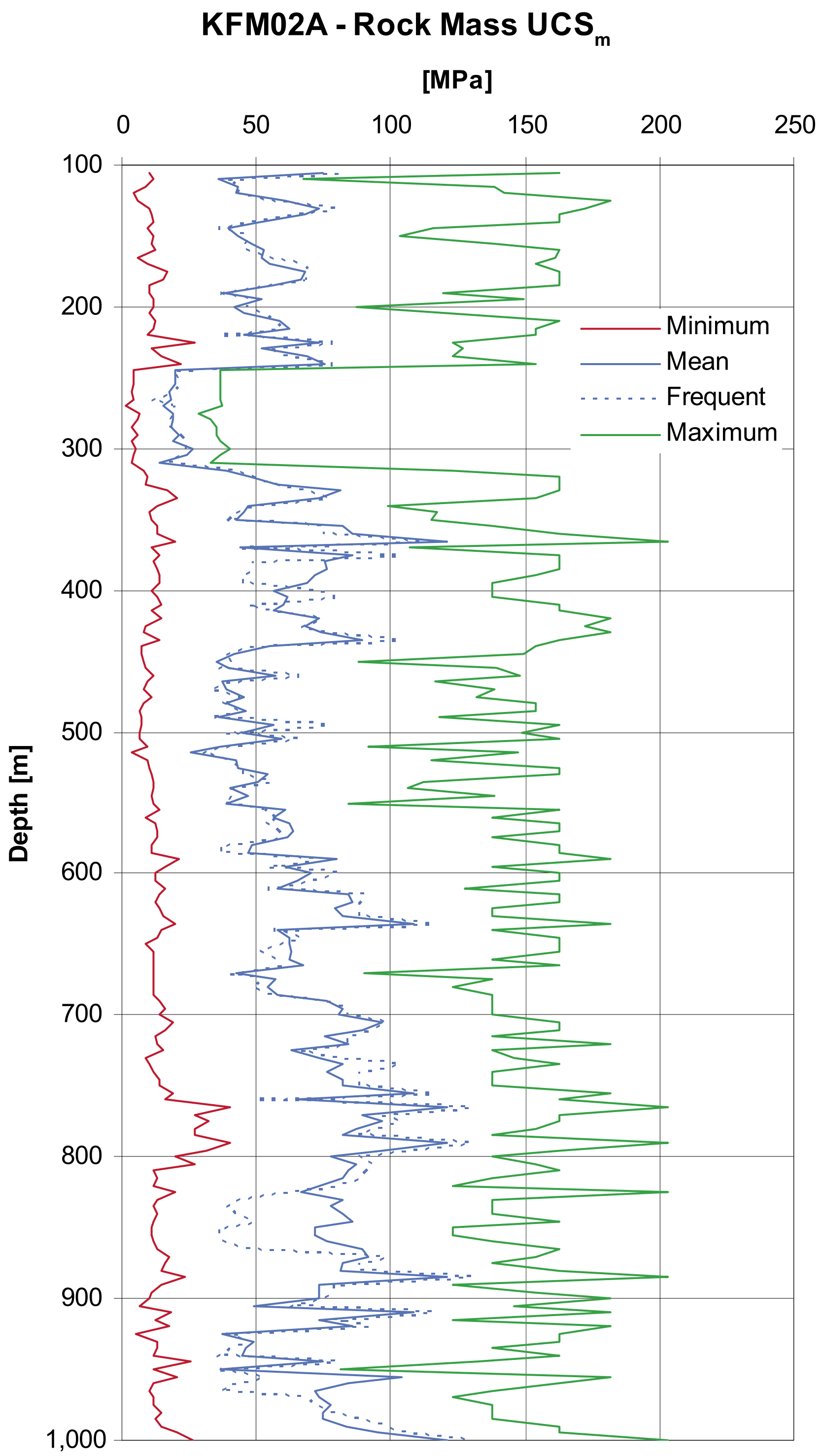
C.2.1 RMR

Summary of the uniaxial compressive strength UCS_m of the rock mass derived from RMR for borehole KFM02A (core sections of 5 m, Hoek and Brown's a = 0.5).

Rock Unit	Depth (m)	Minimum mean UCS_m (MPa)	Average mean UCS_m (MPa)	Frequent mean UCS_m (MPa)	Maximum mean UCS_m (MPa)	Standard deviation UCS_m	Min possible UCS_m (MPa)	Max possible UCS_m (MPa)
RU1	100–110	36.1	55.5	55.5	74.8	27.4	10.5	162.8
DZ2	110–120	42.7	43.0	43.0	43.3	0.5	4.7	142.5
RU1	120–160	39.4	54.7	52.0	73.5	12.0	6.2	182.0
DZ3	160–185	51.7	59.5	56.3	68.2	7.4	6.1	162.8
RU1	185–240	37.9	55.8	52.3	75.4	12.8	9.3	162.8
RU2	240–285	15.2	18.5	19.1	19.5	1.4	1.8	52.5
DZ5	285–310	13.9	20.8	21.0	26.3	4.8	3.7	57.3
RU1	310–415	38.6	65.8	61.6	121.3	19.8	8.4	203.3
DZ6	415–425	68.3	70.7	70.7	73.1	3.4	8.6	182.0
RU1	425–480	35.1	50.3	38.5	89.8	17.5	7.4	182.0
DZ6	480–495	35.9	46.3	46.1	56.8	10.5	6.6	162.8
RU3	495–510	36.8	47.2	44.9	59.8	11.6	6.7	162.8
DZ7	510–520	25.8	34.0	34.0	42.2	11.7	3.9	147.1
RU1	520–540	40.1	47.1	47.2	54.1	6.4	9.9	162.8
RU3	540–575	38.9	55.9	61.2	63.6	9.4	8.6	162.8
RU1	575–600	47.2	61.4	60.6	80.0	14.0	10.9	182.0
RU3	600–635	57.6	80.5	82.2	108.5	16.2	12.3	182.0
RU1	635–835	42.5	78.3	79.1	121.3	16.9	8.6	203.3
RU3	835–865	71.6	79.4	82.2	89.4	7.4	11.2	162.8
RU1	865–885	81.3	94.2	87.1	121.3	18.7	14.4	203.3
DZ8	885–905	49.2	67.4	73.3	73.6	12.1	6.5	182.0
RU4	905–940	37.3	63.7	48.9	108.5	26.4	5.0	182.0
RU1	940–1,000	36.6	81.0	76.4	121.3	20.5	10.0	203.3

Summary of the uniaxial compressive strength UCS_m of the rock mass in the rock units derived from RMR for borehole KFM02A (core sections of 5 m, Hoek and Brown's a = 0.5).

Rock Unit	Minimum UCS_m (MPa)	Average UCS_m (MPa)	Frequent UCS_m (MPa)	Maximum UCS_m (MPa)	Standard deviation UCS_m (MPa)	Min possible UCS_m (MPa)	Max possible UCS_m (MPa)
RU1	35.1	68.0	69.5	121.3	20.3	4.7	203.3
RU2	13.9	19.3	19.1	26.3	3.1	1.8	40.6
RU3	25.8	62.9	61.8	108.5	18.3	3.9	182.0
RU4	37.3	63.7	48.9	108.5	26.4	5.0	182.0
Competent rock	15.2	65.3	65.6	121.3	22.9	1.8	203.3
Fractured rock	13.9	48.1	49.2	73.6	19.6	3.7	182.0
Whole borehole	13.9	63.1	62.8	121.3	23.2	1.8	203.3

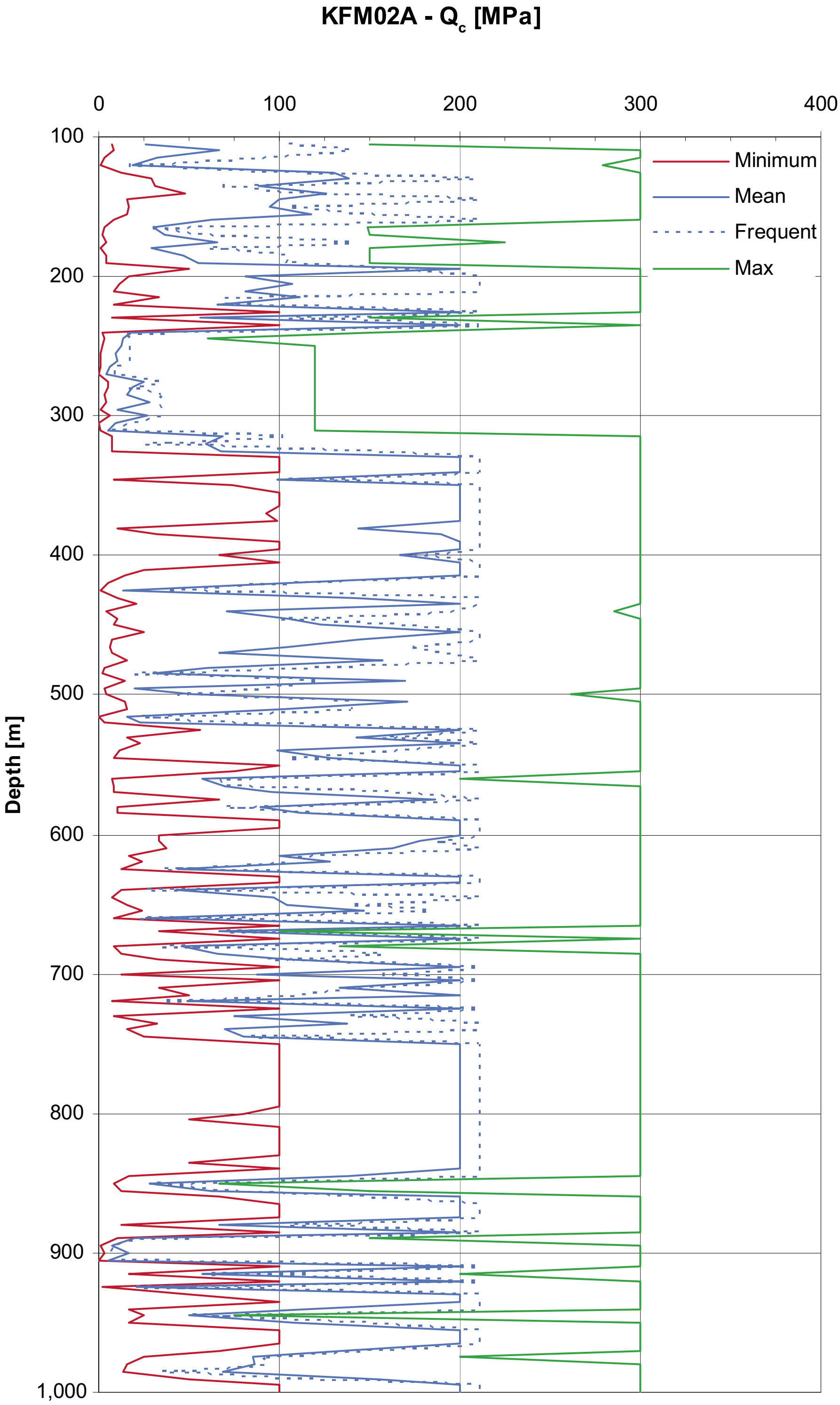


Variation of the uniaxial compressive strength of the rock mass with depth for borehole KFM02A (Hoek and Brown's a=0.5). The values are given every 5 m.

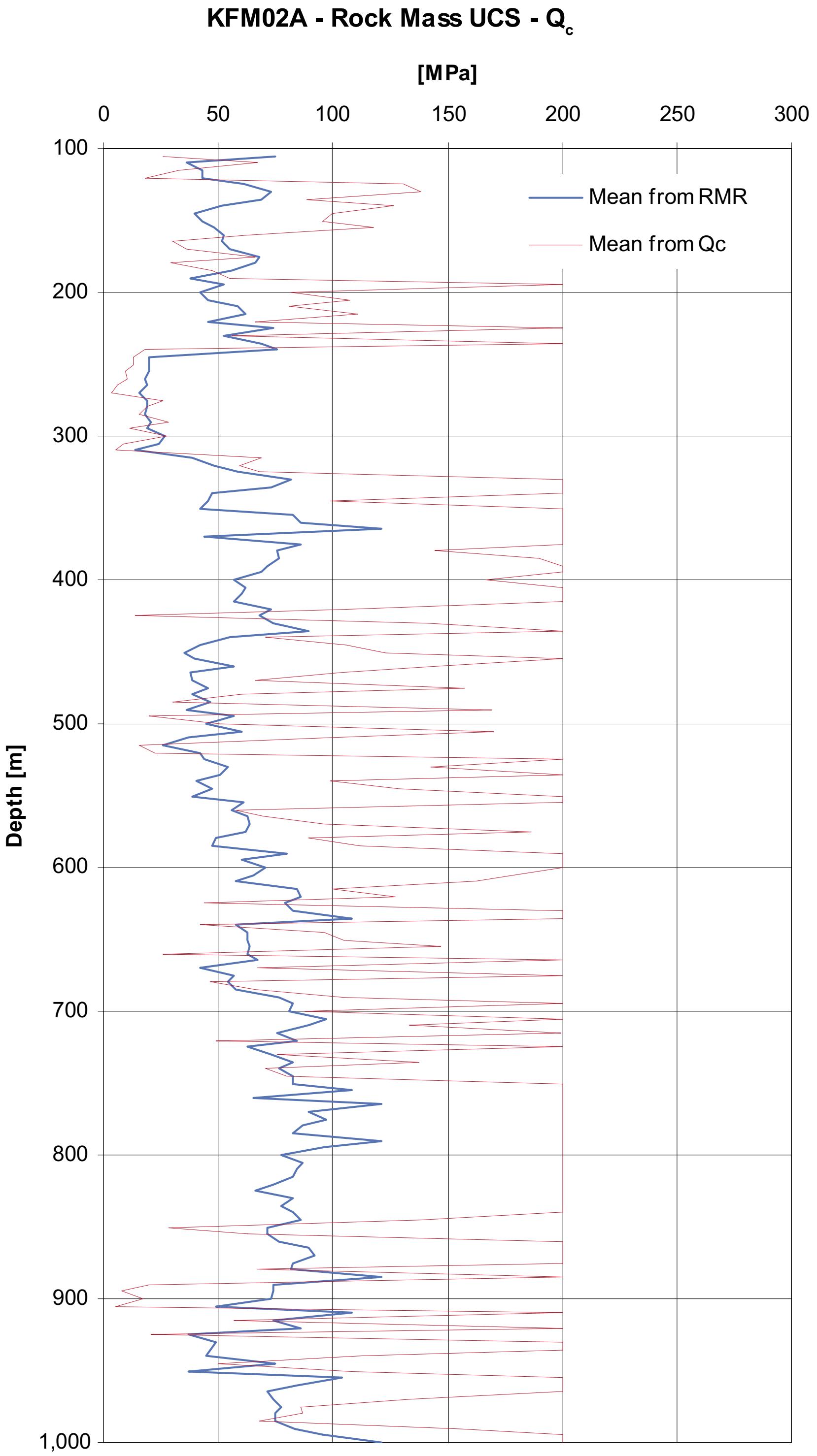
C.2.2 Q

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

Rock Unit	Minimum Q_c (MPa)	Average Q_c (MPa)	Frequent Q_c (MPa)	Maximum Q_c (MPa)	Min possible Q_c (MPa)	Max possible Q_c (MPa)
RU1	5.5	136.9	142.9	200.0	0.4	300.0
RU2	3.6	14.0	11.8	28.3	0.2	120.0
RU3	15.8	108.1	100.0	200.0	0.5	300.0
RU4	20.6	141.5	200.0	200.0	2.6	300.0
Competent rock	3.6	135.3	142.4	200.0	0.2	300.0
Fractured rock	5.2	33.3	22.5	169.6	0.4	300.0
Whole borehole	3.6	122.2	124.5	200.0	0.2	300.0



Variation of Q_c with depth for borehole KFM02A. The values are given every 5 m.



Comparison of the rock mass compressive strength from RMR and Q for borehole KFM02A (Hoek and Brown's a = 0.5).

C.3 Friction angle and cohesion of the rock mass

C.3.1 RMR

Summary of the friction angle ϕ' of the rock mass derived from RMR for borehole KFM02A (10–30 MPa, core sections of 5 m, Hoek and Brown's a = 0.5).

Rock Unit	Depth (m)	Minimum ϕ' (deg)	Average ϕ' (deg)	Frequent ϕ' (deg)	Maximum ϕ' (deg)	Standard deviation ϕ' (deg)	Min possible ϕ' (deg)	Max possible ϕ' (deg)
RU1	100–110	45.8	47.5	47.5	49.2	2.4	35.6	54.7
DZ2	110–120	46.7	46.7	46.7	46.7	0.1	31.3	54.2
RU1	120–160	46.3	47.7	47.6	49.1	1.0	32.8	55.0
DZ3	160–185	47.6	48.2	48.0	48.8	0.6	32.7	54.7
RU1	185–240	46.1	47.8	47.6	49.2	1.1	35.0	54.7
RU2	240–285	38.7	39.7	39.9	40.0	0.4	24.4	47.4
DZ5	285–310	38.2	40.2	40.4	41.6	1.3	28.0	47.8
RU1	310–415	36.2	48.4	48.4	51.0	1.3	34.4	55.3
DZ6	415–425	48.8	49.0	49.0	49.1	0.2	34.5	55.0
RU1	425–480	45.7	47.2	46.2	49.9	1.4	33.7	55.0
DZ6	480–495	45.8	46.9	47.0	48.0	1.1	33.1	54.7
RU3	495–510	45.9	47.0	46.9	48.2	1.1	33.2	54.7
DZ7	510–520	44.1	45.4	45.4	46.6	1.8	30.3	54.3
RU1	520–540	46.4	47.1	47.1	47.8	0.7	35.3	54.7
RU3	540–575	46.2	47.8	48.3	48.5	0.9	34.5	54.7
RU1	575–600	47.1	48.2	48.3	49.5	1.0	35.8	55.0
RU3	600–635	48.1	49.4	49.6	50.7	0.8	36.5	55.0
RU1	635–835	46.6	49.3	49.4	51.0	0.9	34.5	55.3
RU3	835–865	49.0	49.4	49.6	49.9	0.4	36.0	54.7
RU1	865–885	49.5	50.0	49.8	51.0	0.7	37.3	55.3
DZ8	885–905	47.3	48.7	49.1	49.1	0.9	33.1	55.0
RU4	905–940	46.0	48.1	47.3	50.7	1.7	31.6	55.0
RU1	940–1,000	45.9	49.3	49.3	51.0	1.2	35.4	55.3

Summary of the friction angle φ' of the rock mass derived from RMR for borehole KFM02A (10–30 MPa, core sections of 5 m, Hoek and Brown's a = 0.5).

Rock Unit	Minimum ϕ' (deg)	Average ϕ' (deg)	Frequent ϕ' (deg)	Maximum ϕ' (deg)	Standard deviation ϕ' (deg)	Min possible ϕ' (deg)	Max possible ϕ' (deg)
RU1	45.7	48.5	48.8	51.0	1.3	31.3	55.3
RU2	38.2	39.9	39.9	41.6	0.8	24.4	47.8
RU3	44.1	47.9	48.2	49.9	1.4	30.3	54.7
RU4	46.0	48.1	47.3	50.7	1.7	31.6	55.0
Competent rock	38.7	48.1	48.7	51.0	2.4	24.4	55.3
Fractured rock	38.2	46.1	47.3	49.1	3.4	28.0	55.0
Whole borehole	38.2	47.8	48.4	51.0	2.7	24.4	55.3

Summary of the friction angle φ' of the rock mass derived from RMR for borehole KFM02A (10–30 MPa, core sections of 30 m, Hoek and Brown's a = 0.5).

Rock Unit	Minimum φ' (deg)	Average mean φ' (deg)	Frequent mean φ' (deg)	Maximum mean φ' (deg)	Standard deviation φ' (deg)	Min possible φ' (deg)	Max possible φ' (deg)
RU1	39.9	47.2	48.1	49.9	2.8	27.6	55.0
RU2	38.9	39.4	39.4	39.9	0.7	24.4	47.8
RU3	45.7	47.7	47.4	49.6	1.8	29.1	55.0
RU4	48.0	48.0	48.0	48.0	0	31.6	54.7
Competent rock	41.3	48.0	48.5	49.9	2.3	28.9	55.0
Fractured rock	38.9	45.9	46.5	48.0	2.7	27.1	55.0
Whole borehole	38.9	46.8	47.7	49.9	3.1	24.4	55.0

Summary of the cohesion c' of the rock mass derived from RMR for borehole KFM02A (10–30 MPa, core sections of 5 m, Hoek and Brown's a = 0.5).

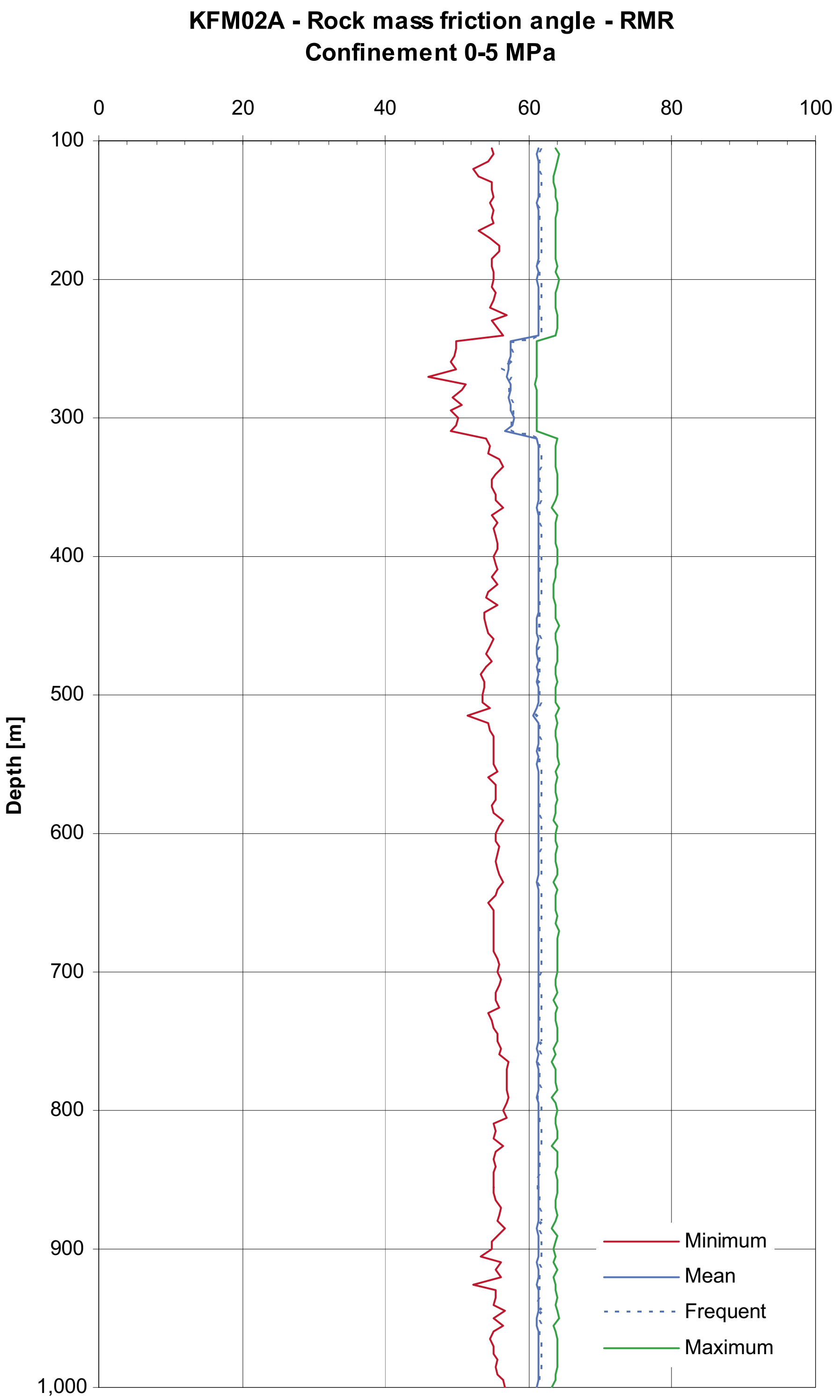
Rock Unit	Depth (m)	Minimum c' (MPa)	Average c' (MPa)	Frequent c' (MPa)	Maximum c' (MPa)	Standard deviation c' (MPa)	Min possible c' (MPa)	Max possible c' (MPa)
RU1	100–110	19.3	21.8	21.8	24.4	3.6	12.7	35.6
DZ2	110–120	20.2	20.3	20.3	20.3	0.1	10.6	33.3
RU1	120–160	19.8	21.8	21.5	24.2	1.6	11.3	37.9
DZ3	160–185	21.4	22.5	22.0	23.6	1.0	11.2	35.6
RU1	185–240	19.5	21.9	21.5	24.5	1.7	12.4	35.6
RU2	240–285	14.3	15.0	15.2	15.2	0.3	7.9	21.4
DZ5	285–310	14.0	15.4	15.5	16.5	0.9	9.3	22.1
RU1	310–415	19.6	23.2	22.7	30.3	2.5	12.1	40.4
DZ6	415–425	23.6	23.9	23.9	24.2	0.4	12.1	37.9
RU1	425–480	19.1	21.2	19.6	26.3	2.3	11.7	37.9
DZ6	480–495	19.2	20.7	20.7	22.1	1.4	11.4	35.6
RU3	495–510	19.4	20.8	20.5	22.5	1.6	11.5	35.6
DZ7	510–520	17.7	18.9	18.9	20.2	1.8	10.2	33.8
RU1	520–540	19.9	20.8	20.8	21.8	0.9	12.5	35.6
RU3	540–575	19.7	22.0	22.7	23.0	1.3	12.1	35.6
RU1	575–600	20.8	22.7	22.6	25.1	1.8	12.8	37.9
RU3	600–635	22.2	25.1	25.4	28.7	2.1	13.2	37.9
RU1	635–835	20.2	24.8	25.0	30.3	2.2	12.1	40.4
RU3	835–865	24.0	25.0	25.4	26.3	0.9	12.9	35.6
RU1	865–885	25.2	26.9	26.0	30.3	2.4	13.7	40.4
DZ8	885–905	21.1	23.5	24.2	24.3	1.6	11.4	37.9
RU4	905–940	19.5	22.9	21.1	28.7	3.4	10.7	37.9
RU1	940–1,000	19.3	25.2	24.6	30.3	2.6	12.6	40.4

Summary of the cohesion c' of the rock mass in the rock units derived from RMR for borehole KFM02A (10–30 MPa, core sections of 5 m, Hoek and Brown's a=0.5).

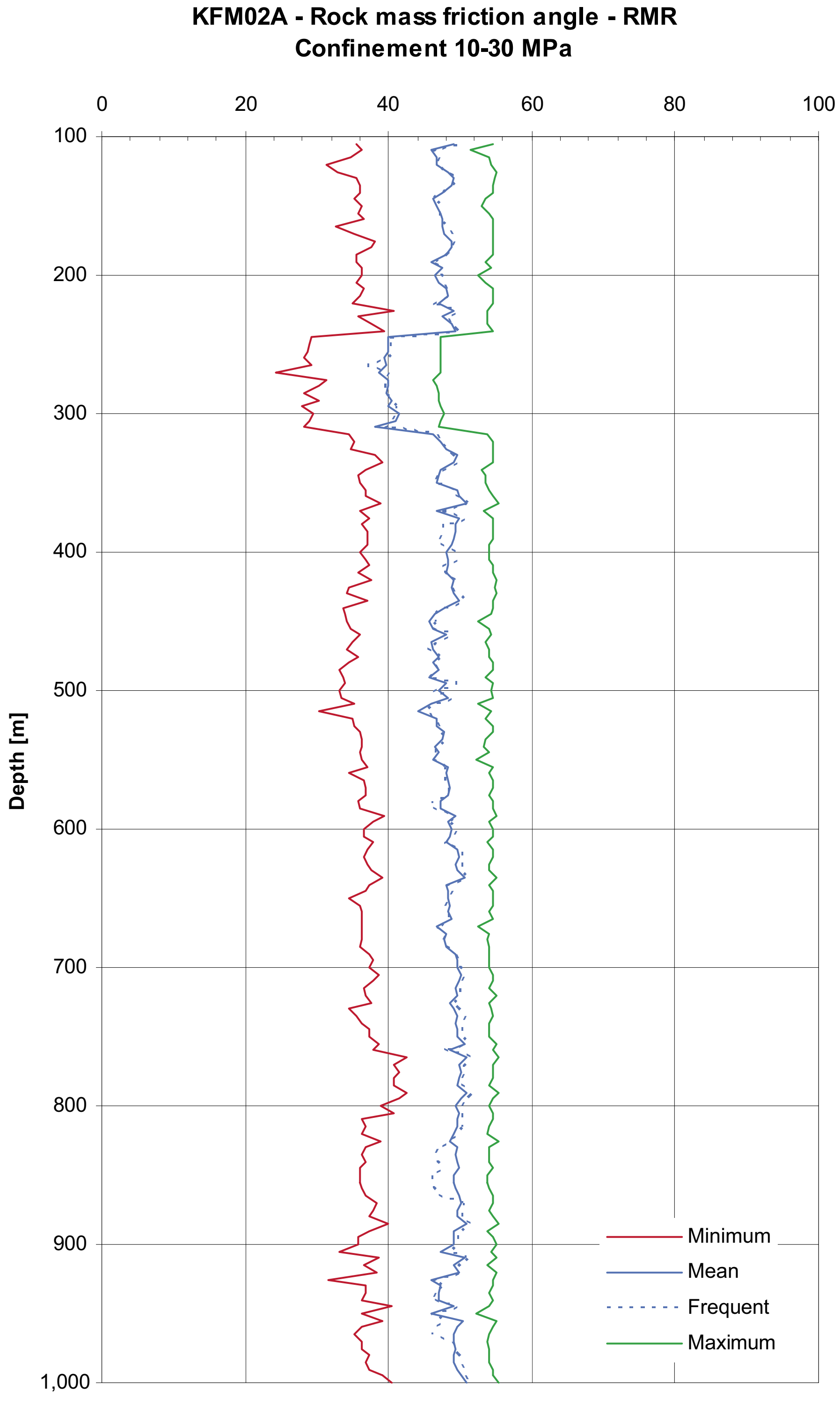
Rock Unit	Minimum c' (MPa)	Average c' (MPa)	Frequent c' (MPa)	Maximum c' (MPa)	Standard deviation c' (MPa)	Min possible c' (MPa)	Max possible c' (MPa)
RU1	19.1	23.5	23.6	30.3	2.7	10.6	40.4
RU2	14.0	15.2	15.2	16.5	0.6	7.9	22.1
RU3	17.7	22.3	22.5	26.3	2.2	10.2	35.6
RU4	19.5	22.9	21.1	28.7	3.4	10.7	37.9
Competent rock	14.3	23.1	23.3	30.3	3.2	7.9	40.4
Fractured rock	14.0	20.5	21.1	24.3	3.2	9.3	37.9
Whole borehole	14.0	22.7	22.9	30.3	3.3	7.9	40.4

Summary of the cohesion of the rock mass derived from RMR for borehole KFM02A (10–30 MPa, core sections of 30 m, Hoek and Brown's a=0.5).

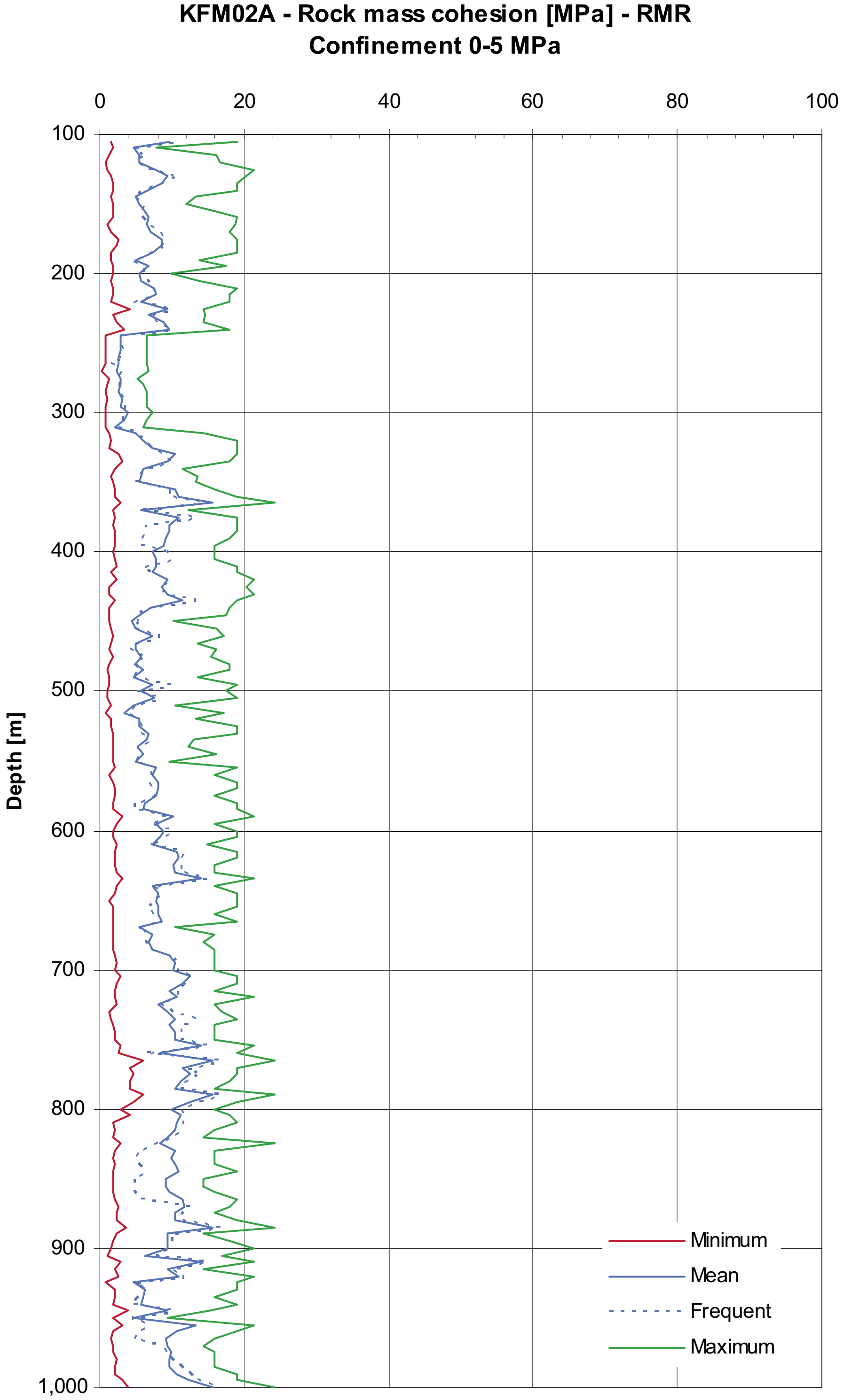
Rock Unit	Minimum c' (MPa)	Average c' (MPa)	Frequent c' (MPa)	Maximum c' (MPa)	Standard deviation c' (MPa)	Min possible c' (MPa)	Max possible c' (MPa)
RU1	15.2	21.9	22.2	26.2	3.1	9.1	37.9
RU2	14.5	14.8	14.8	15.2	0.5	7.9	22.1
RU3	19.1	22.1	21.2	25.4	3.0	9.7	37.9
RU4	22.0	22.0	22.0	22.0	0	10.7	35.6
Competent rock	16.3	23.0	23.0	26.2	2.8	9.7	37.9
Fractured rock	14.5	19.8	20.2	22.0	2.2	8.9	37.9
Whole borehole	14.5	21.5	21.6	26.2	3.4	7.9	37.9



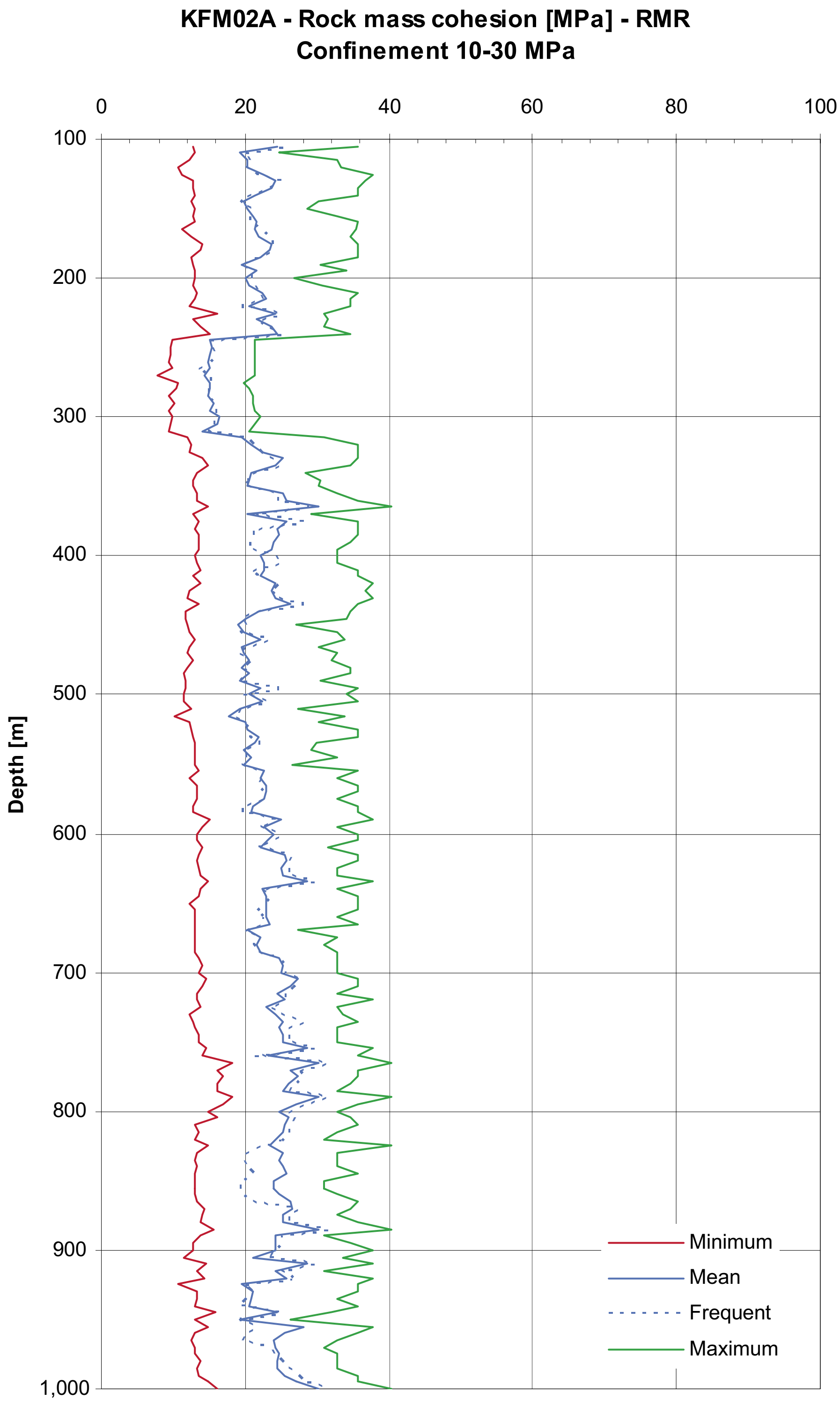
Variation of the rock mass friction angle from RMR for borehole KFM02A under stress confinement 0–5 MPa (Hoek and Brown's a = 0.5).



Variation of the rock mass friction angle from RMR for borehole KFM02A under stress confinement 10–30 MPa (Hoek and Brown's a = 0.5).



Variation of the rock mass cohesion from RMR for borehole KFM02A under stress confinement 0–5 MPa (Hoek and Brown's a = 0.5).



Variation of the rock mass cohesion from RMR for borehole KFM02A under stress confinement 10–30 MPa (Hoek and Brown's a = 0.5).

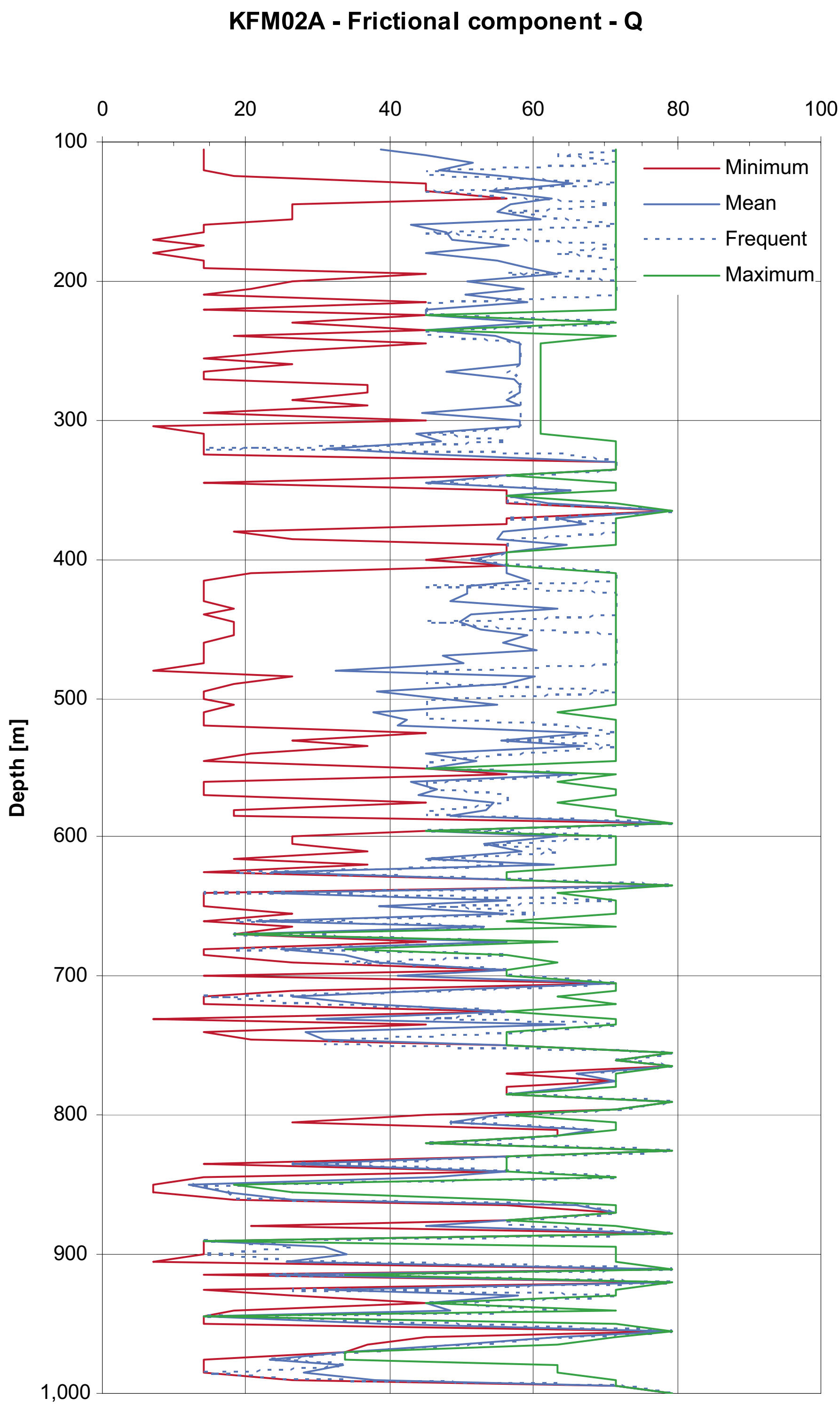
C.3.2 Q

Summary of the frictional component FC of the rock mass derived from RMR for borehole KFM02A (core sections of 5 m).

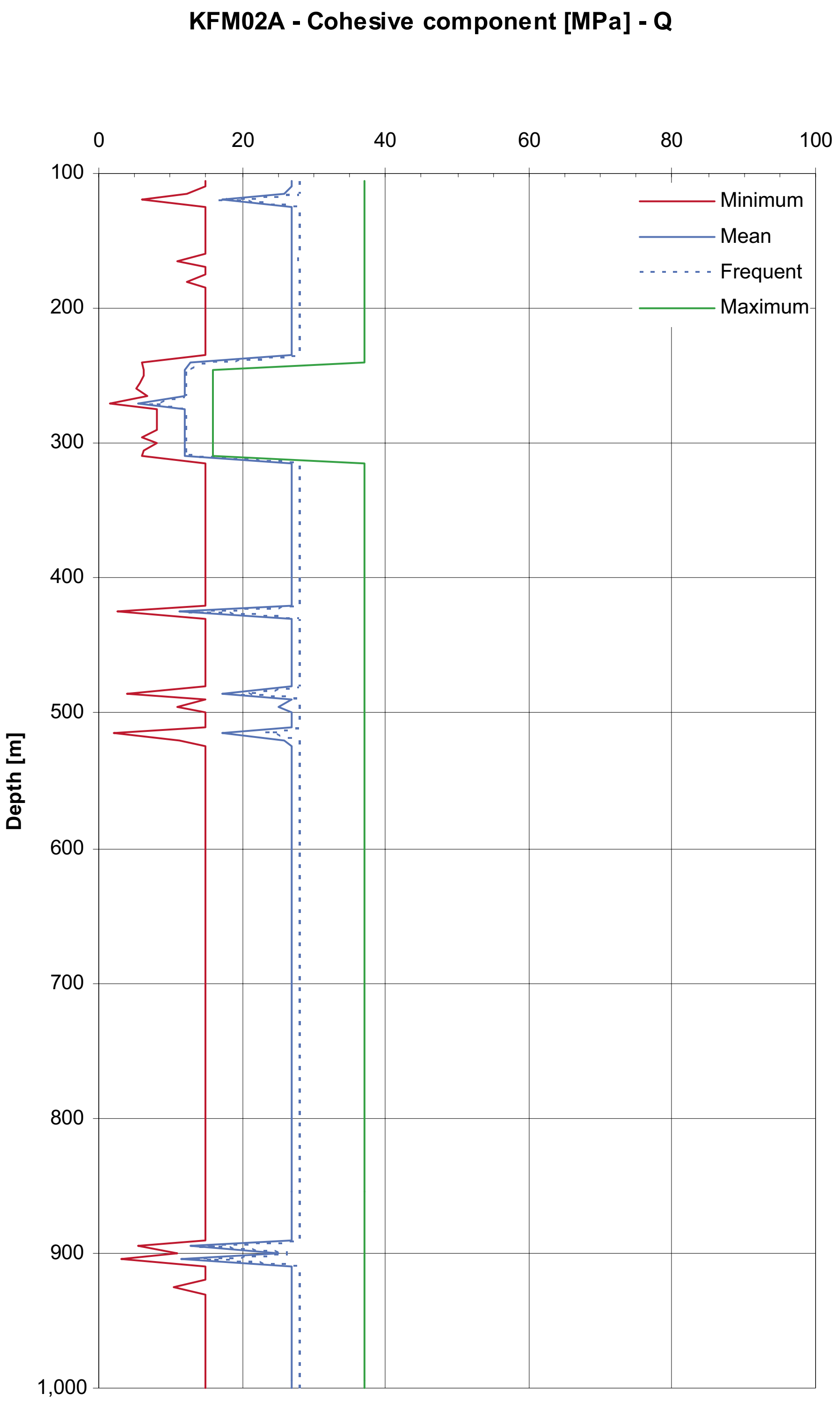
Rock Unit	Minimum FC (deg)	Average FC (deg)	Frequent FC (deg)	Maximum FC (deg)	Standard deviation FC (deg)	Min possible FC (deg)	Max possible FC (deg)
RU1	14.0	53.2	55.4	79.4	14.8	7.1	79.4
RU2	43.7	55.1	58.0	58.0	5.4	7.1	61.0
RU3	12.1	46.3	46.5	66.0	13.1	7.1	71.6
RU4	23.2	52.1	48.4	79.4	21.8	14.0	79.4
Competent rock	12.1	52.6	55.4	79.4	15.2	7.1	79.4
Fractured rock	14.0	46.0	47.9	60.1	11.5	7.1	71.6
Whole borehole	12.1	51.8	54.9	79.4	14.9	7.1	79.4

Summary of the cohesion of the rock mass derived from RMR for borehole KFM02A (core sections of 5 m).

Rock Unit	Minimum CC (MPa)	Average CC (MPa)	Frequent CC (MPa)	Maximum CC (MPa)	Standard deviation CC (MPa)	Min possible CC (MPa)	Max possible CC (MPa)
RU1	11.1	26.7	27.0	27.0	2.1	2.5	37.0
RU2	5.5	11.5	12.0	12.0	1.7	1.6	16.0
RU3	17.2	26.1	27.0	27.0	2.7	2.0	37.0
RU4	27.0	27.0	27.0	27.0	0.0	10.4	37.0
Competent rock	5.5	26.1	27.0	27.0	3.7	1.6	37.0
Fractured rock	11.1	20.2	25.0	27.0	6.9	2.0	37.0
Whole borehole	5.5	25.3	27.0	27.0	4.7	1.6	37.0

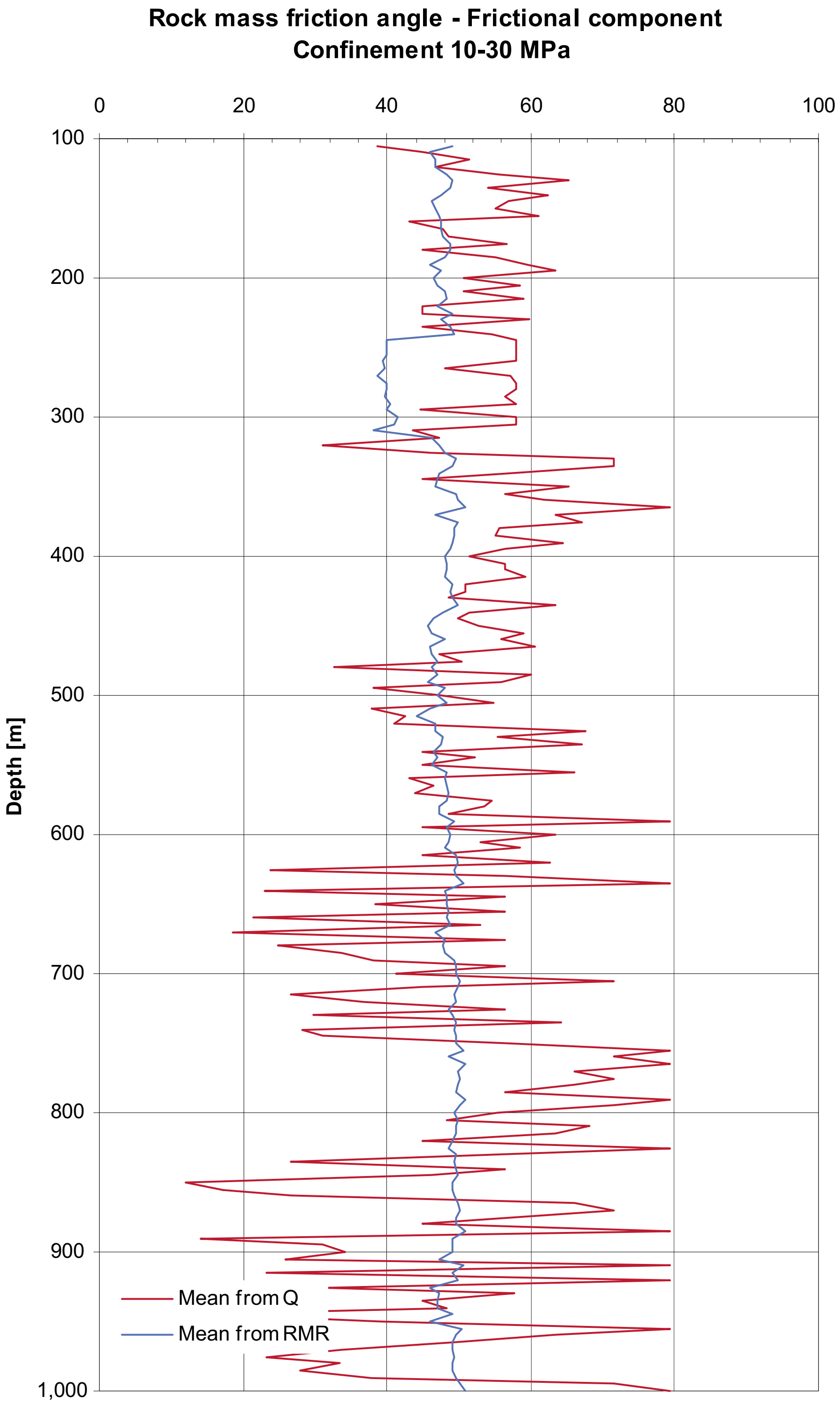


Variation of the frictional component FC from Q for borehole KFM02A.

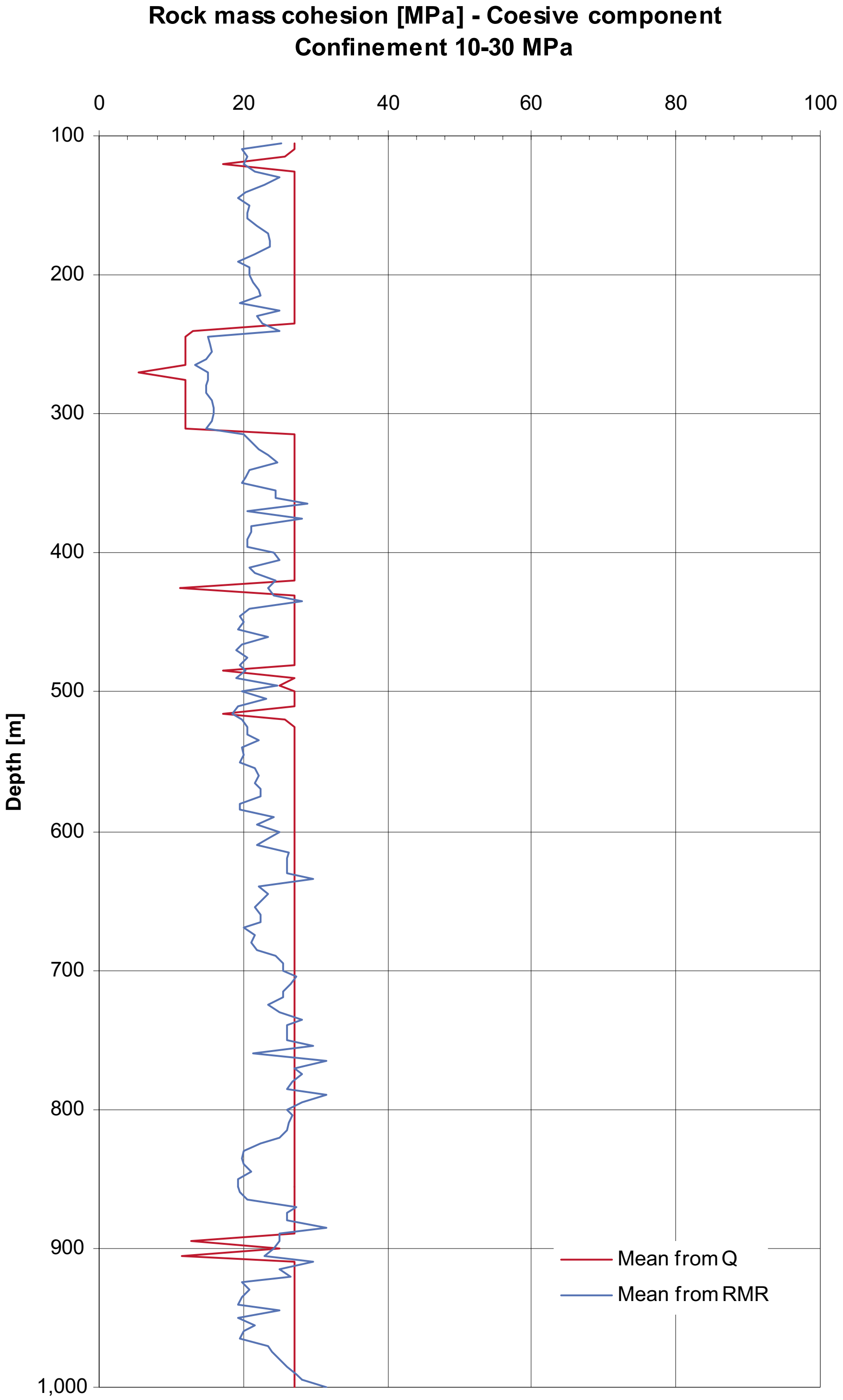


Variation of the cohesive component from Q for borehole KFM02A.

C.3.3 Comparison



Comparison of the rock mass friction angle from RMR and Q for borehole KFM02A under stress confinement 10–30 MPa (Hoek and Brown's a = 0.5).



Comparison of the rock mass cohesion from RMR and Q for borehole KFM02A under stress confinement 10–30 MPa (Hoek and Brown's a = 0.5).