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Keywords: Rock mass characterization, Empirical methods, Rock mass mechanical properties, RMR (Rock Mass Rating), Q (Rock Quality Index), Uncertainty determination.

Abstract

This report presents the characterisation of boreholes KFM01B, KFM07C, KFM09A, and KFM09B at the Forsmark area. The characterisation is performed by means of the two independent empirical systems Q and RMR. The systems are applied to the geomechanical data provided in digital format by Sicada according to SKB's methodology for rock mechanical characterisation of the rock mass.

The values of Q and RMR are calculated for borehole sections of 5 m and 1 m length. Moreover, average values are also provided for the rock mass in some of the rock units (volumes with rather homogeneous mixture of rock types) and deformation zones (volumes with high frequency either of open or sealed fractures) identified by the previously performed "single-hole interpretation" of the boreholes (rounded off to the 5 m and 1 m sections).

From the values of Q and RMR the equivalent deformation modulus of the rock mass is obtained. The two methods provide results very similar to each other. As there is a complete set of relations that correlate RMR to the Poisson's ratio, uniaxial compressive strength, equivalent friction angle and cohesion of the rock mass, it was decided to obtain all these mechanical properties of the rock mass from the values of RMR and its relation with the Geological Strength Index (GSI).

The average RMR and Q generally display values corresponding to the class of "very good" rock mass quality. These values are larger than the average values for deformation zones where the lowest average values for RMR range between 45 and 51, which also indicates very good rock.

The average deformation modulus of the boreholes KFM01B, KFM07C and KFM09B for the competent rock mass ranges between 70 and 74 GPa. Borehole KFM09A instead shows an average deformation modulus of 64 GPa. The average deformation modulus of the deformation zones in borehole KFM01B indicates that the deformation modulus of about 23 GPa is lower than that generally found for boreholes KFM07C, KFM09A and KFM09B, where the zones have a deformation modulus of about 31–33 GPa.

The average equivalent cohesion and the friction angle of the competent rock mass in the boreholes vary between 23 and 27 MPa, and between 47° and 50°, respectively (for confinement stresses between 10 and 30 MPa). The uniaxial compressive strength of the rock mass, determined from the friction angle and cohesion, spans between 125 MPa, for the deformation zones, and 151 MPa, for the competent rock mass.

Based on the range of expected values of the parameters for each 5 m section of the borehole and based on the number of available values for each parameter, the uncertainty of the mechanical properties of the rock mass was estimated. The estimation was performed separately on the properties of the competent rock mass and of the deformation zones.

The general trend displays that the competent rock has a smaller variation than the deformation zones. For example, RMR for the competent rock varies from –2% to +1%, whereas the it varies from –5% to +4% for deformation zones. The Q values show a larger variation due to the scale that is used in this method, whereas RMR for the competent rock varies between –9% to +41% and for the deformation zones between –26% and +89%.

Thresholds were used for identifying the deformation zones. This method can identify the most damaged rock in the upper part of the boreholes. The Q system generally seems to be more sensitive in the identification of the deformation zones. In borehole KFM07C a deformation zone was, however, identified by the RMR system using 1 m sections.

All of the deformation zones identified with the signature can be found in the deformation zones identified during the single-hole interpretation. The deformation zones identified with the signature coincide with areas showing strong indications of larger fracture frequency, or crushed zones. This is perhaps a way to identify the core of the deformation zone,which has a large significance in rock engineering.

Sammanfattning

Föreliggande rapport beskriver empirisk karakterisering av borrhålen KFM01B, KFM07C, KFM09A och KFM09B i Forsmarks platsundersökningsområde. Karakteriseringen baserades på de två oberoende systemen RMR och Q, vilka tillämpades på geomekaniska data i digitalformat från SKB:s databas Sicada enligt SKB:s metodologi för bergmekanisk karakterisering av bergmassan.

Q- och RMR-värdena beräknades för 5 m och 1 m långa borrhålsavsnitt. Medelvärden för ett antal bergenheter och för de deformationszoner som identifierats vid den tidigare utförda geologiska enhålstolkningen (avrundade till närmaste 5 m eller 1 m intervall) redovisas likaså.

Från Q- och RMR-värdena har den ekvivalenta deformationsmodulen för bergmassan beräknats. De två metoderna ger sammanstämmiga resultat. Dock valdes RMR för att uppskatta övriga bergmekaniska egenskaper, därför att det i litteraturen finns ett brett utbud av formler som genom GSI (Geological Strength Index) relaterar Poissons tal, enaxiell tryckhållfasthet, friktionsvinkel och kohesion till RMR.

Medel RMR och Q visar generellt värden som beskriver bergmassan som ur bergmekanisk aspekt av mycket god kvalitet. RMR- och Q-värdena för bergmassan är högre än motsvarande värden för deformationszonerna, där de lägsta medelvärdena för RMR varierar mellan 45 och 51, som fortfarande indikerar mycket god bergkvalitet.

Deformationsmodulen hos den kompetenta bergmassan i borrhål KFM01B, KFM07C och KFM09B varierade mellan 70 och 74 GPa, att jämföra med borrhål KFM09A där deformationsmodulen uppgår till 64 GPa. För deformationszonerna uppvisade däremot borrhål KFM01B ett avvikande lågt värde, ca 23 GPa, jämfört med värdena för KFM07C, KFM09A och KFM09B, vilkas deformations modul varierar mellan 31 och 33 GPa.

Den kompetenta bergmassans ekvivalenta kohesion och friktionsvinkel varierade mellan 23 and 27 MPa respektive mellan 47° och 50° under ett celltryck mellan 10 och 30 MPa. Från friktionsvinkeln och kohesionen kan den enaxliga tryckhållfastheten beräknas. Den varierar mellan 125 MPa för deformationszonerna till 151 MPa för den kompetenta bergmassan.

Osäkerheten hos de mekaniska parametrarna uppskattades med avseende på den förväntade variationen hos parametrarna för varje 5 m-sektion i borrhålen och antalet tillgängliga mätningar för respektive parameter. Detta gjordes separat för varje egenskap uppdelat mellan den kompetenta bergmassan och deformationszonerna.

Generellt visar den kompetenta bergmassan en mindre variation än deformationszonerna. Ett exempel är RMR-värdena för den kompetenta bergmassan som varierar mellan –2 % och +1 %, medan RMR för deformationszonerna varierar mellan –5 % och +4 %. Q-värdena visar en större variation pga den logaritmiska skala som används i den metoden. Q för den kompetenta bergmassan varierar mellan –9 % och +41 % och för deformationszonerna mellan –26 % och +89 %.

Dessutom användes förutbestämda gränsvärden för att identifiera deformationszoner. Dessa gränsvärden identifierade de mest skadade områdena, som generellt hittas i de övre delarna av borrhålen. Det system som generellt påvisade dessa zoner var Q-systemet. I borrhål KFM07C identifierades emellertid en zon med RMR-systemet med indelningen i 1 m intervall.

Alla deformationzoner som identifierats med signatur kan återfinnas i enhålstolkningen. Dock utgör de ett mindre område inom deformationszonerna. De har ofta påvisats i områden med hög sprickfrekvens eller krosszoner. Med signaturidentifikationen, baserad på gränsvärden i Q och RMR, kan man lättare hitta de bergmekaniskt signifikanta områdena i deformationszonerna.

Contents

1 Introduction

This report presents results of the rock mechanical single-hole characterization of four core drilled boreholes, KFM01B, KFM07C, KFM09A and KFM09B, situated within the Forsmark candidate area for a potential deep repository (Figure 1-1).

Normally, site investigations managed by SKB are performed in compliance with a governing document in the form of an Activity Plan. However, regarding the present activity, there exists no Activity Plan, and SKB's instructions to the Contractor were presented by oral communication during 2006 between SKB's Activity Leader for rock mechanics, Rolf Christiansson, and representatives from BBK AB. The study was completed in May 2007.

The methodology for rock mass characterisation applied in the study is described in /Andersson et al. 2002/ and an application of the methodology to the Äspö Test Case is presented in /Röshoff et al. 2002/. According to the methodology, two empirical classification systems, the Rock Mass Rating, RMR, and the Rock Quality Index, Q, have to be used for the purpose of determination of the quality and the mechanical properties of the rock mass.

Figure 1-1. *Overview of the Forsmark site with the candidate area selected for the most comprehensive investigations including the boreholes investigated in this report: KFM01B, KFM07C, KFM09A, and KFM09B.*

Raw data necessary for the rock mass characterization are stored in SKB's primary database Sicada. In this study data on the depth of occurrence, mineralization or infilling, roughness and surface features, alteration conditions, orientation (strike and dip), width and aperture of the fractures have been used, as well as lists of the dominant rock types and other occurrences. The delivery numbers for the Sicada data used in this report are presented in Table 1-1.

Also the resulting data from the rock mechanical single-hole characterization of four core drilled boreholes at Forsmark are stored in Sicada. Primary data from different activities are normally traceable by the Activity Plan number in Sicada. In this case, because no Activity Plan was written, data are traceable by SKB's order number 15112. Only data in SKB's databases are accepted for further interpretation and modelling. The data presented in this report are regarded as copies of the original data. Data in the databases may be revised, if needed. Such revisions will not necessarily result in a revision of the P-report, although the normal procedure is that major data revisions entail a revision of the corresponding P-report. Minor data revisions are normally presented as supplements, available at www.skb.se.

Some borehole geometrical information is given in Table 1-2. Three of the boreholes, KFM01B, KFM09A and KFM09B, are conventional core-drilled boreholes, whereas KFM07C is of telescopic type where the upper 85 m are drilled with a diameter of c 244 mm and cased. The remainder of the hole is, like the conventional core drilled boreholes drilled with a diameter of about 76 to 77 mm.

The sub-vertical borehole KFM07C is drilled with an inclination (at collar) of 85°, whereas the other three boreholes have varying inclinations ranging from 55° to 79°. The borehole lengths vary between c 500 m and 800 m and the holes reach a vertical depth of between 472 m and 621 m (see Table 1-2). BIPS images are available for the major part of the boreholes /Berglund et al. 2004, Petersson et al. 2006ab, Carlsten et al. 2006/.

Borehole KFM09A is a conventional core-drilled borehole located just outside the north-western part of the candidate area. The borehole is directed south-west, thereby penetrating the border between rock domain 29 and domain 44 and continuing into domains 12 and 18. The other three boreholes are all situated within rock domain 29 to their full lengths.

Table 1-1. Information obtained from the Sicada database for the analysis.

	Data delivery number	Boreholes
Data delivery	06_134_1	KFM01B, KFM09A, KFM09B
Data delivery	07_002	KFM07C

Table 1-2. Borehole information.

Borehole	Bearing	Inclination	Borehole length	Vertical depth
KFM01B	268°	79°	501 m	479
KFM07C	143°	85°	500 m	494
KFM09A	200°	60°	800 m	621
KFM09B	141°	55°	616 m	472

2 Objectives and scope

The objectives of this study are as follows:

- Evaluate the rock mass quality along the four selected boreholes KFM01B, KFM07C, KFM09A and KFM09B 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.
- Provide summarising properties for the pseudo-homogeneous rock units identified in the geological single-hole interpretation.
- Test the hypothesis that it is possible to identify signatures for deformation zones by means of the Q and RMR system on the very good rock masses found in the Forsmark area by using "signature 1" presented in /Lanaro and Bäckström 2006/.
- Discuss the results of the characterisation and list the main conclusion of the work.

The report is structured as follows:

- Summary of the BOREMAP data on rock types and fractures. The fracture sets occurring along the boreholes 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 the Appendices).
- Application of the RMR and Q empirical systems for determination of the rock quality along the four boreholes (see also the Appendices). 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 their 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 Appendices).
- Discussion of the results.
- Appendices.

3 Methods

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 properties of the rock mass: the Rock Mass Rating, RMR, and the Rock Quality Index, Q (Table 3-1). 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 constraints due to the shape, orientation, depth, function and safety of a potential excavation are not considered here.

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:

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

where the subscripts strength, RQD, spacing, conditions, water, and 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 /Bieniawski 1989/, 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, takes into account the stresses in the rock mass. Also these parameters are described and tabulated in /Barton 2002/.

Table 3-1. 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 Input data for the characterization

4.1 Mechanical properties of intact rock

Information on the data used in this report on the mechanical properties of the intact rock for the common rock types in the Forsmark area are presented in the site descriptive modelling Forsmark stage 2.1 /SKB 2006/. For the less abundant rock types, like pegmatite, amphibolite and calc-silicate, the mechanical properties of the intact rock are obtained from other sources as seen in Table 4-1, which displays an overview of the available test results when this report was produced. This table also contains the Hoek & Brown's parameters obtained from the uniaxial and triaxial laboratory test results. The mechanical properties of the natural fractures are usually not a direct input parameter of the empirical methods.

4.2 Boremap fracture data

The analysed boreholes were mapped by examining the core and the BIPS images of their walls (for KFM01B: /Berglund et al. 2004/; for KFM07C: /Carlsten et al. 2006/; for KFM09A and KFM09B: /Petersson et al. 2006ab/). For borehole KFM09A, no BIPS information is available for the last 5 m (795–800 m) resulting in lack of orientation data for the fractures occurring in the rock unit located there. The geological parameters obtained and stored in SKB's database Sicada were:

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

Table 4-1. Parameters for the Hoek & Brown's Criterion (uniaxial compressive strength, UCS, and Hoek & Brown's constant, m_i, for intact rock) based on the results of uniaxial and triaxial tests.

Rock type	Number of samples	Minimum		Mean		Maximum	
		USC [MPa]	m_i	UCS [MPa]	m_i	UCS [MPa]	m_i
Granite to granodiorite, metamorphic, medium-grained [1]	123	165	30	227	29	290	27
Tonalite to granodiorite, metamorphic [1]	16	130	10	156	9	180	9
Granite, metamorphic, aplitic [2]	7	150	30	275	30	370	30
Pegmatite, pegmatitic granite [3]	2	80	30	225	30	240	30
Amphibolite [4]	23	50	31	150	31	250	31
Felsic to intermediate volcanic rock, metamorphic [5]	55	30	30	125	30	260	30
Calc-silicate (skarn) [6]	–	30	10	100	10	200	10

[1] UCS and m_i from /SKB 2006/.
[2] m_i estimated based on /Hoek 1999/.
[3] UCS from /SKB 2004/; m_i estimated as for granite.
[4] UCS from /NBG 2000/; m_i from /Hoek, 1999/.
[5] UCS of meta-volcanic rock in /SKB 2004/; m_i estimated as for gneiss.
[6] UCS and m_i estimated as for limestone.

Each fracture observed along the borehole was classified among "open", "partly open" and "closed" (or "sealed"). 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 (Ja) was performed by the geologists based on core observations. Also the information listed above is contained in SKB's digital database Sicada.

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

- Bias correction of the orientation and spacing by Terzaghi's weighting /Terzaghi 1965/.
- Assignation of each fracture to a local fracture set or to a group of random fractures.

The fracture sets are identified according to the DFN model for Forsmark version 1.2 /SKB 2005/, since later DFN models were not available. In the following sections, the stereonet plots of the poles of the open and partly open fractures are presented where the fracture set names are indicated. Once the fracture sets were identified in each rock unit along the borehole, the mean orientation of each set and its Fisher's constant /Fisher 1953/ were determined (see Appendices for the different boreholes). Based on the orientation pole concentrations shown on the stereonet plots, the fractures were assigned to the fracture sets. 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, on average, every 5 m and 1 m of core length. For the fracture spacing, the Terzaghi's correction was applied to correct for the linear sampling of the fractures applied by the borehole.

The plot with depth of the total fracture frequency, the frequency of the sub-horizontal fractures, the Rock Quality Designation (RQD), and the number of fracture sets contemporarily occurring at every 5 m section of the borehole are shown in the following sections. The total frequency of the fractures gives an idea of the degree of fracturing of the core. RQD gives the sum of the length of core pieces longer than 100 mm per every metre of the drill core, which is another indicator of the degree of fracturing of the rock mass. Sometimes, for measuring the entity of the bias due to the borehole sampling, it is interesting to observe the fraction of sub-horizontal fractures compared to the total number of fractures which is also given in graphical form. Finally, by counting the fracture sets occurring in each 5 m section of core, the plot of the number of fracture sets contemporarily occurring in the borehole can be obtained.

Based on the DFN model, the fracture length rating for RMR was determined for fracture lengths between 1 and 3 m.

4.2.1 KFM01B

In Figure 4-1 the stereonet plot of the poles of the fracture planes for borehole KFM01B is shown. The fractures are subdivided into fracture sets according to the DFN Model for Forsmark 1.2 /SKB 2005/. The fractures intersected by this borehole are prevalently sub-horizontal (about 78%). Out of the totally 628 fractures used in the fracture orientation analysis, the NW fracture set includes only 5 fractures (about 0.7%), thus does not produce any cluster in the pole plot, whereas the NS fracture set includes about 7% of the fractures, about the same amount of fractures as for the random group. The NS fracture set is the most prominent of the sub-vertical sets.

The variation of the total fracture frequency, the estimated fracture spacing and RQD along the borehole are shown in Figure 4-2. In this borehole, a strong peak at shallow depth (15–55 m) can be seen in both the total fracture frequency and sub-horizontal fracture frequency. As for the plot of the number of sets, not only the sub-horizontal fractures are abundant at shallow depth, but also several sub-vertical sets are identified. This increase coincides with deformation zone 1. It is only at shallow depth that the RQD responds strongly to the increase of the fracture frequency. The peaks at the depths 120, 135, 225 and 420 m are only shown as a drop in RQD of 5 units, still within the class of excellent rock.

4.2.2 KFM07C

In Figure 4-3, the stereonet plot of the poles of the fracture planes for borehole KFM07C is shown. The fractures are subdivided into fracture sets according to the DFN Model for Forsmark version 1.2 /SKB 2005/. The fractures intersected by this borehole are mainly divided into the sub-horizontal set and NE set.

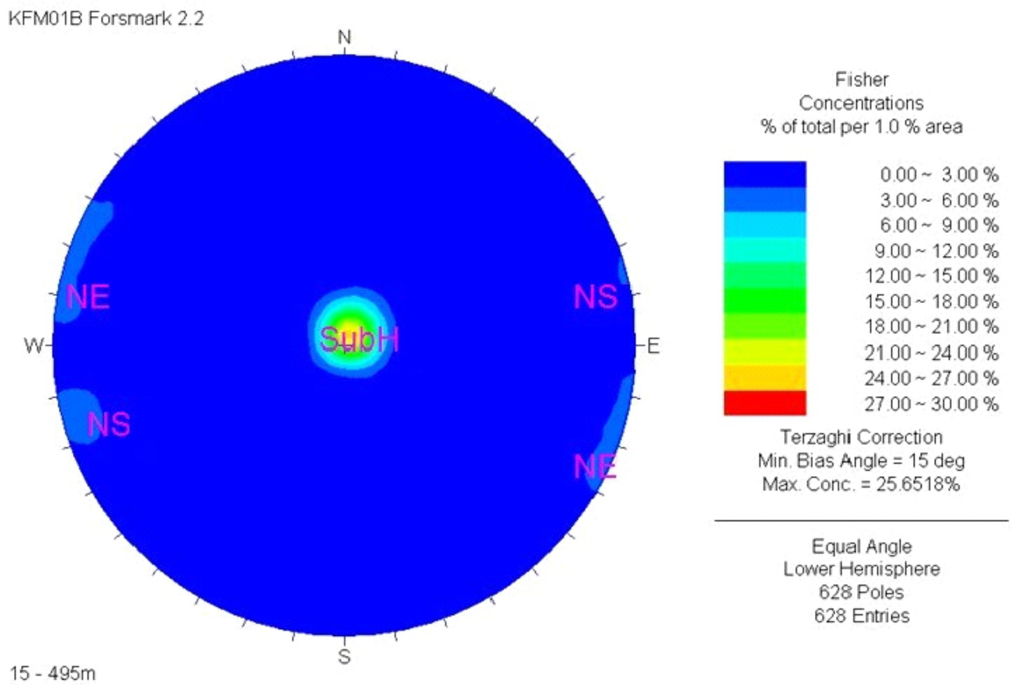

Figure 4-1. *Equiangular pole plot of the fractures logged along borehole KFM01B and indication of the main fracture sets.*

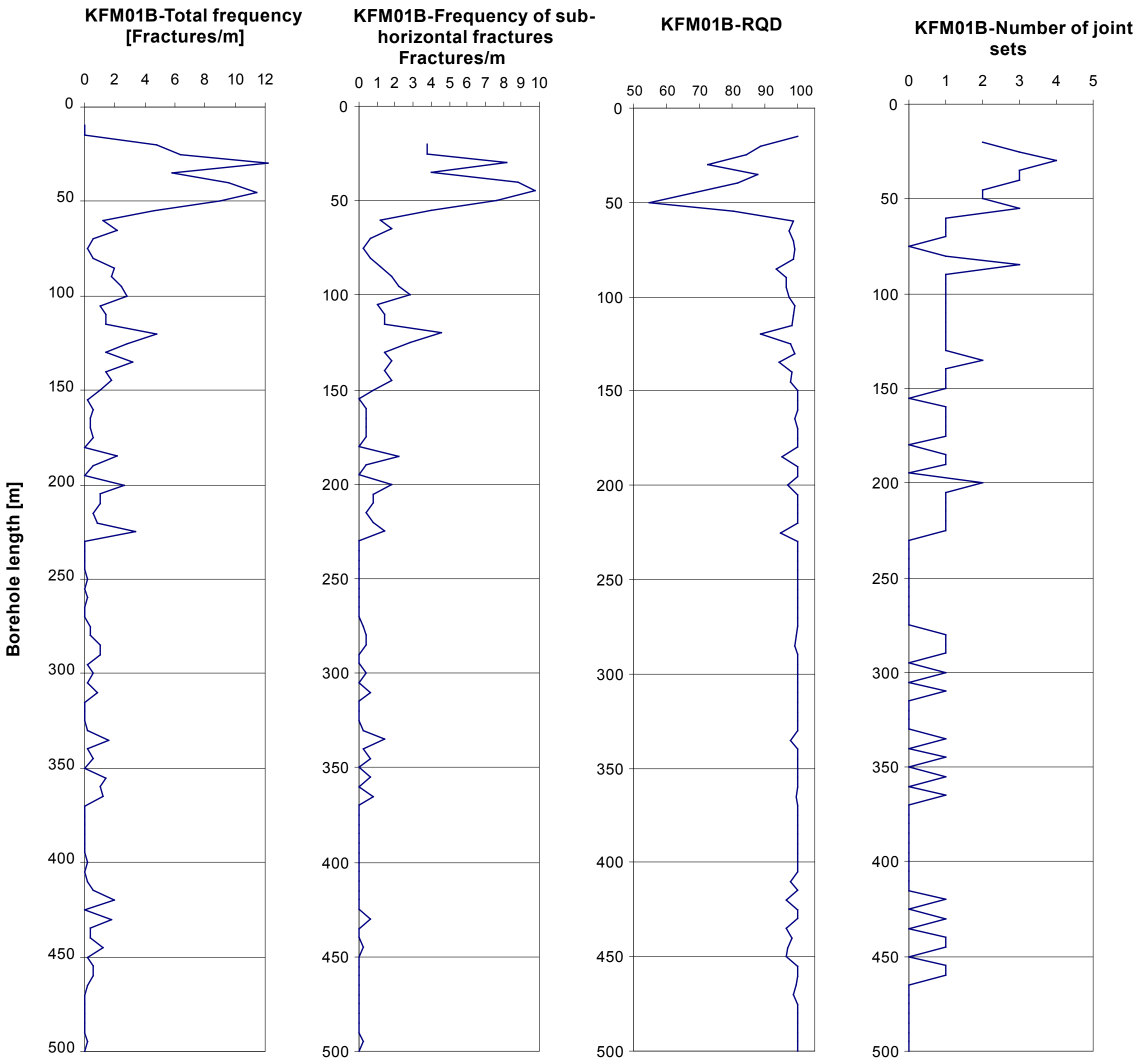

Figure 4-2. Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM01B. The values are averaged for each 5 m length of borehole.

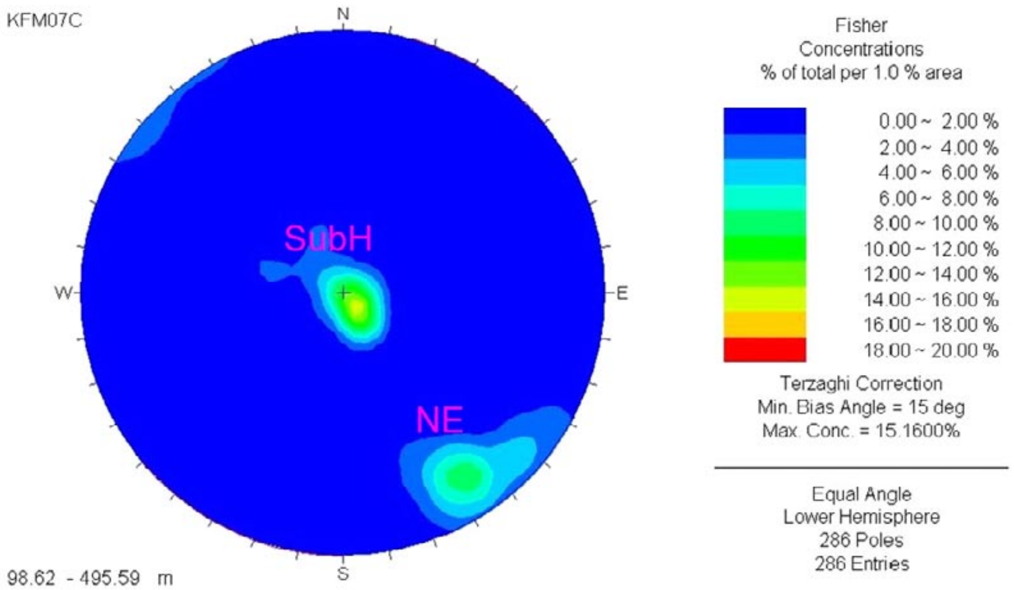

Figure 4-3. Equiangular pole plot of the fractures logged along borehole KFM07C and indication of the main fracture sets.

In the plot of the total fracture frequency in Figure 4-4, an increase is located between 320 and 390 m with a maximum value at a depth of 380 m. Compared to the fracture frequency for the sub-horizontal fractures, this increase is more prominent compared to the sub-horizontal plot and can be explained as depending on other occurring fracture sets. An increase from the general number of sets of 1–2 to 2–3 sets can be noticed over the same interval of increased fracture frequency. The lack of response in the RQD to this increase in fracture frequency is a sign that this increase is quite small or the fractures are rather evenly spaced.

4.2.3 KFM09A

The fractures are subdivided into fracture sets according to the DFN Model for Forsmark 1.2 /SKB 2005/.

Borehole KFM09A shows a predominance of sub-horizontal fractures (Figure 4-5). The fracture set oriented EW is rather well defined as shown in the stereonet plot. Fracture sets with orientation EW and NW are not indicated in the stereonet plot due to the small number of fractures in each set compared to the total amount of 1,133 entries for this borehole. The fracture set oriented EW contains 42 entries and the fracture set NW contains 77 entries.

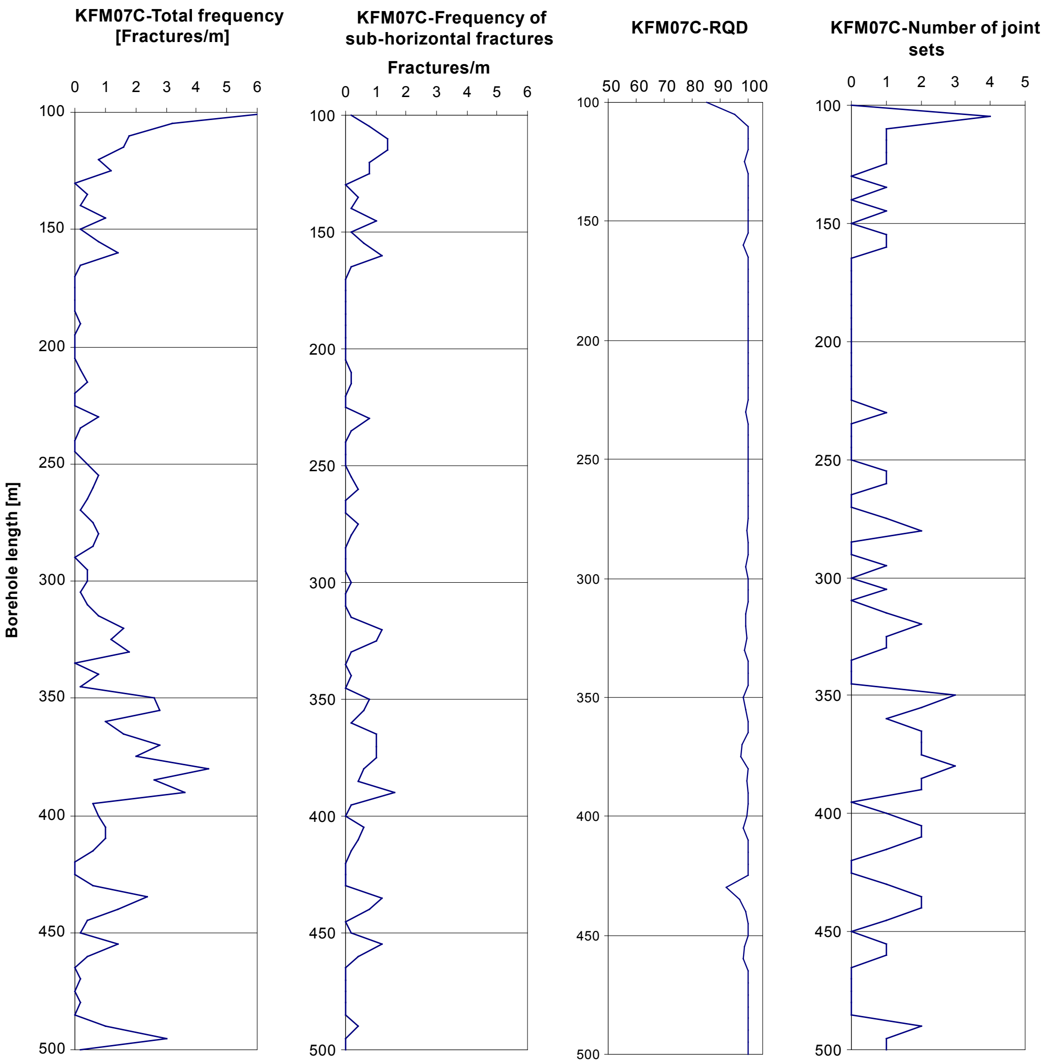

Figure 4-4. Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM07C. The values are averaged for each 5 m length of borehole.

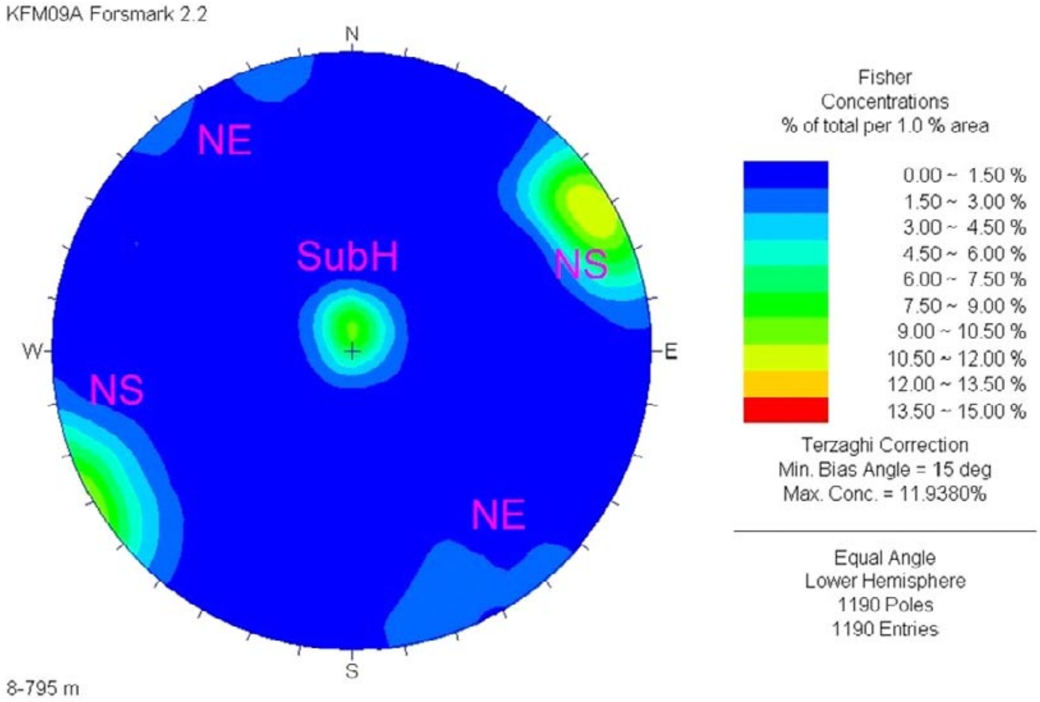

Figure 4-5. *Equiangular pole plot of the fractures logged along borehole KFM09A and indication of the main fracture sets.*

About 51% of the fractures in the entire borehole are sub-horizontal, hence the trend shows similarity between the total fracture frequency and the frequency for sub-horizontal fractures (Figure 4-6). A pronounced peak can be seen in the frequency values, and a matching trough in the RQD values at about 255 m. This is a part of a deformation zone occurring between 217–280 m. The strong peak in total fracture frequency at about 725 m depth also has a matching trough in the RQD values. This increase in fracture frequency is an effect of fractures from different sub-vertical sets rather than an increase in sub-horizontal fractures as seen in the increase in fracture sets but not in the response of the frequency of sub-horizontal fractures.

4.2.4 KFM09B

The fractures are subdivided into fracture sets according to the DFN Model for Forsmark 1.2 /SKB 2005/.

In this borehole the sub-horizontal and the NE fracture set dominate the scene (Figure 4-7). The NE set makes up 36% and the sub-horizontal fracture set about 48% of the total number of fractures, which implies a strong dominance of these two sets in the borehole. About 34 of the totally 761 fractures in the orientation analysis are random, which is quite few.

A general similarity between the frequency of total and sub-horizontal fractures, respectively, can be seen above about 350 m in this borehole (Figure 4-8). There are several strong peaks in the total fracture frequency beneath this depth that can not be discerned in the plot of the sub-horizontal fracture frequency. At about 570 m the peak in the total fracture frequency is mirrored in the response from RQD, although the decrease in RQD is only to a minimum of 84, which qualifies as good rock.

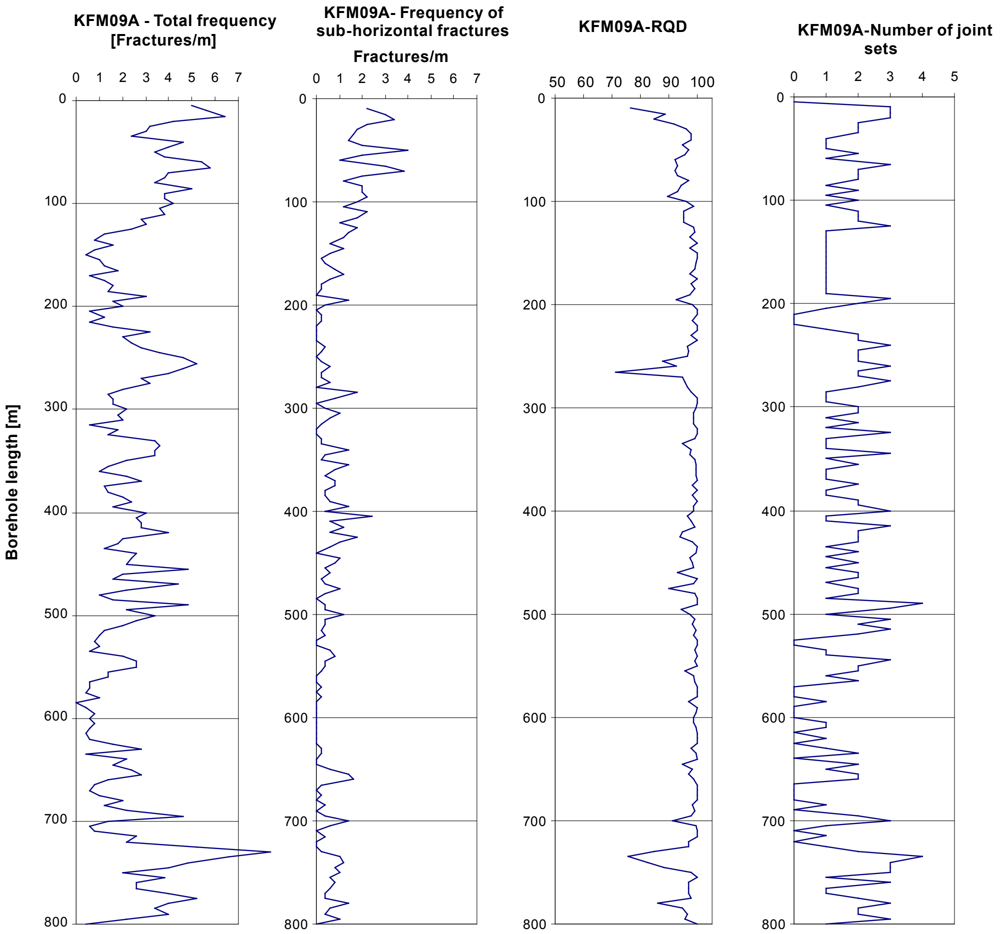

Figure 4-6. *Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM09A. The values are averaged for each 5 m length of borehole.*

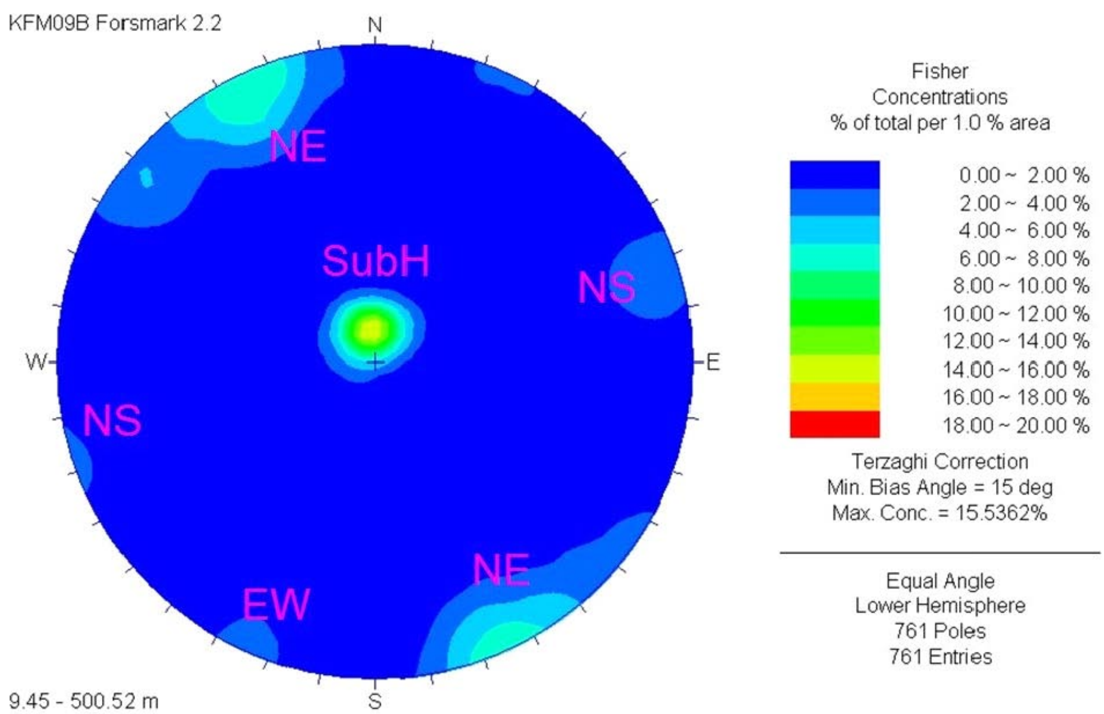

Figure 4-7. *Equiangular pole plot of the fractures logged along borehole KFM09B and indication of the main fracture sets.*

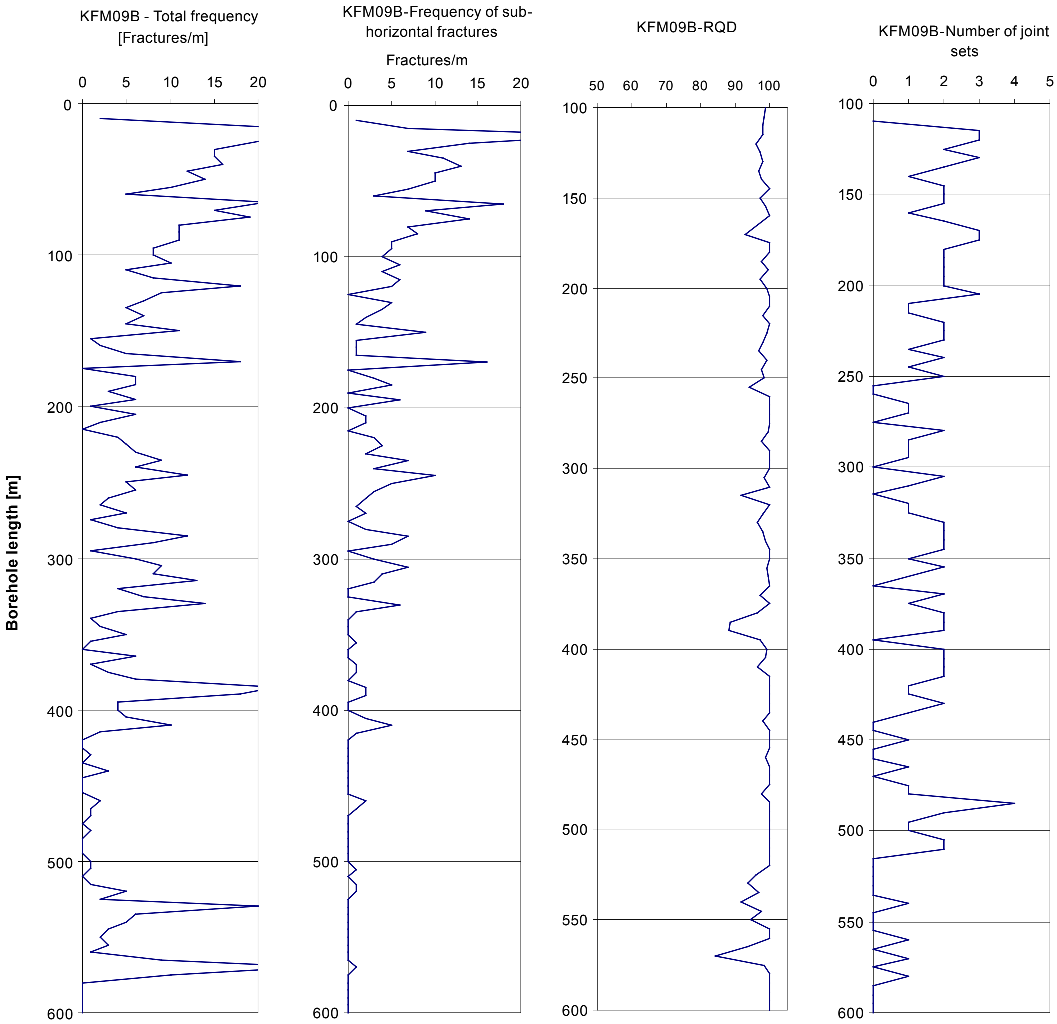

Figure 4-8. *Variation of the total fracture frequency, frequency of the sub-horizontal fractures, RQD and number of joint sets with depth for borehole KFM09B. The values are averaged for each 5 m length of borehole.*

5 Results

5.1 Rock mechanics characterisation of the rock mass along the boreholes

The characterization of the rock mass along the respective boreholes was performed mainly based on data derived from the previously performed geological single-hole interpretation of boreholes KFM01B, KFM07C, KFM09A, and KFM09B as well as on other available information/reports about the boreholes. Results from new determinations of uniaxial compressive strength were not available at the time the data in this report were processed. Instead, the uniaxial compressive strength used here was originated from earlier investigations /SKB 2006, 2004, NBG 2000/. For the rock type amphibolite, the information is extracted from the literature /NBG 2000/. When comparing the results for different depths, the spatial variation along the boreholes can be highlighted.

The "single-hole interpretation" provides the partitioning of the boreholes into rock units (pseudo-homogeneous rock volumes with a predominant rock type or particular mixture of them) and deformation zones (zone of higher fracture frequency and alteration, often observed as seismic and radar reflectors). The sources here are the reports by /Berglund et al. 2004/, /Petersson et al. 2006ab/ and /Carlsten et al. 2006/.

5.1.1 KFM01B

Partitioning

The geological single-hole interpretation /Berglund et al. 2004/ provides a partitioning of borehole KFM01B into pseudo-homogeneous sections that is also applied for the rock mechanics characterization. The borehole is not divided into several rock type groups, but only one such group is identified. Three fractured/deformation zones are recognized along the borehole. In Table 5-1, the rock units, rock type groups and the decision process for the choice of the fractured zones for rock mechanics characterisation are reported. The SKB name code for the rock type can be read within the parenthesis;

- RU1: Medium-grained metagranite-granodiorite (101057) with subordinate pegmatitic granite (101061), amphibolite (102017) and fine-grained granitoid (101051).

The deformation zones are described as follows:

- DZ1: Several crushed zones and strongly increased frequency of open fractures. The most common fracture filling minerals are calcite, chlorite and asphalt. Also with a variable degree of oxidation (faint to medium).
- DZ2: Increased frequency of sealed fractures with epidote and laumontite as dominant fracture filling minerals. Also with a variable degree of oxidation (faint to weak).
- DZ3: Two crushed zones and increased frequency of sealed fractures. Calcite, laumontite, chlorite and prehnite as the dominant fracture filling minerals. Also with a variable degree of oxidation, ranging from faint to strong in intensity.

Table 5-1. Partitioning of borehole KFM01B: Rock units and deformation zones.

Extension of rock unit (borehole length) [m]	Rock unit	Depth (borehole length) [m]	Deformation zones
		16–53	DZ1
16–454	RU1	107–135	DZ2
		415–454	DZ3

Characterisation with RMR

For each 5 m section of the borehole, the geomechanical parameters from borehole logging were scrutinized (Figure 5-1 and Appendix 1). The minimum, average, most frequent and maximum rating for RMR were determined for each borehole section. The plots in Figure 5-1 obtained for the RQD, fracture conditions and spacing rating are according to ranges suggested by the RMR system.

RMR varies between 65 and 95, which corresponds to from good to very good rock. At 45 m borehole length a minimum value of about 45 can be found which is reflected in the RQD value, and to some extent in fracture conditions. This minimum value of about 45 still represents fair conditions. The first deformation zone (DZ1 16–53 m) can be identified as the zone where the minimum RMR value is found, whereas the second and third deformation zones (at 107–135 m and 415–454 m, respectively) display a more gentle decrease in RMR.

The RMR values were also summarised for each rock type group. Values are presented in Appendix 1 for competent rock, fracture zones and for the whole borehole. In summary:

1 The poorest rock in the borehole is classified as "fair rock" (RMR = 45).

2 The fractured rock in the deformation zones shows an average RMR of about 77, which means a rock displaying "good rock" conditions.

3 The competent rock has a mean RMR of 86 that places it in the range of "very good rock" (RMR between 81 and 100).

4 The best rock quality observed in the borehole reaches an RMR of 97 ("very good rock").

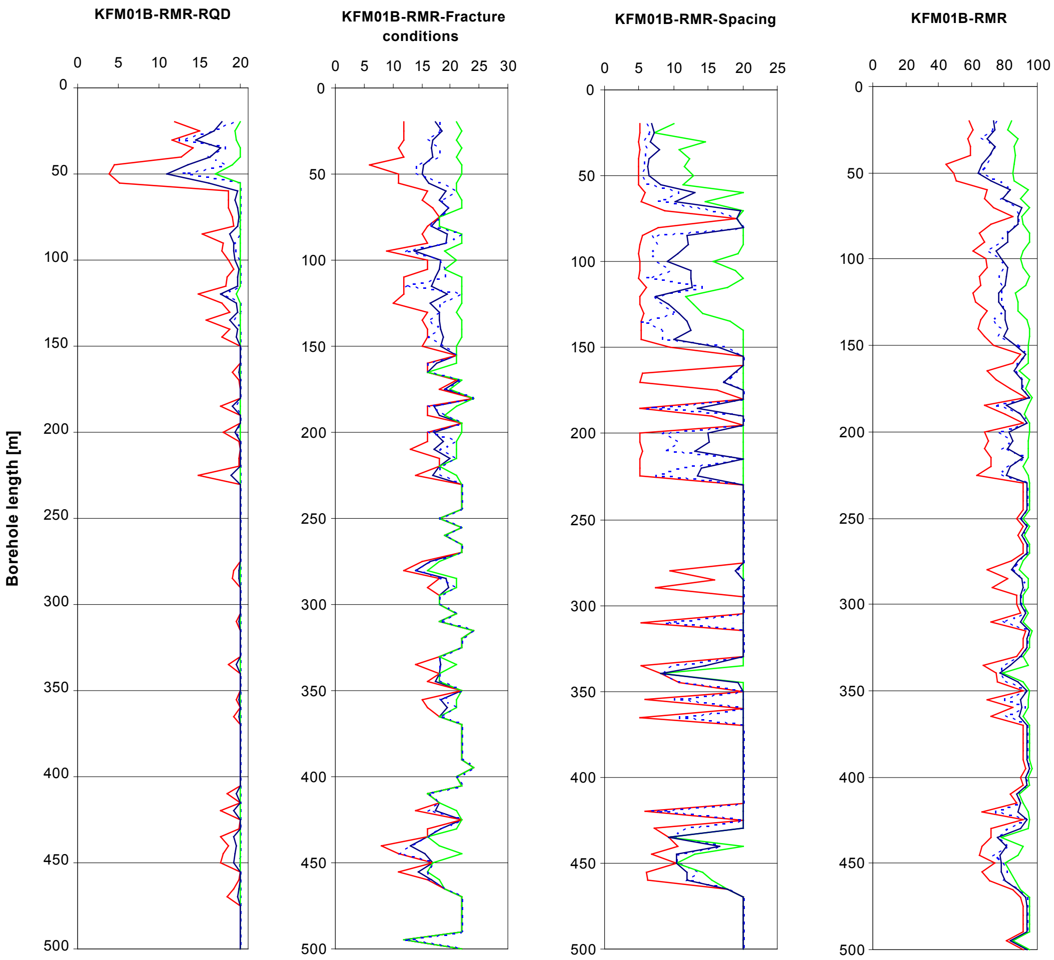

***Figure 5-1.** Ratings for RMR characterisation and resulting RMR values for borehole KFM01B. The ratings for RQD, fracture conditions, and fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

Characterisation with Q

The input numbers for the Q system and the resultant rock quality index for 5 m are plotted in Figure 5-2. As for RMR, the Q-numbers are obtained through the choice of minimum, average, most frequent and maximum values of the geomechanical parameters logged along the borehole. The fracture-set, roughness and alteration numbers are obtained for each borehole section of 5 m (see also Appendix 1). 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. The Q parameter for water was assumed equal to 1 (dry borehole) as it is usually done for rock mass characterisation.

The three deformation zones can also be identified as depressions in the plot of Q. The first deformation zone contains the minimum Q value (0.1) similarly to the plot of RMR. Such a low value is not found elsewhere in the borehole. In fact, the other two deformation zones show a more moderate low (min. 1.2 and 2, respectively). The third deformation zone occurs in an area of generally "extremely to exceptionally good" rock and can thus be seen as a distinct drop in Q value although the mean Q value for that deformation zone is 130, which is in the lower range of "extremely good rock".

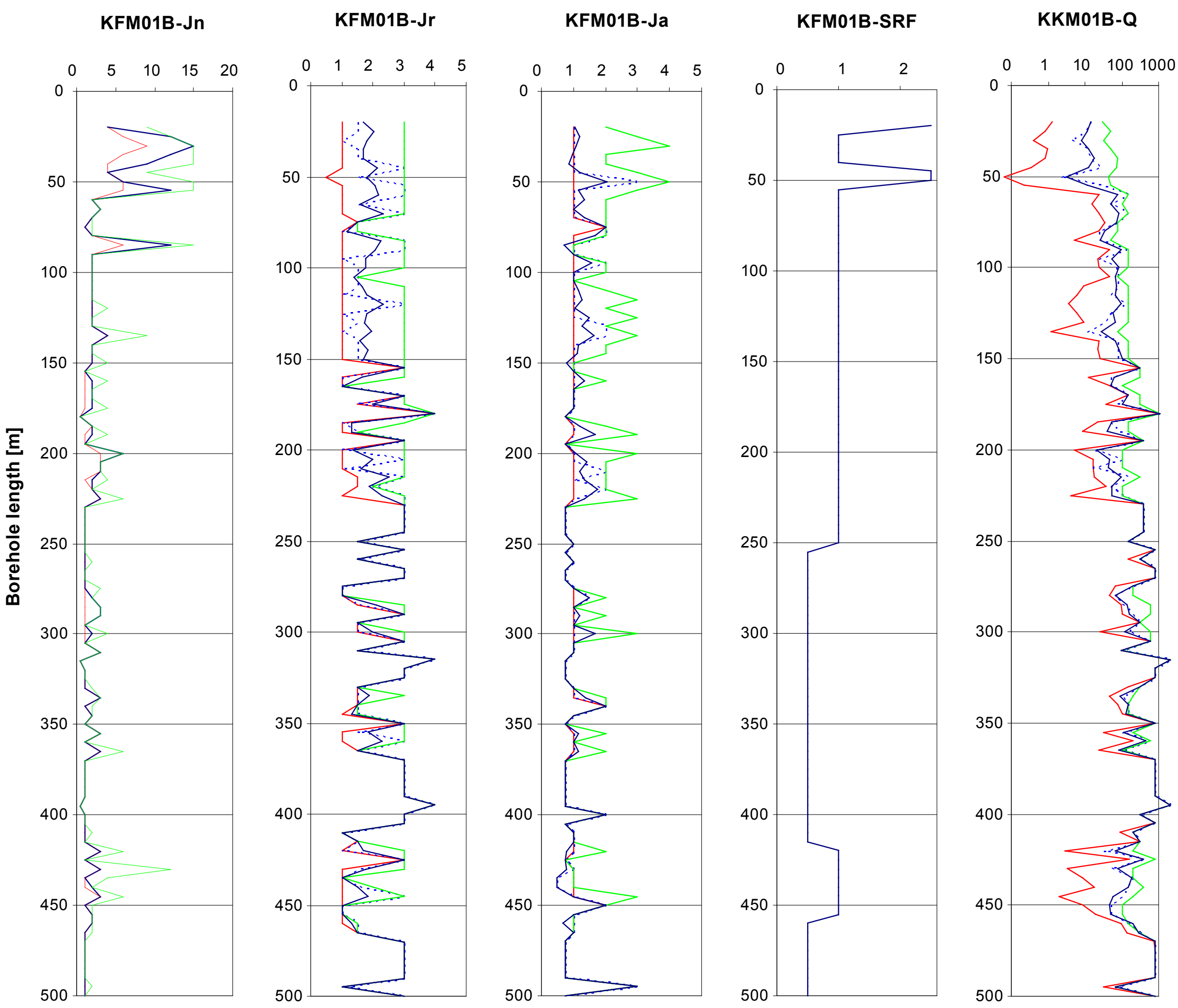

__Figure 5-2.__ Input numbers for Q characterisation and resulting Q values for borehole KFM01B. The fracture set number, fracture roughness, fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

The values of Q can be summarised as follows:

1 The poorest rock occurs in deformation zone DZ1 and has Q 0.1 ("very poor rock").

2 The rock in the deformation zones has an average of 69 classed as "very good rock".

3 The competent rock has an average and frequent Q of 380 and 196, respectively, thus belonging in the class of "extremely good rock".

4 The best rock within the competent rock has a Q of 2,133, which means "exceptionally good rock".

5.1.2 KFM07C

Partitioning

The rock units and deformation zones observed by the single-hole interpretation of the core and borehole pictures for borehole KFM07C are summarized in Table 5-2 /Carlsten et al. 2006/. The rock units are characterised by the following rock types:

- RU1: Medium-grained metagranite-granodiorite (101057) with subordinate pegmatitic granite (101061).
- RU2: Medium-grained metagranite-granodiorite (101057) with subordinate occurrence of pegmatitc granite (101061), amphibolite (102017), fine- to medium-grained metagranitoid (101051) and aplitic metagranite (101058).

The deformation zones are described as follows:

- DZ1: Increased frequency of open and sealed fractures. Most fractures strike NE and show a variable dip. Two crushed zones at the top of the possible deformation zone.
- DZ2: Increased frequency of sealed and open fractures, including a common occurrence of sealed fracture network. Fractures that strike WSW and dip steeply to the NNW and fractures that are gently dipping to sub-horizontal dominate. Several brecciated intervals.
- DZ3: Increased frequency of sealed fractures in the lower part and a crush zone in the upper part (429.2–429.6 m).

Characterisation with RMR

For each 5 m section of the borehole, the geomechanical parameters from the borehole logging were scrutinized. The minimum, average, most frequent and maximum rating for RMR were determined for each borehole section, sometimes through averaging processes (see Appendix 2). The plots in Figure 5-3 show the RQD, fracture condition, and spacing rating that results in the RMR ranges for rock mass characterisation.

Table 5-2. Partitioning of borehole KFM07C: Rock units and deformation zones.

Extension of rock units (borehole length) [m]	Rock unit	Depth (borehole length) [m]	Deformation zones
85–123	1	92–103	DZ1
123–498	2	308–388	DZ2
		429–439	DZ3

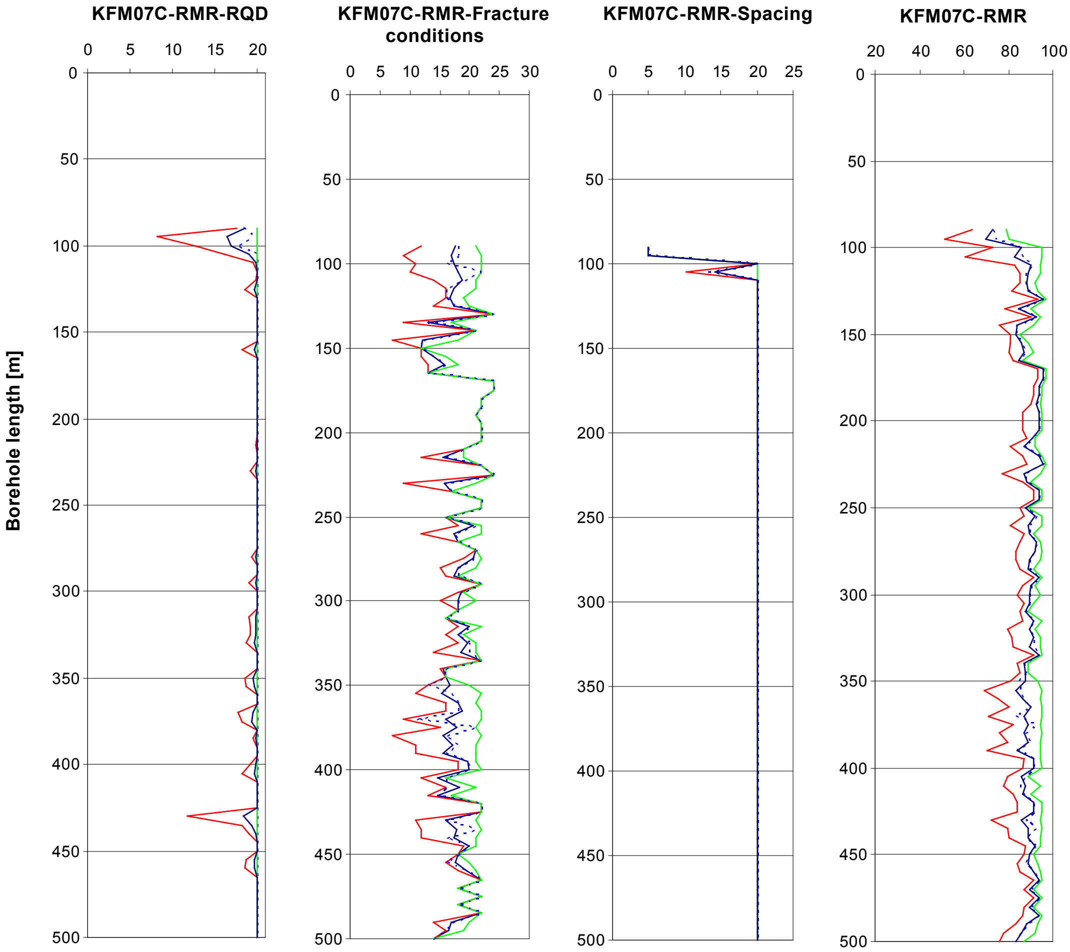

Figure 5-3. Ratings for RMR characterisation and resulting RMR values for borehole KFM07C. The ratings for RQD, fracture conditions, and fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

The RMR for the whole borehole ranges between 51 and 96, with a general average difference of about 2 between the competent rock and the deformation zones. The rock in this borehole is generally classified as "good" to "very good rock" and there is generally no strong indication of the deformation zones DZ2 and DZ3, whereas DZ1 displays the lowest RMR value (RMR = 51) which is an indication of "fair rock". In more detail, The borehole reveals:

1 The poorest rock in the deformation zones has a minimum RMR of 51 ("fair rock").

2 The average RMR in the deformation zones is 87, placing it in the range of the "very good rock" class.

3 The average rock quality in the competent rock mass is 90, thus in "very good rock".

4 The maximum RMR in the competent rock is 96, also in the "very good rock".

Characterisation with Q

The input numbers for the Q systems and the resultant rock quality index for 5 m are plotted in Figure 5-4. Like for RMR, the Q-numbers are obtained through the choice of minimum, average, most frequent and maximum values of the geomechanical parameters logged along the borehole (see Appendix 2). 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. The Q number for water (J_w) was assumed equal to 1 (dry borehole) as it is usually done for rock mass characterisation.

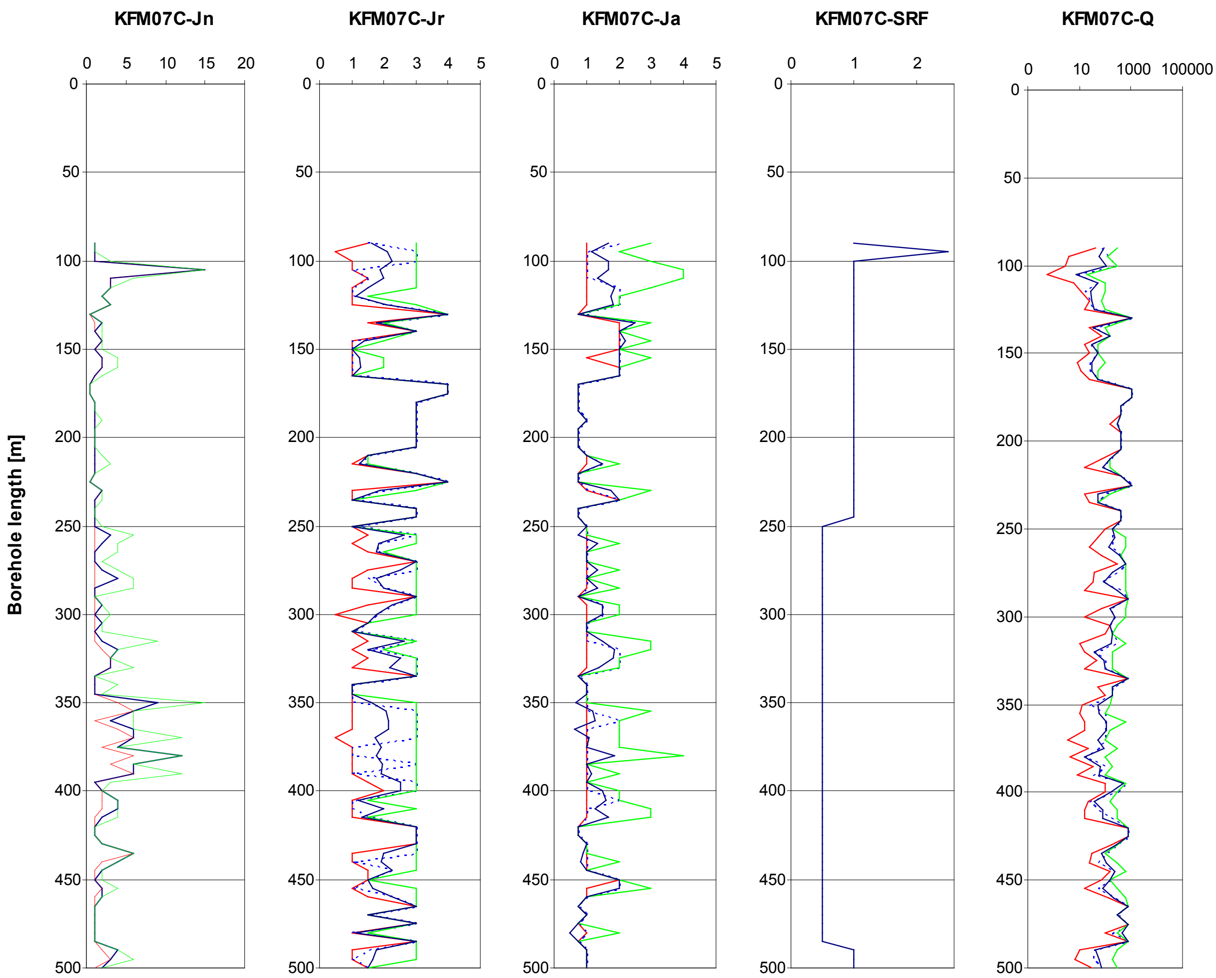

Figure 5-4. Input numbers for Q characterisation and resulting Q values for borehole KFM07C. The fracture set number, fracture roughness, fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

Similarly to RMR, the Q values show that the rock quality in the borehole is generally good to very good with the lower values for the deformation zone 1 ranging into the "fair rock" range (minimum Q value of 7).

The rock mass can be classified for the purposes of characterisation as follows:

1 The poorest rock in the deformation zones has a minimum Q of 7 that corresponds to "fair rock".

2 The deformation zones have an average and frequent value of Q of 123 and 90, respectively, the values ranging from "extremely good rock" to "very good rock".

3 The average and frequent Q values for the competent rock are in the range of "extremely good rock", respectively being 308 and 200.

4 The best rock section in the competent rock is classified as "exceptionally good rock" according to Q (maximum value 1,067).

5.1.3 KFM09A

Single-hole interpretation

Table 5-3 contains the list of the rock units and deformation zones identified along borehole KFM09A /Petersson et al. 2006a/. The rock units are shortly described as:

- RU1a: Medium-grained metagranite-granodiorite (101057), locally rich in biotite and with intense ductile deformation. Subordinate occurrence of amphibolite and pegmatitic granite.
- RU1b: Medium-grained metagranite-granodiorite (101057), locally rich in biotite and with intense ductile deformation. Subordinate occurrences of amphibolite (102017), pegmatitic granite (101061) and one occurrence of aplitic metagranite (101058).
- RU2: Pegmatitic granite (101061) with high natural gamma radiation.
- RU3: Fine- to medium-grained metagranitoid (101051) with subordinate occurrence of pegmatitic granite (101061), medium-grained metagranite-granitoide (101057) and amphibolite (102017).
- RU4: Medium-grained metagranite-granodiorite (101057), genereally rich in biotite and with intense ductile deformation. Heterogeneous with subordinate occurrences of pegmatitic granite (101061), amphibolite (102017), felsic to intermediate metavolcanic rock (103076), aplitic metagranite (101058) and fine- to medium-grained metagranitoid (101051).
- RU5: Heterogenous mixture of medium-grained metagranite-granodiorite (101057), amphibolite (102017), aplitic metagranite (101058), pegmatitic granite (101061), felsic to intermediate metavolcanic rock (103076) and fine- to medium-grained metagranitoid (101051).
- RU6: Pegmatitic granite (101061) and, in the upper part, medium-grained metagranite-granodiorite (101057), both of which are oxidized and vuggy.
- RU7: Medium-grained metagranite-granodiorite (101057) with subordinate occurrences of pegmatitic granite (101061), amphibolite (102017) and felsic to intermediate metavolcanic rock (103076). One crushed zone at 592 m.
- RU8: Medium-grained metagranite-granodiorite (101057), generally with intense ductile deformation and with subordinate occurrences of pegmatitic granite (101061), amphibolite (102017), fine- to medium-grained metagranitoid (101051) and felsic to intermediate metavolcanic rock (103076).
- RU9: Felsic to intermediate metavolcanic rock (103076) with subordinate occurrences of metagranodiorite (101056), amphibolite (102017), metagranite-granodiorite (101057), metatonalite-granodiorite (101054) and fine- to medium-grained metagranitoid (101051). Virtually the whole borehole section has been affected by intense ductile deformation.

Table 5-3. Partitioning of borehole KFM09A: Rock units and deformation zones.

Extension of rock unit (borehole length) [m]	Rock unit	Depth (borehole length) [m]	Deformation zone
8–21	RU1	15–40	DZ1
21–52	RU2		
52–124	RU1b	86–116	DZ2
124–242	RU3	217–280	DZ3
242–440	RU4		
440–512	RU5		
512–522	RU6		
522–641	RU7		
641–758	RU8	723–754	DZ4
758–800	RU9		

Five possible deformation zones have been identified in KFM09A:

- DZ1: Increased frequency of sealed fractures and sealed fracture networks. Increased frequency of open fractures in the upper part.
- DZ2: Increased frequency of sealed fractures and sealed fracture networks.
- DZ3: Increased frequency of sealed fractures and sealed fracture networks. Increased frequency of open fractures in the lower part.
- DZ4: Increased frequency of open fractures, sealed fractures and sealed fracture networks. No apertures exceed 1 mm. Fractures show variable orientation.
- DZ5: Increased frequency of sealed fractures and sealed fracture networks. No apertures exceed 1 mm. Fractures show variable orientation.

Characterisation with RMR

The minimum, average, most frequent and maximum ratings for RMR were determined for each borehole section of 5 m and are show in Appendix 3. The plots in Figure 5-5 show the RQD, fracture condition, and spacing rating, respectively, that result in the ranges of RMR on the right. 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.

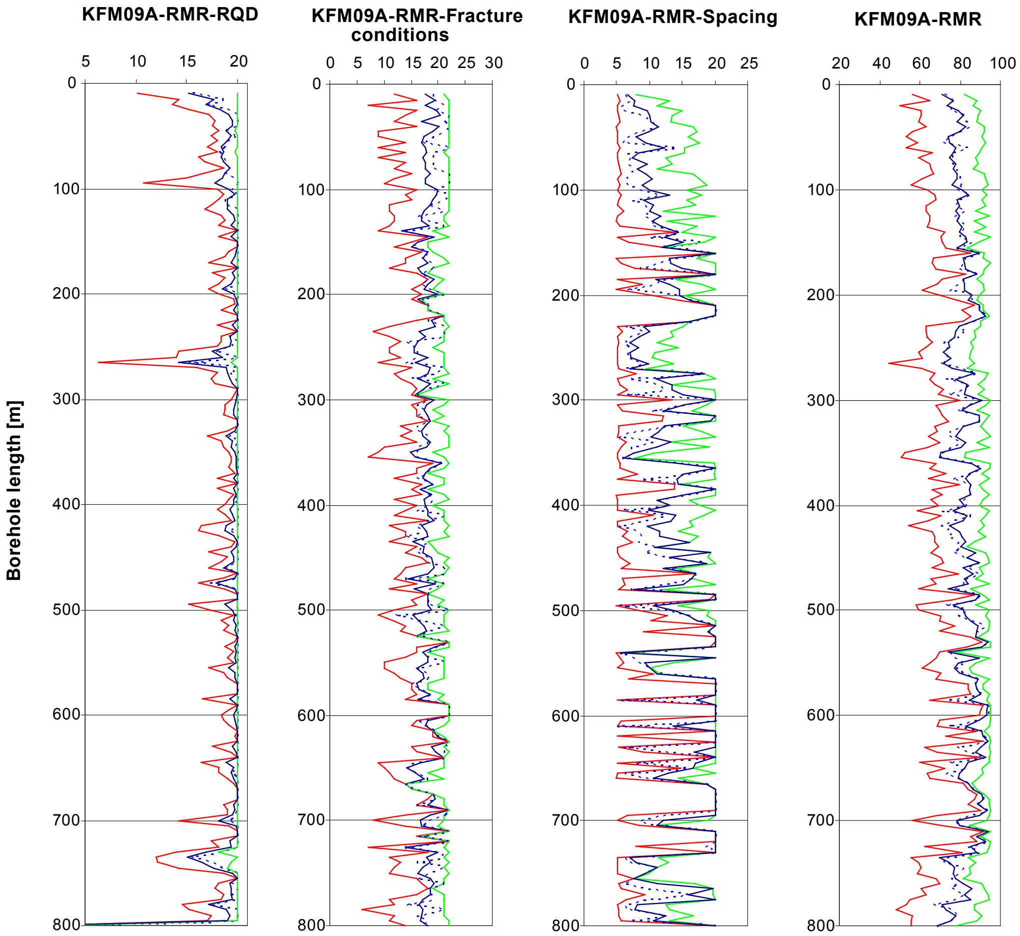

Figure 5-5. *Ratings for RMR characterisation and resulting RMR values for borehole KFM09A. The ratings for RQD, fracture conditions, and fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

The average RMR values found for the different rock units in the borehole range between 70 and 95, from "good" to "very good rock". There is generally no strong indication of the deformation zones. In fact, the lowest RMR value is found in deformation zone DZ3 (RMR = 45) that indicates "fair rock", although the mean value for this interval shows no strong indication of diminishing RMR values (mean value for DZ3 is 79 in the upper part of the "good rock" class). A general decrease in RMR values can be seen at borehole lengths below 735 m where two deformation zones are indicated (DZ4 and DZ5). The mean RMR value in this area is at its lowest but still around 70, which indicates "good rock" conditions.

The quality of the competent versus fractured rock can be summarised as follows.

1 The poorest rock quality observed in the borehole is RMR = 45 ("fair rock").
2 The average RMR in the deformation zones is 82 ("very good rock").
3 The average RMR for the competent rock is 83 ("very good rock").
4 The maximum rock mass quality in the competent rock was RMR = 94, which means "very good rock".

Characterisation with Q

The input Q-numbers and the resultant rock quality index Q for 5 m intervals are plotted in Figure 5-6. Here, the Q-numbers are obtained by choosing the minimum, average, most frequent and maximum values of the geomechanical parameters logged along the borehole. The fracture-set number, roughness and alteration are obtained for each borehole section of 5 m (see also Appendix 3). SRF was assigned for "characterisation" in the same way as for the other boreholes in this report.

The characterisation with Q shows that the deformation zones DZ1, DZ3, DZ4 and DZ5 present from "poor" to "fair" rock quality, whereas deformation zone DZ2 is not identified as a decrease in the plot of Q. This is probably due to a generally poorer rock quality in the upper part of the borehole from 8 to 125 m compared to the lower part. In the lower part, where deformation zones DZ3, DZ4 and DZ5 are situated, the competent rock is generally classified as "very good rock". This environment makes the deformation zones more prominent. The differences between competent and fractured rock can be summarised as:

1 The poorest rock quality in the deformation zone is Q = 0,2 ("very poor rock").
2 An average Q of 22 is observed in the deformation zones ("good rock").
3 The competent rock has an average Q of 121 that indicates "extremely good rock".
4 The maximum observed Q value belongs to the competent rock and is 286 ("extremely good rock").

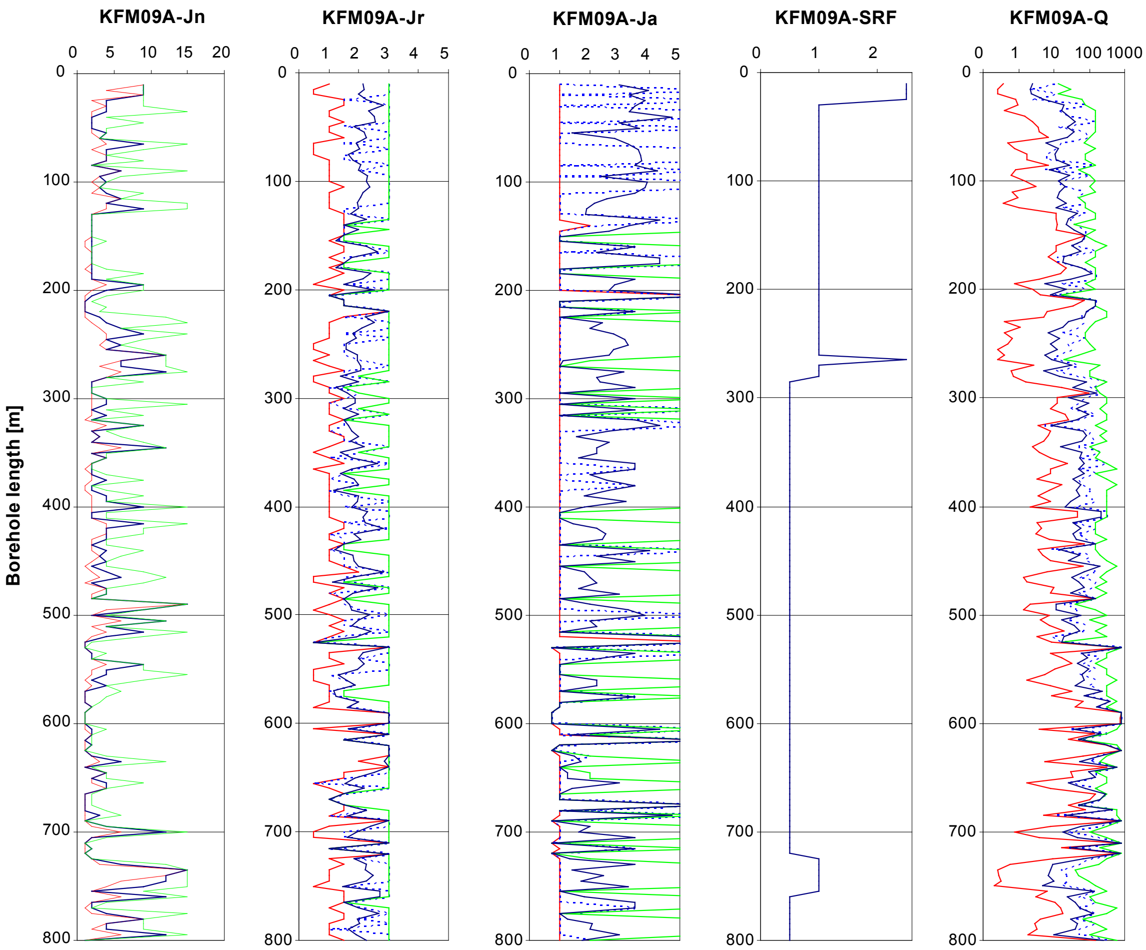

Figure 5–6. Input numbers for Q characterisation and resulting Q values for borehole KFM09A. The fracture set number, fracture roughness, fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

5.1.4 KFM09B

Single-hole interpretation

Table 5-4 contains the list of the rock units and deformation zones identified along borehole KFM09B /Petersson et al. 2006b/. The following rock units were recognized:

Table 5-4. Partitioning of borehole KFM09B: Rock units and deformation zones.

Extension of rock unit (borehole length) [m]	Rock unit	Depth (borehole length) [m]	Deformation zone
9–110	RU1a	9–132	DZ1
110–169	RU2		
169–259	RU1b		
259–318	RU3a	308–340	DZ2
318–445	RU4a	363–413	DZ3
445–480	RU3b		
480–616	RU4b	520–550	DZ4
		561–574	DZ5

- RU1a: Medium-grained metagranite-granodiorite (101057) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017).
- RU1b: Medium-grained metagranite-granodiorite (101057) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017).
- RU2: Pegmatitic granite (101061) with subordinate occurrences of medium-grained metagranite-granodiorite (101057). Also a few minor occurrences of amphibolite (102017).
- RU3a: Medium-grained metagranite-granodiorite (101057) affected by faint to medium albitization. Subordinate occurrences of pegmatitic granite (101061), calc-silicate rock (108019) and amphibolite (102017).
- RU3b: Medium-grained metagranite-granodiorite (101057) affected by faint to weak albitization. Subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017).
- RU4a: Medium-grained metagranite-granodiorite (101057) with subordinate occurrences of pegmatitc granite (101061). Also a few minor occurrences of amphibolite (102017).
- RU4b: Medium-grained metagranite-granodiorite (101057) with subordinate occurrences of pegmatitic granite (101061) and amphibolite (102017), and one occurrence of fine-to medium-grained metagranitoid (101051).

Five deformation zones were identified by the single-hole interpretation:

- DZ1: Increased frequency of sealed and open fractures and sealed fracture networks. Gently dipping to sub-horizontal fractures and steeply dipping fractures with SW strike dominate. Open fractures are predominately gently dipping. Two, approximately 3 dm wide crushed zones occur at 20 m borehole length.
- DZ2: Increased frequency of sealed and open fractures and sealed networks. Steeply dipping fractures with NE strike as well as gently dipping fractures dominate. One 3 cm wide crushed zone at 311 m. Apertures are typically less than 1 mm. The most frequent fracture filling minerals in the order of decreasing abundance include calcite, chlorite, laumontite and hematite.
- DZ3: Increased frequency of sealed and open fractures and sealed fracture networks. Steeply dipping fractures with NE strike as well as gently dipping fractures with variable strike dominate. Apertures are typically less than 1 mm, with a few ranging up to 5 mm.
- DZ4: Increasing frequency of sealed and open fractures and sealed fracture networks. Steeply dipping fractures with a strike that varies from NNW to ENE dominate. Apertures are 1 mm or less. Faint to weak oxidation. The most frequent fracture filling minerals in the order of decreasing abundance include calcite, chlorite, laumontite and hematite.
- DZ5: Increased frequency of sealed and open fractures. Steeply dipping fractures dominate. Fracture apertures are 1.5 mm or less. Faint to weak oxidization. The most frequent fracture filling minerals in order of decreasing abundance include chlorite, calcite and clay minerals.

Characterisation with RMR

For each 5 m section of the borehole, the geomechanical parameters from borehole logging were scrutinized to determine the minimum, average, most frequent and maximum rating for RMR (see Appendix 4). The plots in Figure 5-7 are obtained for the RQD, fracture condition, and spacing rating that result in the RMR ranges shown on the right plot. 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.

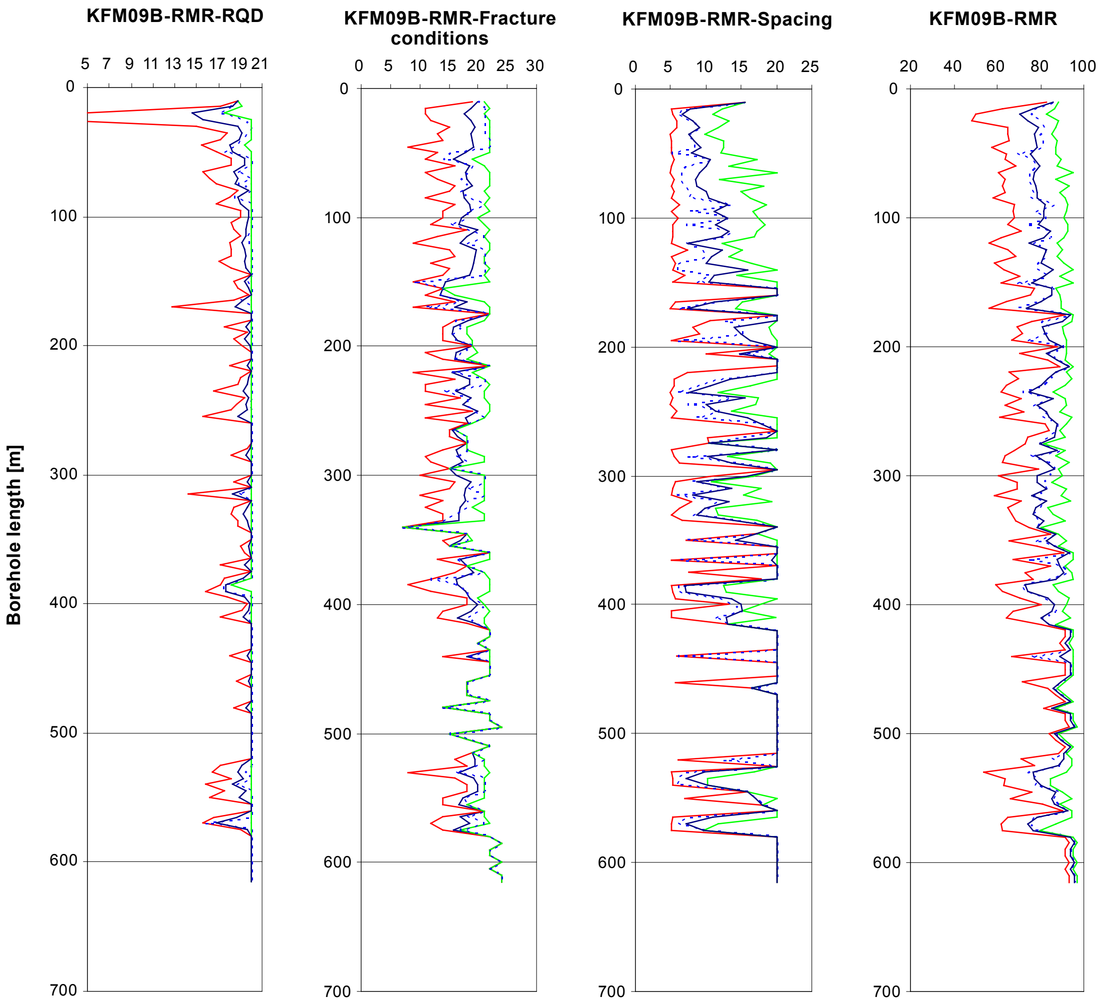

Figure 5-7. Ratings for RMR characterisation and resulting RMR values for borehole KFM09B. The ratings for RQD, fracture conditions, and fracture spacing are plotted with depth together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

The general trend is a gentle increase of the RMR with depth along the borehole. The five deformation zones display a somewhat lower RMR value than for the rest of the borehole. The mean RMR for the fractured rock is about 80 which still indicates "good rock". The minimum RMR can be found in the uppermost part of the borehole, in deformation zone DZ1 (RMR = 48, which falls within the "fair rock" class). More in detail:

1 The deformation zones show a minimum RMR of about 48 ("fair rock").

2 On average, the RMR in the deformation zones is rather high, on the upper limit of the "good rock" class with values around 80.

3 The competent rock exhibits an average RMR of 88 ("very good rock").

4 The rock mass quality is topped by some sections of the competent rock that have a maximum RMR of 97 ("very good rock").

Characterisation with Q

The input Q-numbers are obtained through the choice of minimum, average, most frequent and maximum values of the geomechanical parameters logged along the borehole (see also Appendix 4). The Q-numbers and the resultant rock quality index Q for 5 m borehole sections are plotted in Figure 5-8. SRF and water factor are assigned according to the procedure for rock mass characterisation.

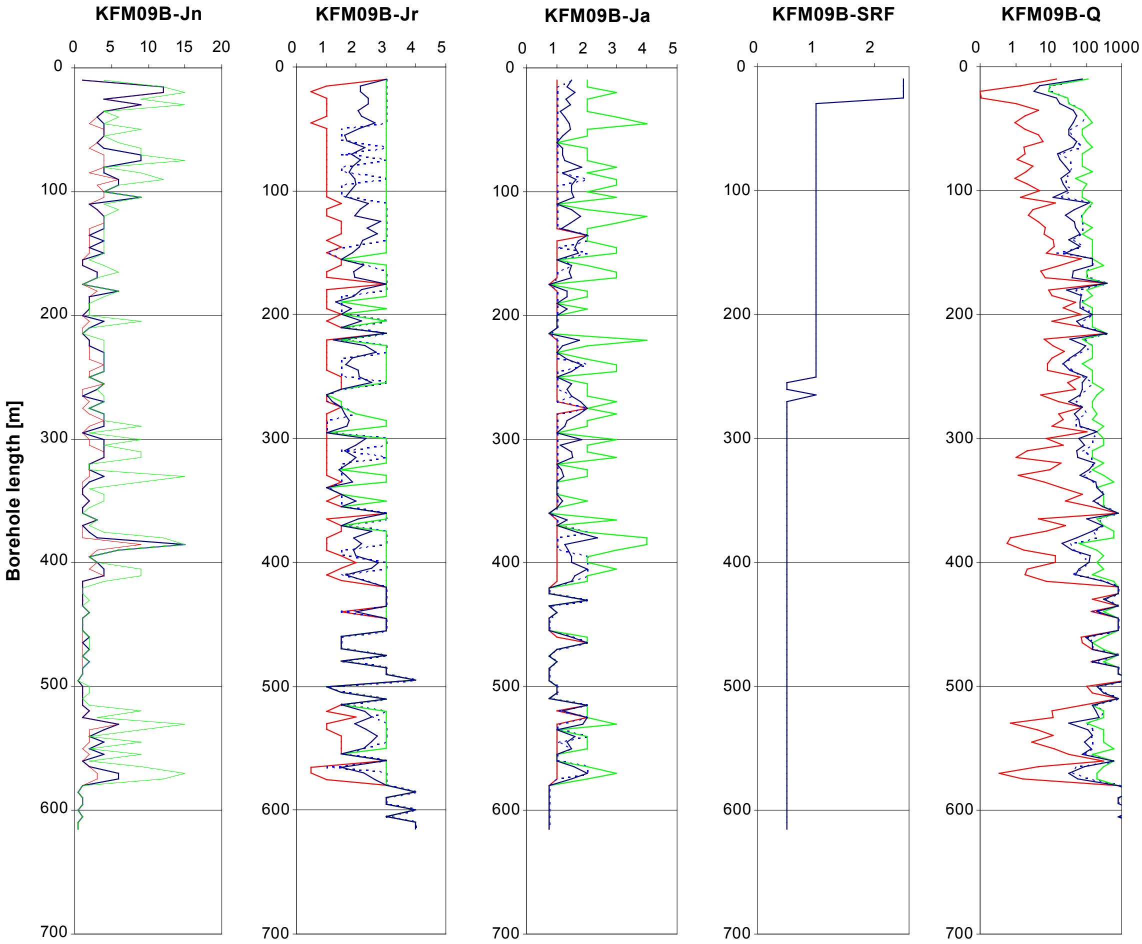

Figure 5-8. Input numbers for Q characterisation and resulting Q values for borehole KFM09B. The fracture set number, fracture roughness, fracture alteration and SRF are plotted with depth together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

The increase in Q with depth can be seen here like in the RMR plot, although in the Q plot this trend ends at a borehole length of about 360 m. At this depth the deformation zone DZ3 shows a mean Q of 120 which is "extremely good" rock. The lowest mean value for Q can be found in the deformation zone five with a Q value of 45, which is "very good" rock. The quality of the competent and fractured rock can be listed as:

1 The worse part in the fractured rock has a minimum Q value of 0.1 ("very poor" rock).

2 The average quality in the deformation zones is Q = 77 ("very good" rock).

3 The average quality in the competent rock is Q = 416 ("exceptionally good" rock).

4 The best quality rock is within the competent rock, which has a maximum Q value of 2,133 ("exceptionally good" rock).

5.1.5 Evaluation of the uncertainties

Background

The empirical classification systems for characterisation of the rock mass are affected by the uncertainties inherent in the geological and rock mechanical parameters and intrinsic uncertainties due to the structure of the empirical systems themselves. The uncertainty of a single parameter can vary widely 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 a borehole may result from the combination of the possible ratings that range from a minimum to a maximum value in a certain rock mass volume.

In this report, it was decided to correlate the uncertainty in 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 of the mean $\Delta_{conf\,mean}$ 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 each sample. For example, in KFM07C there are on average 16 sections of 5 m length within each rock unit in competent rock, and around 7 sections of 5 m length 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:

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

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 (see Section 5.2) such as: deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass.

Uncertainty of RMR and Q

In Table 5-5, the confidence of the RMR mean value is summarised for the competent rock and deformation zones in boreholes KFM01B, KFM07C, KFM09A, and KFM09B. The uncertainty of the mean value is larger for the deformation zones than for the competent rock. This is due to the local variability of the geological features that can give rise to different interpretations and resulting RMR. In Table 5-6, the confidence of the Q mean value is also summarised for the competent rock and deformation zones in the four boreholes. The confidence of RMR is generally higher than that of Q due to the wide range of variation of the Q values (that usually vary over several orders of magnitude). However, this kind of variations is compatible with the use of Q for design applications.

Table 5-5. Confidence of the mean values of RMR for boreholes KFM01B, KFM07C, KFM09A, and KFM09B with borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–1%	+1%	–5%	+4%
KFM07C	–1%	+0%	–2%	+1%
KFM09A	–2%	+1%	–4%	+3%
KFM09B	–1%	+1%	–3%	+2%

Table 5-6. Confidence of the mean values of Q for boreholes KFM1B, KFM07C, KFM09A, and KFM09B with borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–4%	+8%	–26%	+89%
KFM07C	–5%	+14%	–15%	+44%
KFM09A	–9%	+41%	–19%	+76%
KFM09B	–6%	+12%	–14%	+30%

5.2 Mechanical properties of the rock mass

5.2.1 Deformation modulus of the rock mass

By means of some empirical formulas, it is possible to obtain an estimation of the equivalent deformation modulus of the rock mass. According to /Serafim and Pereira 1983/ the deformation modulus of the rock mass is given by:

$$E_m = 10^{\frac{RMR-10}{40}} \quad (5)$$

and according to /Barton 2002/:

$$E_m \approx 10\ Q_c^{1/3}\ \text{(GPa)} \quad (6)$$

Below, the deformation modulus is determined according to both equations, and the results are compared.

In this report, the determination of the deformation modulus is made for core sections of 5 m length (see Appendix 1 to 5). The figures in the following sections report the variation of the deformation modulus with a continuous blue line, while the maximum possible and minimum values are plotted in red and green, respectively. These two values are used in Section 5.2.2 for the evaluation of the uncertainties according to Section 5.1.5. In the following sections, reference to the minimum and maximum deformation modulus is given when addressing the peaks and troughs of the blue continuous curve, which represent the expected average value of the deformation modulus at each depth. In all figures, the dotted line represents the expected most frequent values.

KFM01B

In Figure 5-9, the plots of the minimum, average, most frequent and maximum expected deformation modulus of the rock mass are given for borehole KFM01B. Comparing the mean values obtained independently by means of RMR and Q, a rather good agreement can be observed in the borehole. On average; the deformation modulus of the competent rock is 72 GPa, when obtained from RMR, and 66 GPa when obtained from Q. The values are as similar to each other when the deformation zones are concerned: the deformation modulus from RMR is on average 49 GPa while the deformation modulus from Q is 47 GPa, respectively. The minimum obtained deformation modulus is in the more fractured rock of the deformation zones and is 23 GPa according to RMR and 19 according to Q. The maximum value of the deformation modulus coincides in both cases because a threshold of 76 GPa was adopted to limit upwards the range of variation of the results of Equations (5) and (6). This value corresponds to the Young's modulus determined from the laboratory samples of intact rock.

KFM07C

In Figure 5-10, the plots of the minimum, average, most probable and maximum expected deformation modulus are given for borehole KFM07C. For this borehole a comparison between the mean values obtained independently by means of RMR and Q shows less agreement as the deformation modulus derived from RMR is quite close to the maximum value along the

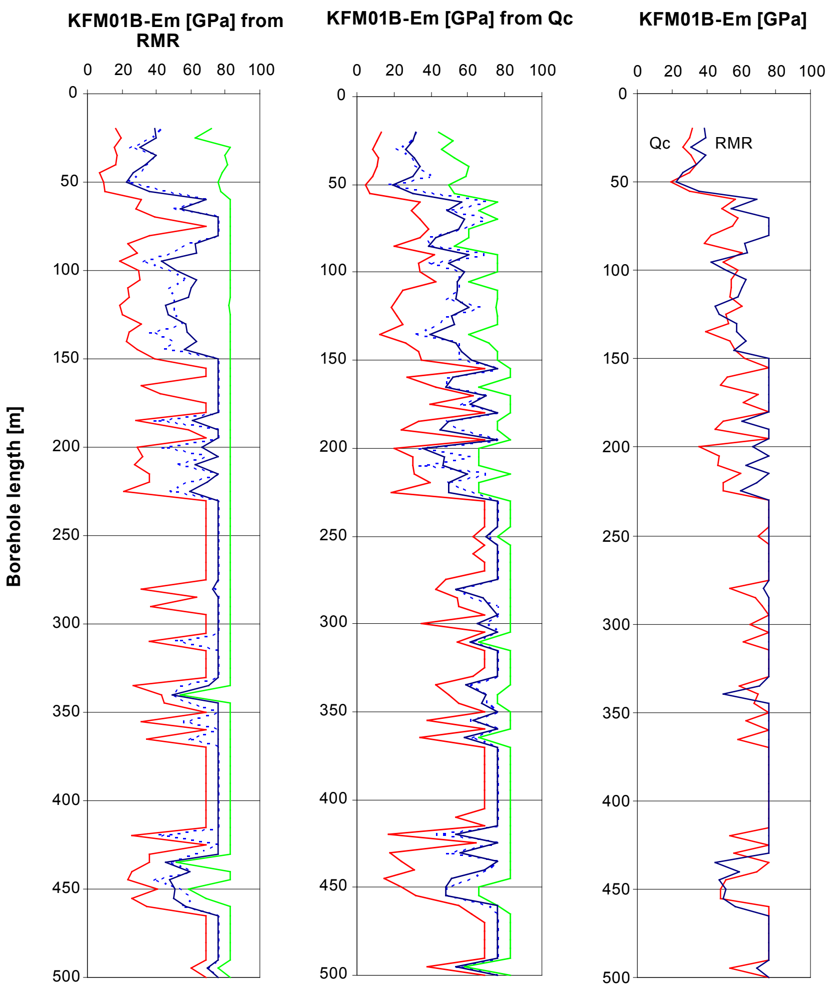

Figure 5-9. *Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m length for borehole KFM01B. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

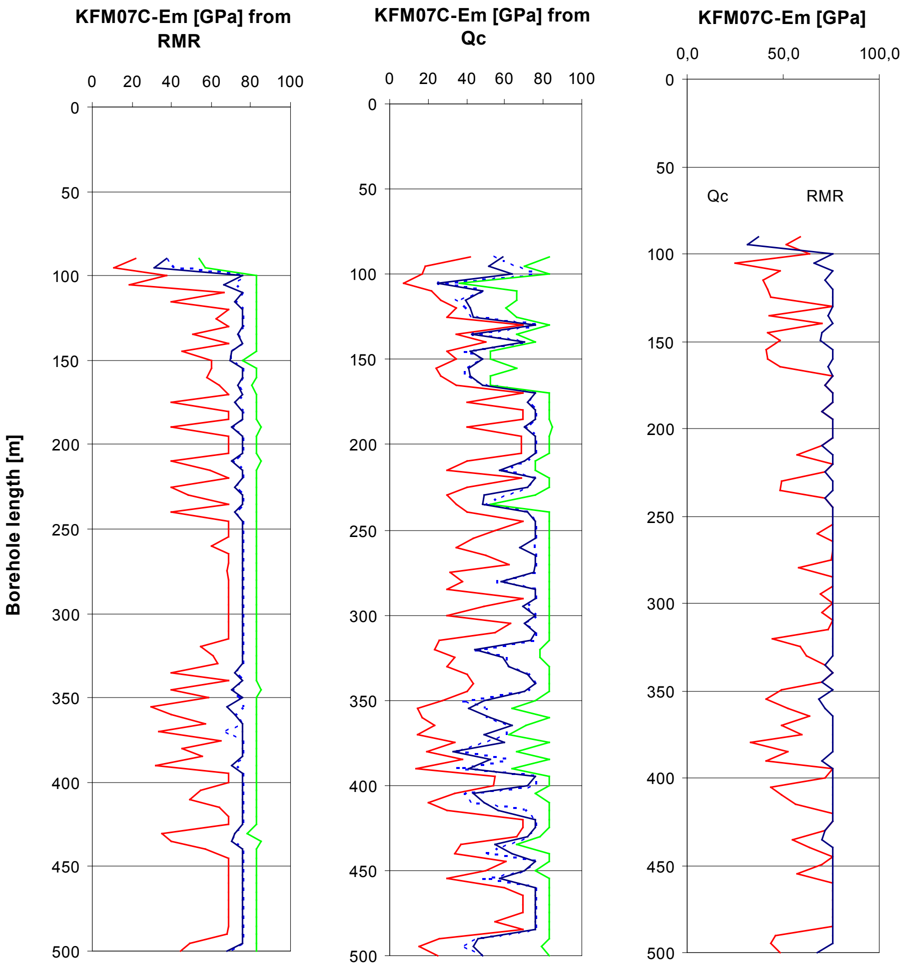

***Figure 5-10.** Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m length for borehole KFM07C. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

entire borehole, whereas the deformation modulus from Q varies quite much. On average, the deformation modulus of the competent rock is 74 GPa, when obtained from RMR, and 65 GPa when obtained from Q. The values have a larger range of varitation when the deformation zones are concerned, and they are generally lower: the deformation modulus from RMR is 72 GPa while the deformation modulus from Q is 55 GPa, respectively. The variation of the deformation modulus from RMR is very gentle because of the use of the value of intact rock as upper limit for the Equation (5). Although we are using the same limit for the deformation modulus from Q, these values are not achieving the upper limit as often as the deformation modulus values for RMR. Both the empirical Equations (5) and (6) provide minimum values of the deformation modulus between 32 and 25 GPa in the deformation zones.

KFM09A

In Figure 5-11, the plots of the minimum, average, most probable and maximum expected deformation modulus are given for borehole KFM09A. On average, the deformation modulus of the competent rock is 64 GPa, when obtained from RMR, and 50 GPa when obtained from Q. The values are closer to each other than the corresponding values for the deformation zones are: the deformation modulus from RMR is on average 52 GPa while the deformation modulus from Q is 33 GPa, respectively. The minimum obtained deformation modulus in the more fractured rock of the deformation zones is between 31 and 17 GPa, according to RMR and Q, respectively. This information can, besides in Figure 5-11, be found in Appendix 3.

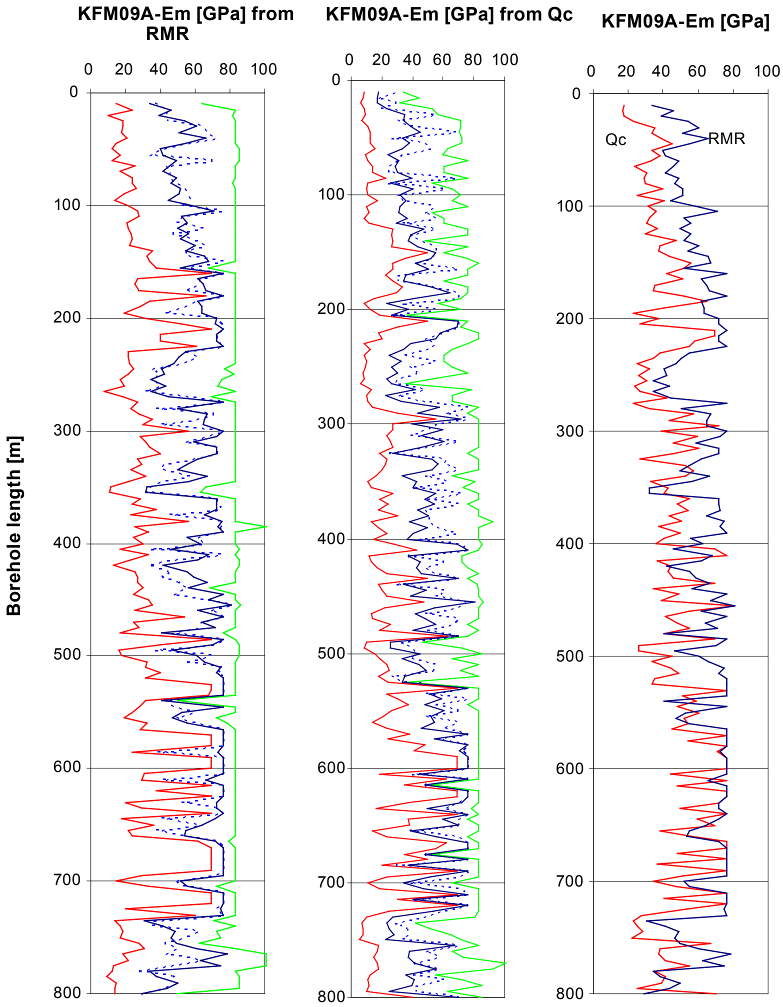

Figure 5-11. *Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m length for borehole KFM09A. A comparison of the mean values along the borehole is given in the graph on the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

KFM09B

In Figure 5-12, the plots of the minimum, average, most probable and maximum expected deformation modulus are given for borehole KFM09B. When comparing the two empirical systems, a good agreement between them can be noticed. For the competent rock, the average deformation modulus predicted varies between 70 and 64 GPa for RMR and Q, respectively. The correspondent value for the deformation zones is 57 and 51 GPa, the first value being obtained by means of RMR. The minimum value observed for the competent rock is very similar for the two methods, which is between 33 and 37 GPa. In Figure 5-12, the area between the borehole lengths of about 420 and 520 m distinguishes itself by showing high elastic modulus in both systems. The calculated values are affected by the upper limit of the elastic modulus for the intact rock imposed on all the empirically calculated values.

5.2.2 Uncertainties

Based on the technique presented in Section 5.1.5, the uncertainties of the deformation modulus could be evaluated for the two empirical methods. The uncertainty determination is shown in Table 5-7. According to RMR and Equation (5), it can be noticed that the uncertainty estimated for the deformation modulus of the deformation zones is several times larger than the uncertainty for the competent rock mass. This is due, first, to less variation of the geomechanical

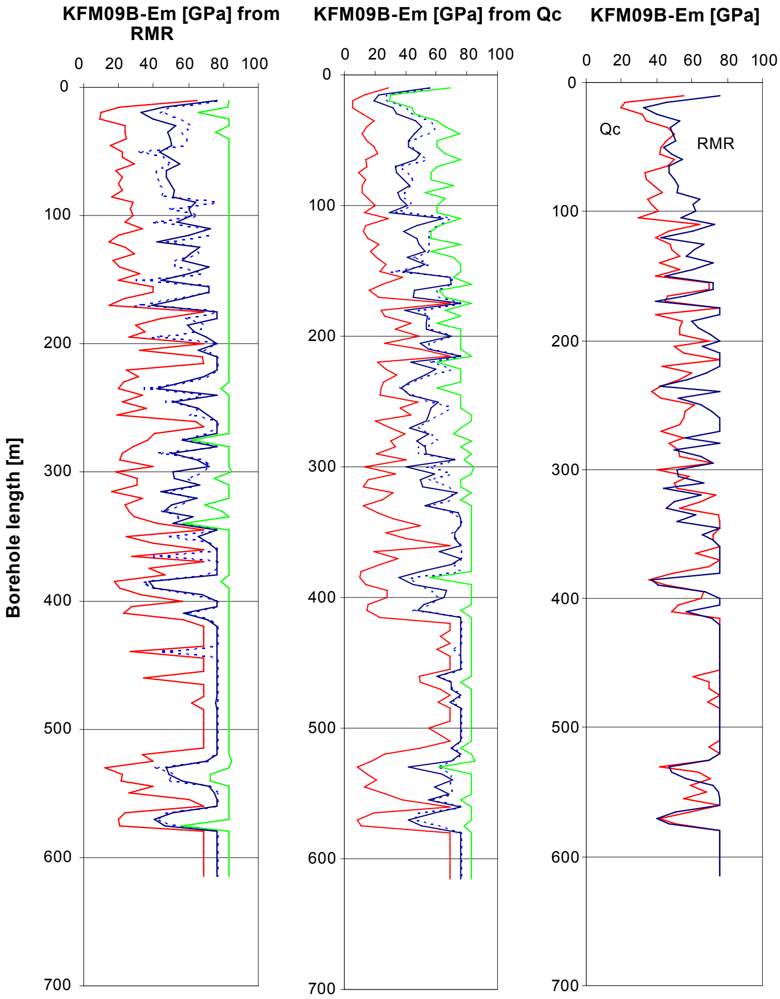

Figure 5-12. Deformation modulus of the rock mass derived from RMR and Q values for each core section of 5 m length for borehole KFM09B. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

Table 5-7. Confidence of the mean values of the deformation modulus Em from RMR for boreholes KFM01B, KFM07C, KFM09A, and KFM09B and borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–3%	+2%	–15%	+21%
KFM07C	–2%	+1%	–7%	+3%
KFM09A	–6%	+4%	–12%	+13%
KFM09B	–4%	+3%	–8%	+7%

parameters in the competent rock mass than in the deformation zones. Secondly, the fact that the estimation of the mean deformation modulus of the competent rock is made based on a much larger sample of values than for the deformation zones greatly diminishes the uncertainties. The uncertainty of the mean value for competent rock might, in this case, range from –6% to +4% (for KFM09A). For example, if an average deformation modulus of 72 GPa is calculated, the actual range of variation of the mean value might be between 67.7 GPa and 74.8 GPa for the competent rock mass.

RMR was chosen as main parameter for the determination of the rock mass mechanical properties because it is provided with a set of formulas that quantify the rock mass as a continuous, isotropic, elastic medium. These parameters are often required for continuum numerical modelling.

5.3 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. Since there are two available values of the deformation modulus, the Poisson's ratio can be derived from both Q and RMR. In the Appendices, however, only the value from RMR is reported since a good agreement between the two methods was observed in Section 5.2.1. The uncertainty on the Poisson's ratio can easily be obtained from that of the deformation modulus of the rock mass in Section 5.2.2.

5.3.1 KFM01B

Figure 5-13 shows the variation of the Poisson's ratio determined by means of RMR and Q along borehole KFM01B. The average Poisson's ratio for the rock units based on RMR varies between 0.07 and 0.24. For the competent rock, the average Poisson's ratio is 0.23 with maximum values of 0.25. For the rock in the deformation zones (more fractured rock), the estimated average Poisson's ratio is 0.15 while the minimum expected value is 0.07.

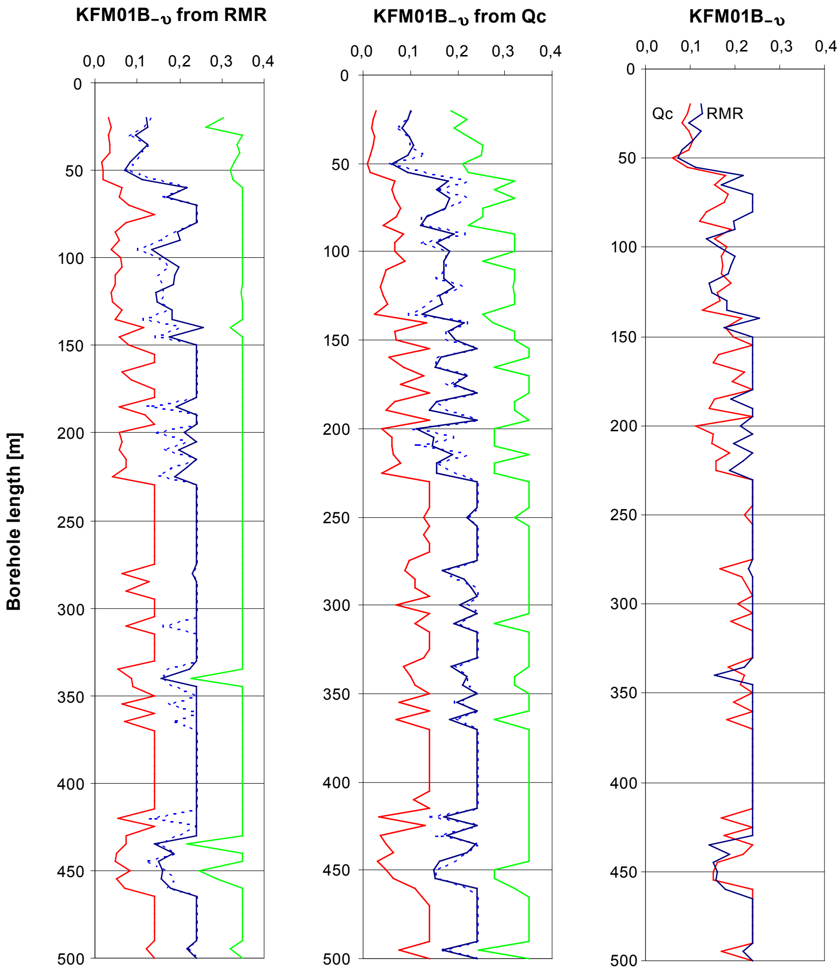

Figure 5-13. *Poisson's ratio derived from RMR and Q values for each core section of 5 m length for borehole KFM01B. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.3.2 KFM07C

For borehole KFM07C, the average Poisson's ratio can be estimated at about 0.24 for both the competent and fractured rock. The maximum and minimum values of the Poisson's ratio along the borehole are 0.30 and 0.12, respectively (Figure 5-14).

5.3.3 KFM09A

In Figure 5-15, the variation of the Poisson's ratio with depth for borehole KFM09A is shown. In this borehole, the competent rock shows an average and maximum value of 0.22 and 0.37, respectively. The rock in the deformation zones (more fractured rock), has an average Poisson's ratio of 0.18 and a minimum value of 0.10. The estimated average Poisson's ratio of the entire borehole is 0.21 while the minimum expected value is 0.10.

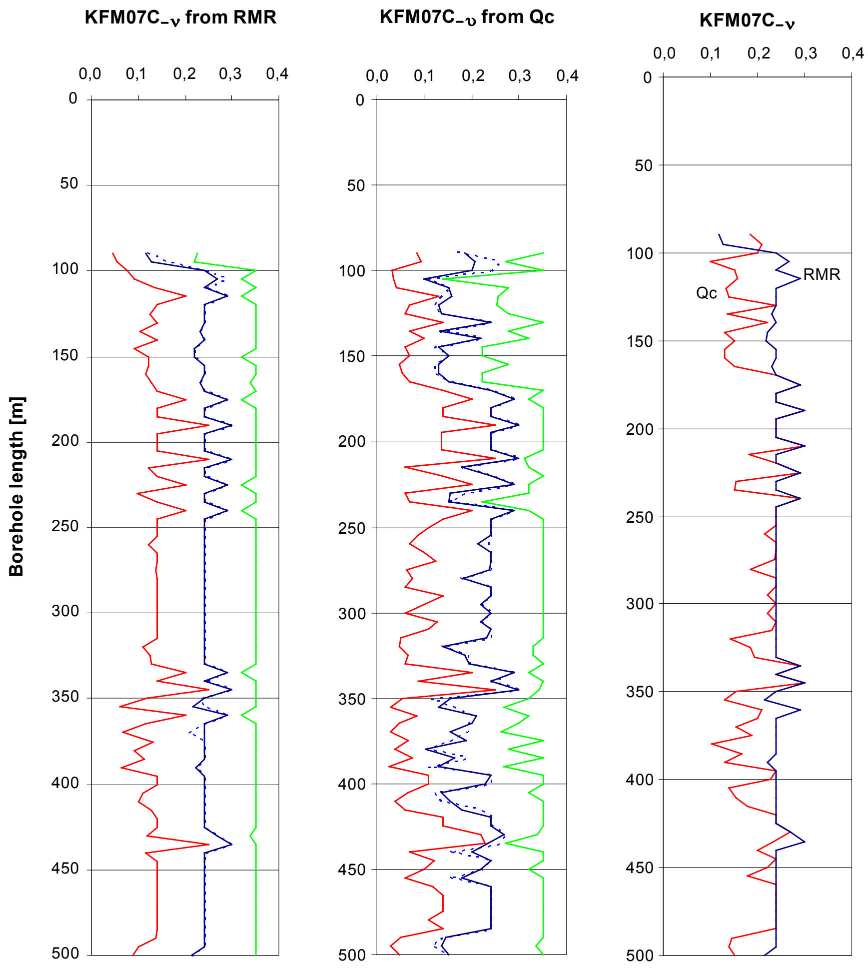

Figure 5-14. *Poisson's ratio derived from RMR and Q values for each core section of 5 m length for borehole KFM07C. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

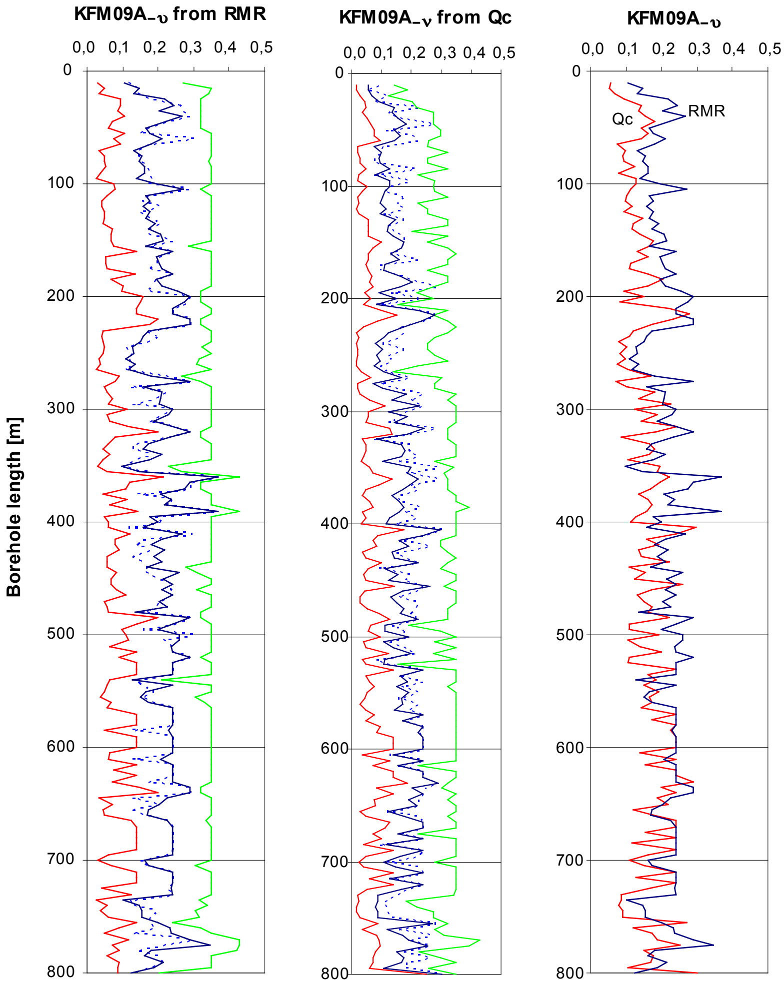

Figure 5-15. Poisson's ratio derived from RMR and Q values for each core section of 5 m length for borehole KFM09A. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

5.3.4 KFM09B

Borehole KFM09B presents Poisson's ratio values between 0.10 and 0.30 (Figure 5-16). The average Poisson's ratio in the competent rock and deformation zones is 0.23 and 0.19, respectively. For the competent rock compared to the deformation zones the estimated minimum Poisson's ratio is 0.12 and 0.10, respectively.

5.4 Uniaxial compressive strength of the rock mass

The equivalent uniaxial compressive strength of the rock mass takes into account the strength of the intact rock and the negative contribution of the rock fractures. Thus, it is not the same thing as the uniaxial compressive strength given in Section 4.1. The uniaxial compressive strength of the rock mass (UCS) is here determined in two ways:

- by means of the relations between GSI /Hoek et al. 2002/, RMR and the Hoek & Brown's Criterion, where the exponent "a" is assumed to be 0.5. This Criterion is curvilinear and tends to rapidly decrease towards $UCS_{H\&B}$ for low confinement stresses;
- by means of the friction angle and cohesion of the rock mass. These parameters can be obtained by linear interpolation of the Hoek & Brown's Criterion, thus do linearly decrease toward $UCS_{M\text{-}C}$ for low confinement stresses. At Forsmark, it can be observed that $UCS_{M\text{-}C}$ is often about 1.5 to 2 times $UCS_{H\&B}$.

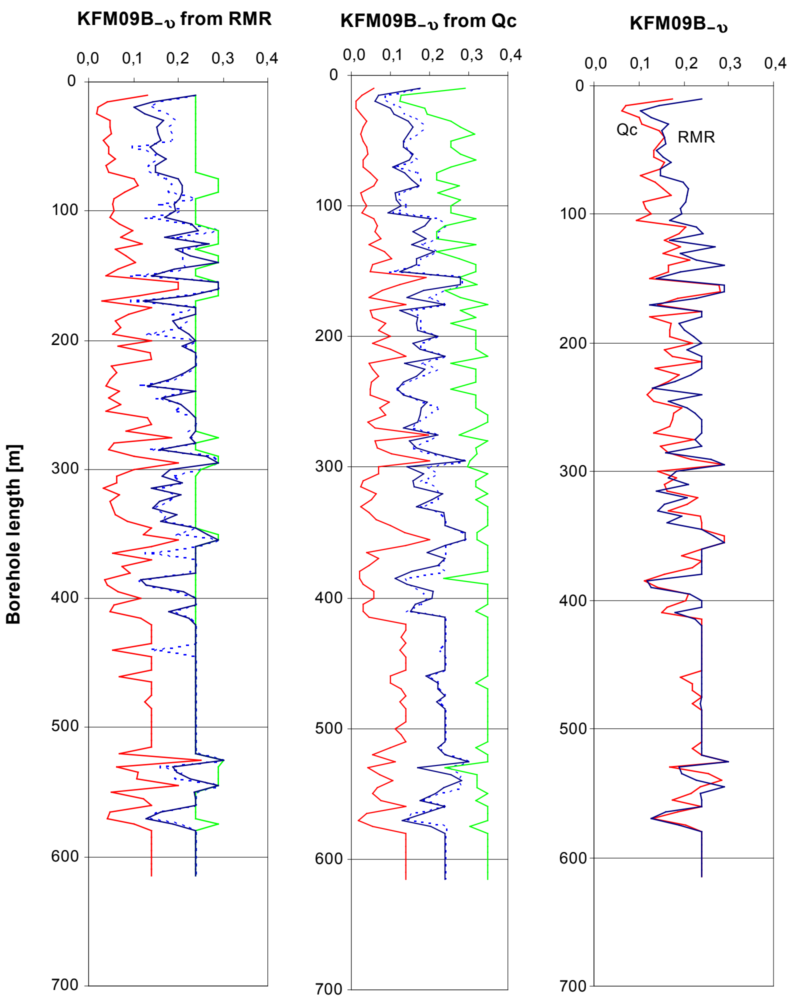

Figure 5-16. *Poisson's ratio derived from RMR and Q values for each core section of 5 m length for borehole KFM09B. A comparison of the mean values along the borehole is given in the graph to the right. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

The values obtained from the Hoek & Brown's Criterion for the four boreholes are tabulated and plotted in Appendices 1 to 4, whereas the values of UCS $_{M\text{-}C}$ are plotted in Figure 5-17 to Figure 5-20 for comparison and can be easily obtained from the following equation /Hoek et al. 2002/:

$$UCS_{M-C} = \frac{2\,c'\cos\phi'}{1-\sin\phi'} \qquad (7)$$

where c' and ϕ' are the cohesion and friction angle resulting from the linear fit of the Hoek & Brown's Criterion for a certain confinement stress interval. Typically in this report, the confinement stress interval considered to calculate c' and ϕ' is between 10 and 30 MPa, as it will be presented in Section 5.5.

5.4.1 KFM01B

The variation of the rock mass compressive strength from RMR derived by the Hoek & Brown's Criterion ($UCS_{H\&B}$) and the Mohr-Coulumb Failure Criterion ($UCS_{M\text{-}C}$) for KFM01B is shown in Figure 5-17. The $UCS_{H\&B}$ from RMR in the rock units varies between 54 and 98 MPa; the $UCS_{M\text{-}C}$ from RMR in the rock units varies between 113 and 152 MPa. The competent rock mass exhibits an average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ of 97 MPa and 150 MPa, respectively, while the fractured rock in the deformation zones has an average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ of 53 MPa and 111 MPa, respectively. The average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ vary along the borehole between 24 and 135 MPa and 81 and 183 MPa, respectively.

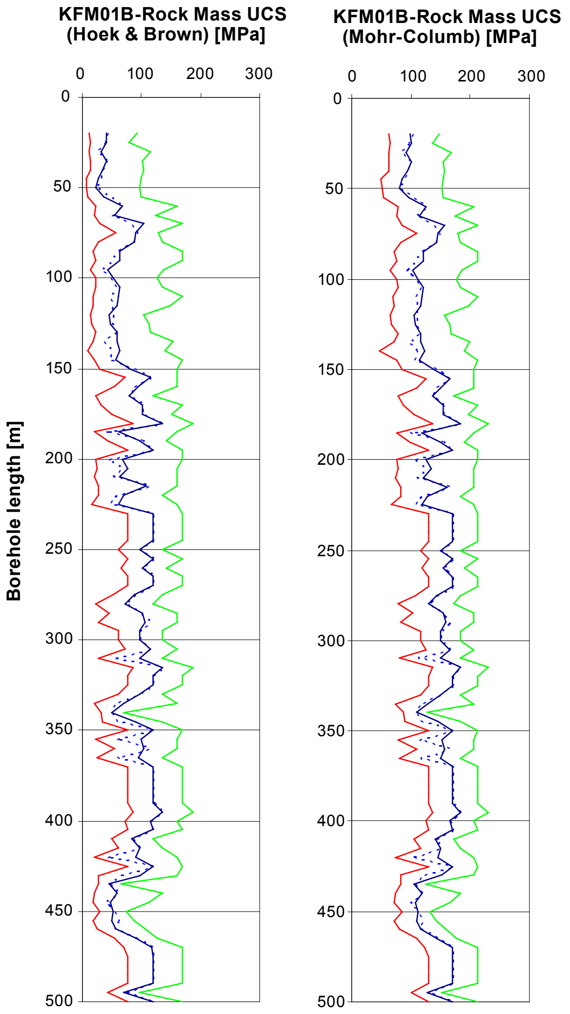

Figure 5-17. *Variation of the rock mass compressive strength from RMR using the Hoek & Brown Failure Criterion (left) or the Mohr-Coulumb Criterion (right) for borehole KFM01B. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.4.2 KFM07C

Figure 5-18 shows the variation of the rock mass compressive strength from RMR derived by Hoek & Brown's Criterion ($UCS_{H\&B}$) and the Mohr-Coulumb Failure Criterion ($UCS_{M\text{-}C}$) for borehole KFM07C. The average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ from RMR for the three rock units range between 32 and 135 MPa and 73 and 184 MPa, respectively. For the entire borehole, the same variation applies. The competent rock exhibits an average value of 141 MPa for $UCS_{H\&B}$ and 151 MPa for $UCS_{M\text{-}C}$, whereas the deformation zones show an average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ of 85 and 98 MPa, respectively.

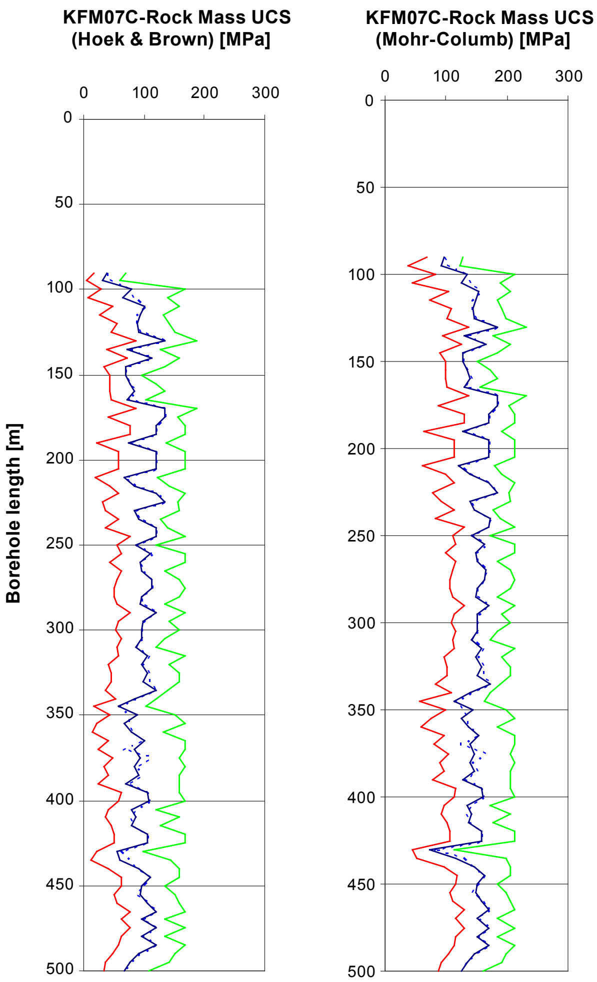

Figure 5-18. Variation of the rock mass compressive strength from RMR using the Hoek & Brown Failure Criterion (left) or the Mohr-Coulumb Criterion (right) for borehole KFM07C. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

5.4.3 KFM09A

The rock mass compressive strength from RMR derived by the Hoek & Brown's Criterion ($UCS_{H\&B}$) and the Mohr-Coulumb Failure Criterion (UCS_{M-C}) can be seen in Figure 5-19. The average $UCS_{H\&B}$ and UCS_{M-C} of the rock units vary between 18 and 121 MPa and 51 and 151 MPa, respectively. On average, for the competent rock mass and deformation zones, $UCS_{H\&B}$ and UCS_{M-C} vary between 54 and 69 MPa and 112 and 125 MPa, respectively. For the whole borehole, the average $UCS_{H\&B}$ and UCS_{M-C} vary along the borehole between 18 and 121 MPa and 51 and 171 MPa, respectively.

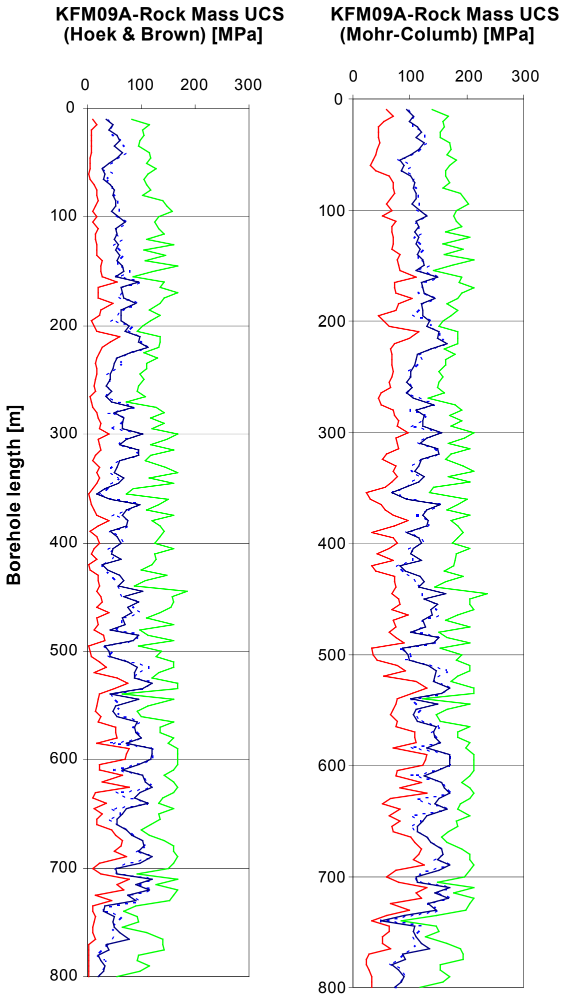

Figure 5-19. *Variation of the rock mass compressive strength from RMR using the Hoek & Brown Failure Criterion (left) or the Mohr-Coulumb Criterion (right) for borehole KFM09A. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.4.4 KFM09B

The variation of the rock mass compressive strength UCS from RMR derived by the Hoek & Brown's Criterion ($UCS_{H\&B}$) and the Mohr-Coulumb Failure Criterion ($UCS_{M\text{-}C}$) along borehole KFM09B can be seen in Figure 5-20. The average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ in the six rock units range between 53 and 128 MPa and 112 and 157 MPa, respectively. For the entire borehole, the maximum and minimum observed values of $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ are 23 and 135 MPa, and 44 and 183 MPa, respectively. The competent rock shows an average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ of 90 MPa and 145 MPa, respectively, which is about 30 MPa larger than the average $UCS_{H\&B}$ and $UCS_{M\text{-}C}$ of the deformation zones.

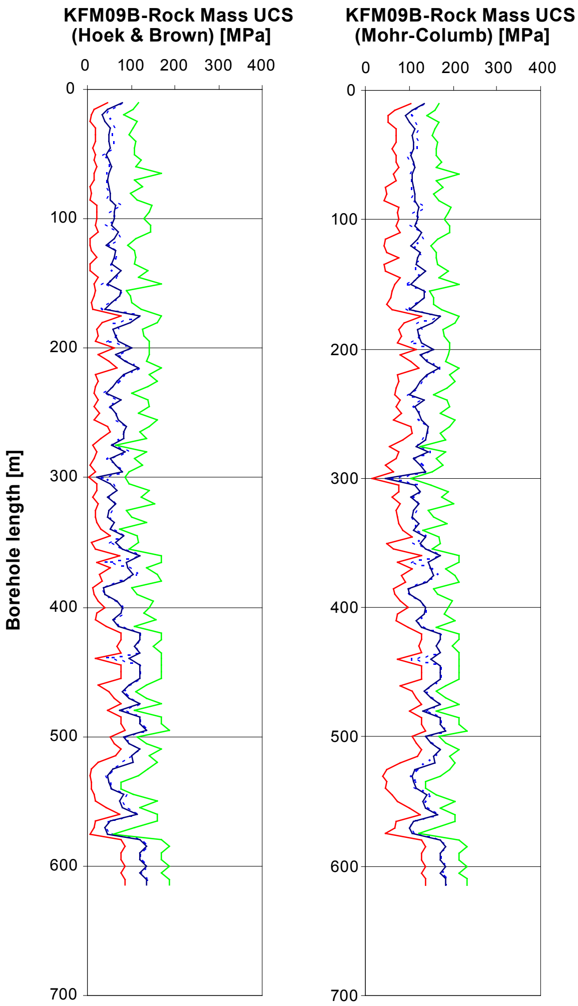

Figure 5-20. *Variation of the rock mass compressive strength from RMR using the Hoek & Brown Failure Criterion (left) or the Mohr-Coulumb Criterion (right) for borehole KFM09B. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.4.5 Uncertainties

Table 5-8 summarises the uncertainty of the mean uniaxial compressive strength from RMR derived by the Hoek & Brown's Criterion ($UCS_{H\&B}$) reported in the former sections. It can be seen that the uncertainty for the competent rock in the rock units ranges between –7% and +10%, where it can found that the largest range applies to borehole KFM09A, although the range of uncertainty is quite small compared to the uncertainty for the deformation zones. For the deformation zones, it ranges between –14% and +30%, with the largest range in borehole KFM01B.

5.5 Cohesion and friction angle of the rock mass

Based on the Hoek & Brown's Criterion /Hook et al. 2002/, the approximated Coulomb's parameters (cohesion and friction angle) can be obtained when a certain confinement stress range is specified. In this report, the stress range of the confinement stress is specified between 10 and 30 MPa. The values of the cohesion and friction angle for the rock units, the deformation zones and at different depths are tabulated and plotted in Appendix 1 to 5.

Table 5-8. Confidence on the mean values of the Uniaxial Compressive Strength of the rock mass derived from RMR ($UCS_{H\&B}$) using the Hoek & Brown Failure Criterion for boreholes KFM01B, KFM07C, KFM09A, and KFM09B and borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–6%	+8%	–14%	+30%
KFM07C	–6%	+7%	–13%	+17%
KFM09A	–6%	+10%	–13%	+21%
KFM09B	–7%	+8%	–10%	+15%

5.5.1 KFM01B

The plot of the cohesion and friction angle for borehole KFM01B is shown in Figure 5-21. The average cohesion in the rock units ranges between 17 and 32 MPa, while that of the deformation zones and competent rock ranges between 22 and 27 MPa. For the whole borehole, the cohesion spans between 17 and 32 MPa.

For the same range of confinement stress (10 to 30 MPa), the friction angle along the borehole ranges between 44° and 52°. The two rock units have an average friction angle varying between 48° and 50°. A similar difference can be observed between the average friction angle of the competent rock and that of the deformation zones, which are 50° and 47°, respectively.

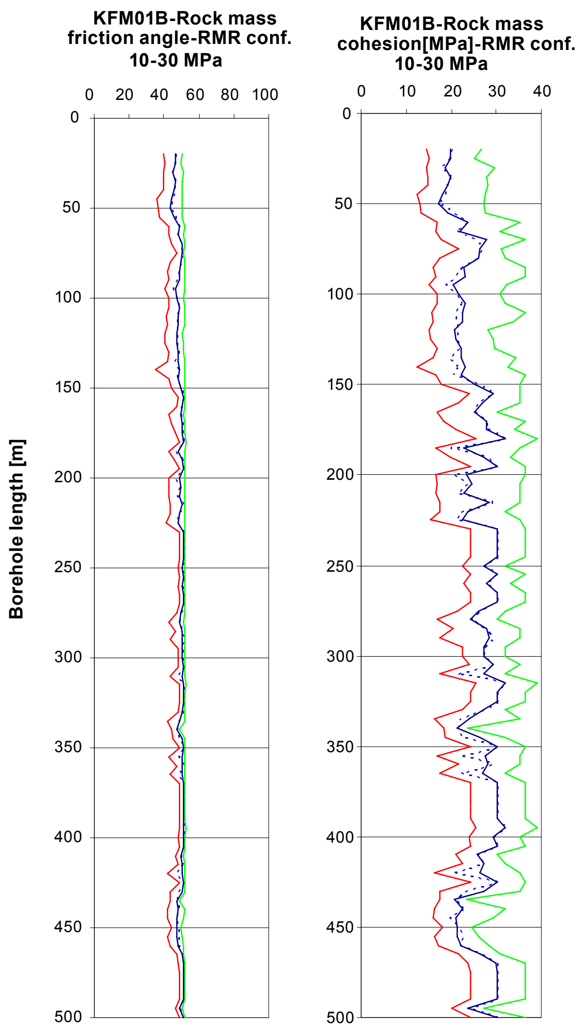

Figure 5-21. Variation of the rock mass friction angle and cohesion from RMR and Q under confinement stress between 10 and 30 MPa for borehole KFM01B. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

5.5.2 KFM07C

Figure 5-22 shows the plots of the cohesion and friction angle calculated for a confinement stress between 10 and 30 MPa along borehole KFM07C.

On average, the cohesion of the rock mass in the deformation zones is 26 MPa, whereas it is 27 MPa for the competent rock mass. The average cohesion for the two rock units varies between 24 and 27 MPa. For the entire borehole, the cohesion spans between 19 and 32 MPa.

The friction angle of the rock mass varies between 36° and 52° degrees for the whole borehole. The average values are instead 50° for both the deformation zones and competent rock.

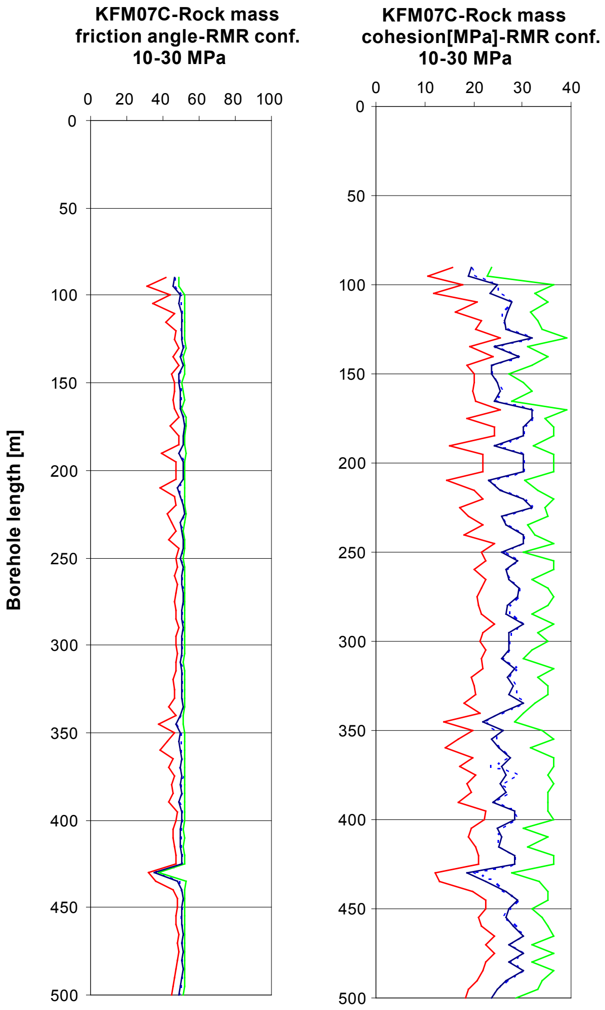

Figure 5-22. Variation of the rock mass friction angle and cohesion from RMR and Q under confinement stress between 10 and 30 MPa for borehole KFM07C. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.

5.5.3 KFM09A

For KFM09A, the cohesion and friction angle obtained by the empirical methods plot as in Figure 5-23. These values are determined for a confinement stress between 10 and 30 MPa.

The average cohesion of the competent rock mass and deformation zones ranges between 24 MPa and 22 MPa. For the whole borehole, cohesion values are observed within the interval 14 to 30 MPa.

Along the borehole, the friction angle varies between 33° and 52°. The average values for the competent rock and deformation zones are instead 47° and 48°, respectively.

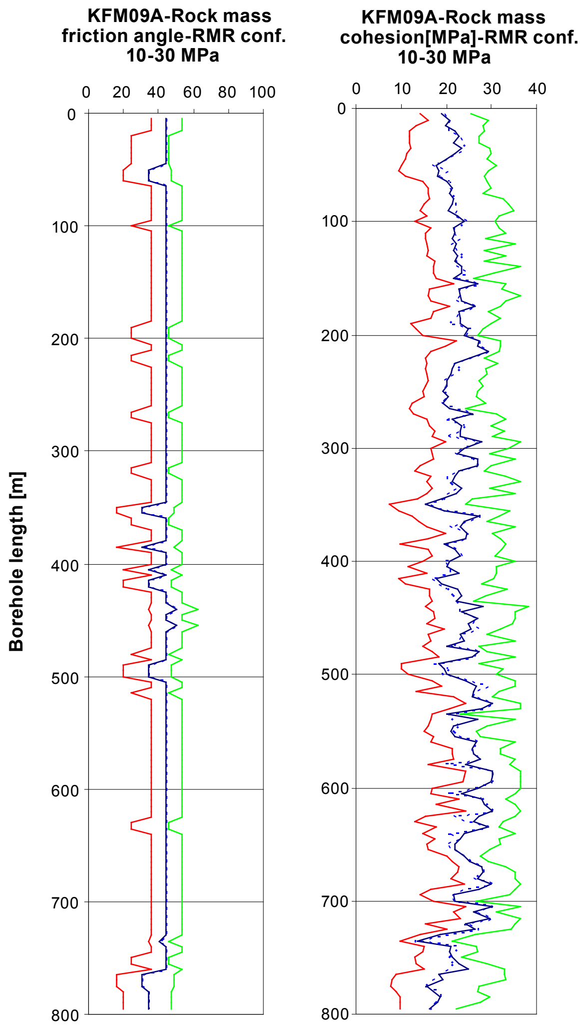

Figure 5-23. *Variation of the rock mass friction angle and cohesion from RMR and Q under confinement stress between 10 and 30 MPa for borehole KFM09A. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.5.4 KFM09B

Figure 5-24 shows the plots of the cohesion and friction angle along borehole KFM09B. These values are obtained by interpolating the Hoek & Brown's Criterion between the stresses of 10 and 30 MPa.

On average, the cohesion of the rock mass varies between 12 and 32 MPa, with an average value for the deformation zones of 22 MPa, and an average value for the competent rock of 26 MPa. The average cohesion of the seven rock units ranges between 22 and 31 MPa.

The friction angle varies between 32° and 52° for the whole borehole. The average friction angle of the seven rock units instead ranges between 47° and 51°. The competent rock has an average friction angle of 50°, which is slightly larger than the average friction angle of the deformation zones, 48°.

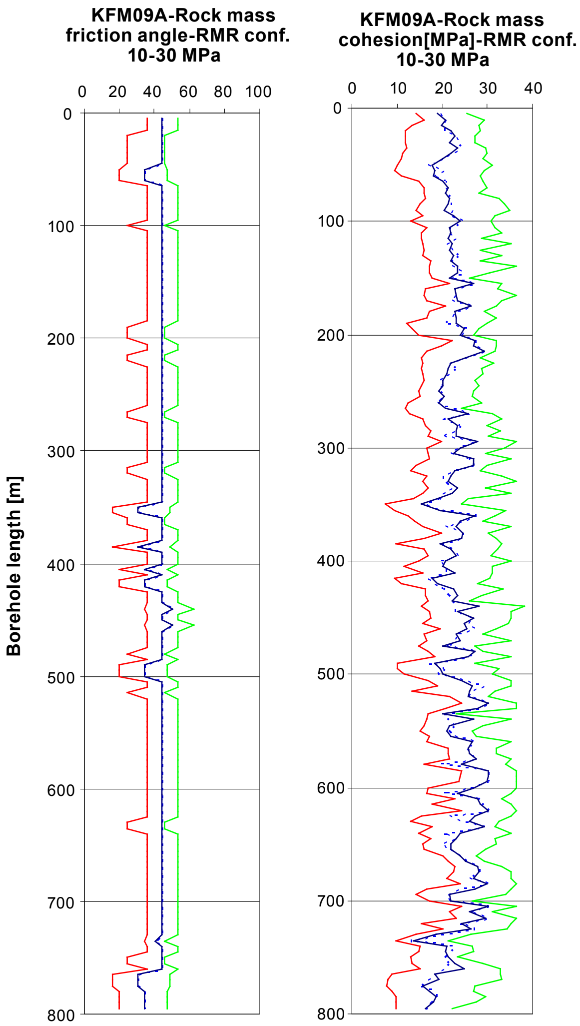

Figure 5-24. *Variation of the rock mass friction angle and cohesion from RMR and Q under confinement stress between 10 and 30 MPa for borehole KFM09B. The lines in red, blue, dashed blue and green represent the minimum, average, most frequent and maximum values observed in every core section of 5 m length.*

5.5.5 Uncertainties

The uncertainties of the average cohesion reported in the former section are presented in Table 5-9. In general, for the competent rock, the uncertainty of the cohesion varies between –3% and +3%. The range of uncertainty of the average cohesion of the deformation zones is at most –6% and +8%. The four boreholes have quite similar ranges.

The uncertainty of the friction angle (Table 5-10) shows a similar pattern as for cohesion, with a similar range for all four boreholes. For the deformation zones, the boreholes have uncertainties that range from –3% to +2% at the most (for KFM01B). The uncertainty of the mean friction angle for the competent rock does not exceed the range ±1%.

5.6 Identification of deformation zones in the boreholes based on thresholds of the empirical systems Q and RMR

The characterisation in Section 5.1 can be used to investigate the presence of a particular signature that identifies the deformation zones, not only in geological terms, but also in terms of rock mass quality for rock mechanics applications. In this section, the filter applicable to very good rock masses (e.g. Forsmark site /SKB 2006/) is applied to the plots of Q and RMR. The sections of a borehole with Q and RMR lower than the threshold values are assumed to be minor deformation zones and can sometimes be grouped together with contiguous sections to form larger or deterministic deformation zones. This filter is applied to both the 5 m and 1 m sections. Conclusion about the applicability of this filter to the Forsmark site will also be drawn.

Table 5-9. Confidence of the mean values of the rock mass cohesion (confinement stress 10–30 MPa) for boreholes KFM01B, KFM07C, KFM09A, and KFM09B and borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–3%	+3%	–6%	+8%
KFM07C	–3%	+3%	–6%	+7%
KFM09A	–2%	+2%	–5%	+3%
KFM09B	–3%	+2%	–4%	+2%

Table 5-10. Confidence of the mean values of the rock mass friction angle (confinement stress 10–30 MPa) for boreholes KFM01B, KFM07C, KFM09A, and KFM09B and borehole sections of 5 m length.

	Competent rock		Deformation zones	
	Lower confidence on the mean	Upper confidence on the mean	Lower confidence on the mean	Upper confidence on the mean
KFM01B	–1%	0%	–3%	+2%
KFM07C	–1%	0%	–3%	+1%
KFM09A	–1%	+1%	–3%	+1%
KFM09B	–1%	0%	–2%	+1%

5.6.1 Signature 1: Q < 4 and/or RMR < 60

The signature or criterion for identifying minor and deterministic deformation zones was assumed for a rock mass with generally good quality where a few sections are intersected by deformation zones (e.g. Forsmark /SKB 2006/). This signature can be expressed by the following thresholds for Q and RMR:

$$\textit{Deformation Zone Signature } 1\text{: } Q < 4 \text{ and/or } RMR < 60 \tag{8}$$

The application of this signature to the data in Section 5.1 results in the plots in Figure 5-25 to Figure 5-32 for the two empirical systems used on the four boreholes in this study.

KFM01B

The deformation zones identified by Equation (8) are highlighted in grey in Figure 5-25, whereas no deformation zone is identified in Figure 5-26. It can be observed that the characterisation performed on 5 m borehole sections cannot recognize the smallest deformation zones. But when a larger zone of lower quality rock is concerned, it is identified in the 5 m interval (see also Table 5-11). The deformation zones are only seen using the Q system. Both of the identified deformation zones are included in the rock mass determined as the deformation zone DZ1 from the single-hole interpretation /Berglund et al. 2004/.

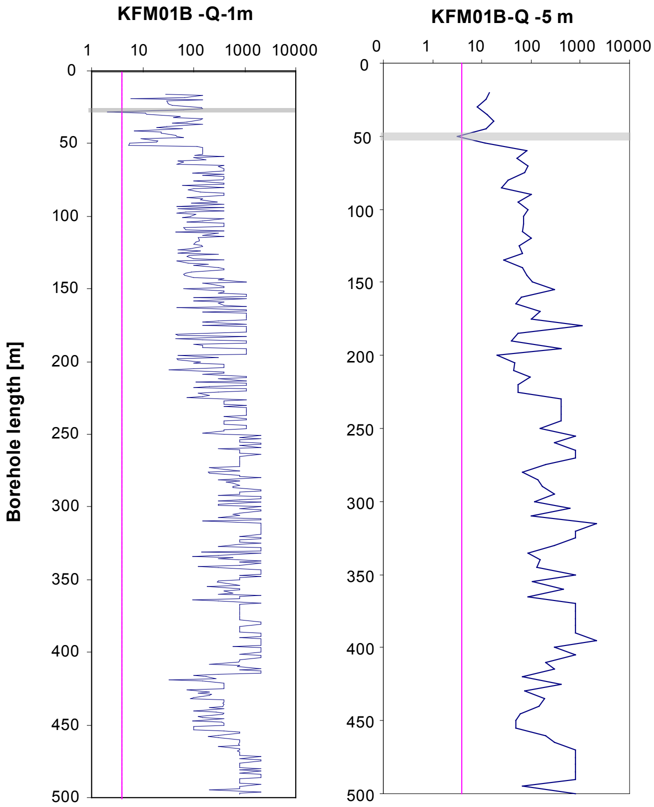

Figure 5-25. *Mean Q for borehole KFM01B sectioned in 1 m (left) and 5 m (right) along the borehole. The deformation zones identified according to the signature for very good quality rock in Equation (8) are marked in grey and the limit according to the signature is marked in pink.*

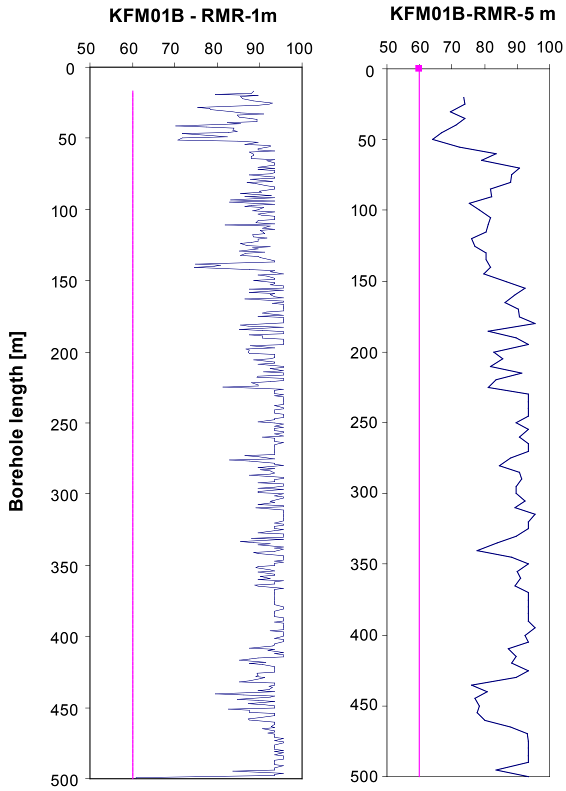

Figure 5-26. *Mean RMR for borehole sections of 1 m (left) and 5 m (right) along KFM01B. No deformation zones are identified according to Signature 1 in Equation (8).The limit according to the signature is marked in pink.*

Table 5-11. Deformation zone identified in KFM01B by means of Signature 1 in Equation (8).

Deformation zone 1 m sections	Apparent thickness 1 m sections	Deformation zone 5 m sections	Apparent thickness 5 m sections
27–28 m	≥ 1 m	45–50 m	≥ 5 m

KFM07C

The deformation zone identified by Equation (8) is highlighted in grey in Figure 5-28, whereas no deformation zone is identified in Figure 5-27. The rock in borehole KFM07C is of a high quality. The characterisation performed on 5 m borehole sections cannot recognize any deformation zones for either the Q or RMR system. However, the plot in Figure 5-28 of RMR, shows a zone of about 1 m (see also Table 5-12). This zone coincides with the deformation zone DZ1 (92–103 m) identified in the single-hole interpretation /Carlsten et al. 2006/.

Table 5-12. Deformation zone identified in KFM07C by means of Signature 1 in Equation (8).

Deformation zone 1 m sections	Apparent thickness 1 m sections
92–93 m	≥ 1 m

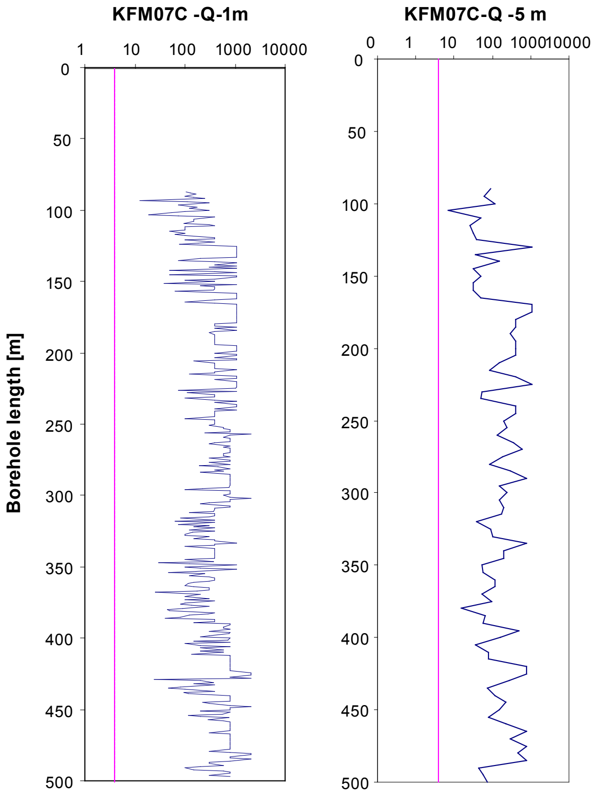

Figure 5-27. *Mean Q for borehole KFM07C sectioned in 1 m (left) and 5 m (right) along the borehole. The limit according to the signature for very good quality rock in Equation (8) is marked in pink.*

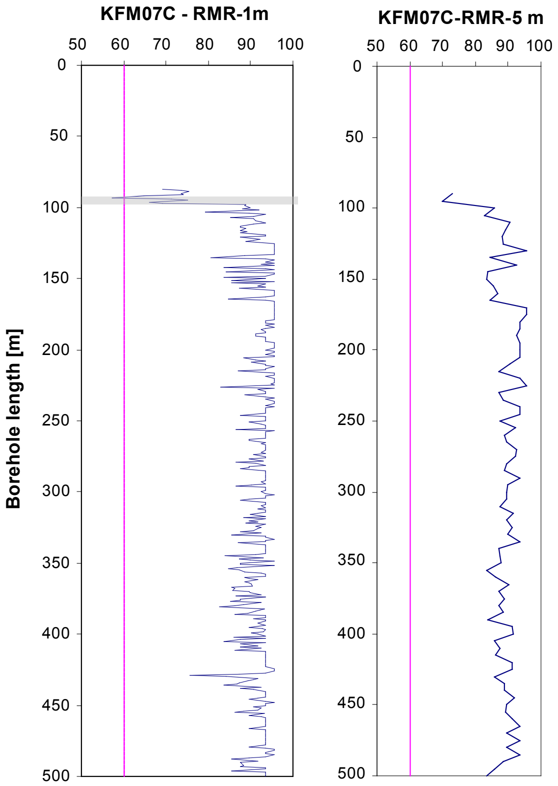

Figure 5-28. *Mean RMR for borehole sections of 1 m (left) and 5 m (right) along KFM07C. The deformation zone identified according to Signature 1 in Equation (8) is marked in grey and the limit signifying the signature is pink.*

KFM09A

The deformation zone identified by Equation (8) is highlighted in grey in Figure 5-29. It can be observed that the characterisation performed on 5 m borehole sections using the Q system shows a deformation zone at the upper part of the borehole (Figure 5-29, see also Table 5-13). But this zone is not indicated by the RMR system (Figure 5-30). Thus, the deformation zone is in this borehole is only seen when using the Q system. This zone is located within the deformation zone (DZ1) identified in the single-hole interpretation /Petersson et al. 2006a/.

Table 5-13. Deformation zone identified in KFM09A by means of the Signature 1 in Equation (8).

Deformation zone 5 m sections	Apparent thickness 5 m sections
10–20 m	≥ 10 m

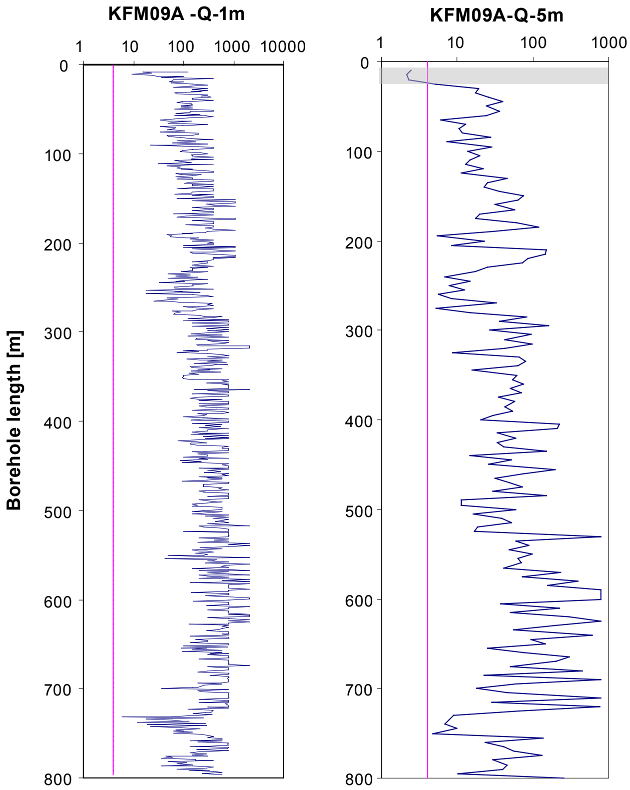

Figure 5-29. *Mean Q for borehole KFM09A sectioned in 1 m (left) and 5 m (right) along the borehole. The deformation zone identified according to the signature for very good quality rock in Equation (8) is marked in grey and the limit according to the signature is marked in pink.*

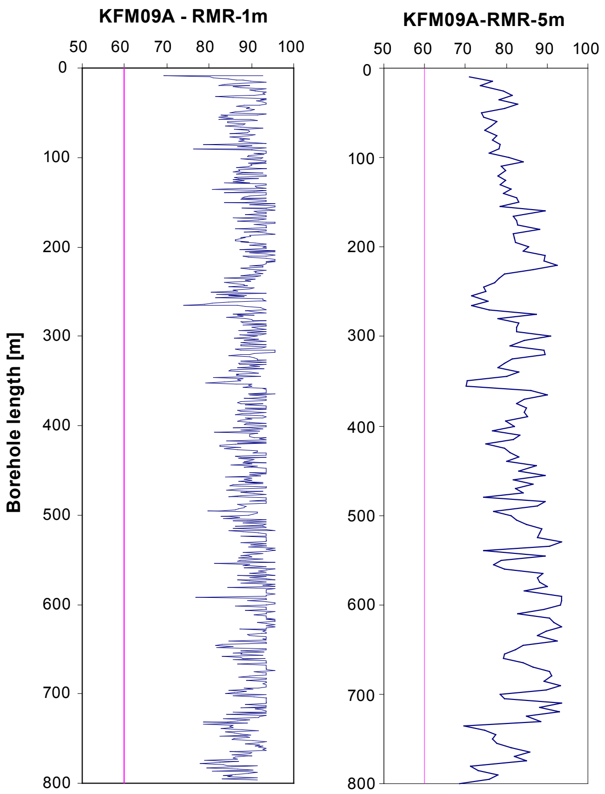

Figure 5-30. *Mean RMR for borehole sections of 1 m (left) and 5 m (right) along KFM09A. The limit identified according to the signature in Equation (8) is marked in pink.*

KFM09B

In Figure 5-31 a deformation zone identified by Equation (8) is highlighted in grey (see also Table 5-14). A section at a shallow depth can be identified in the Q system when sectioning the borehole into 5 m intervals. This zone is a result of the 5 m interval with low quality rock, whereas it can not be identified in the 1 m sectioned plot (Figure 5-31). The deformation zone is only seen using the Q system and not in the plots of the RMR system (Figure 5-32). This zone is located within the deformation zone (DZ1) identified in the single-hole interpretation /Petersson et al. 2006b/.

Table 5-14. Deformation zone identified in KFM09B by means of the signature.

Deformation zone 5 m sections	Apparent thickness 5 m sections
15–20 m	≥ 5 m

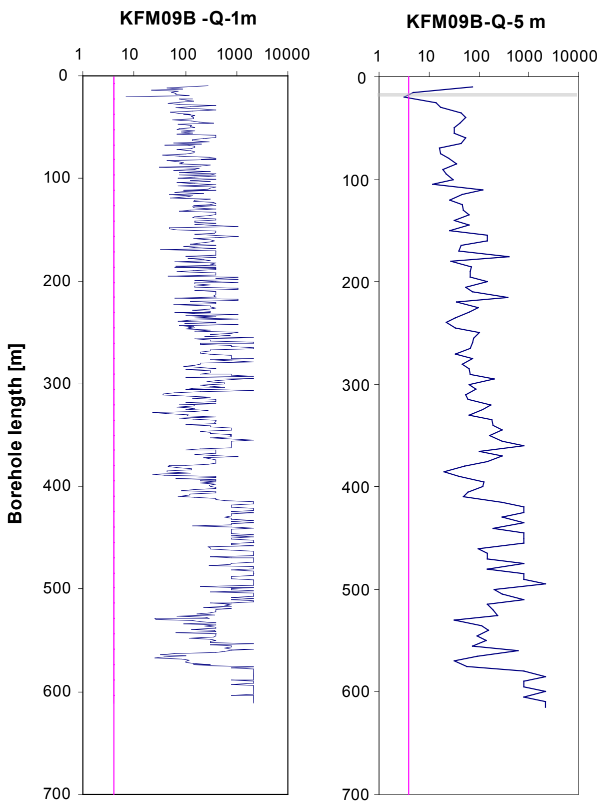

Figure 5-31. *Mean Q for borehole KFM09B sectioned in 1 m (left) and 5 m (right) along the borehole. The deformation zone identified according to the signature for very good quality rock in Equation (8) is marked in grey and the limit identified according to the signature is marked in pink.*

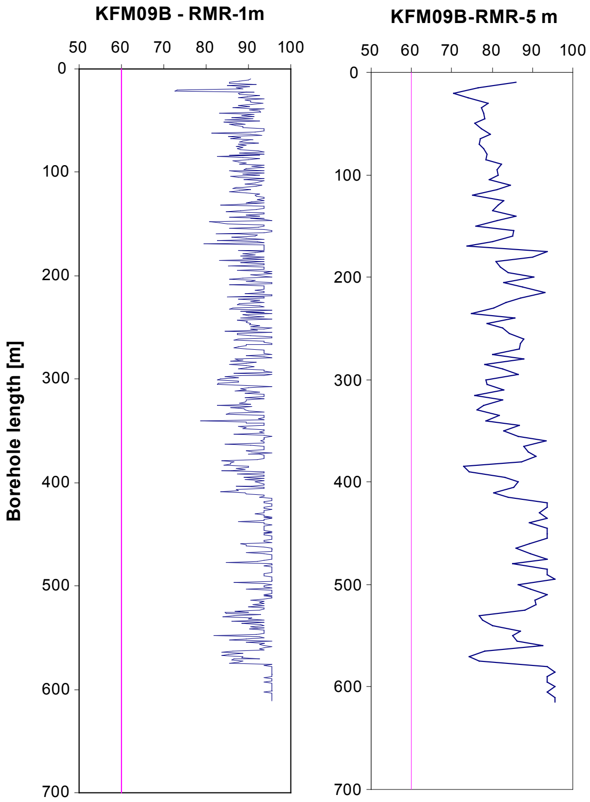

Figure 5-32. *Mean RMR for borehole sections of 1 m (left) and 5 m (right) along KFM09B. The limit identified according to the signature in Equation (8) is marked in pink.*

6 Discussion and conclusions

When comparing the plots with depth of RMR and Q for different boreholes, the following observations can be made (cf. Table 6-1):

- All the rock mass quality values and the mechanical properties of the rock mass in this report represent the rock mass as a continuous, homogeneous and isotropic medium. Anisotropy is not considered here, since all boreholes are sub-parallel, thus, strictly, give information only in the vertical direction.
- Boreholes KFM09A and B show rather high and uniform values of RMR with depth. The values of Q vary slightly more. Even though the rock mass quality varies more in borehole KFM01B and KFM07C, the RMR rating indicates a rock class of "good rock" for the deformation zones whereas the Q system occasionally indicates "fair rock".
- In general, the competent rock in KFM07C exhibits the best (RMR = 90, Q = 1,067) rock quality among all boreholes (RMR around 85, Q around 300).
- The deformation zones present an average RMR as low as 80 and Q of about 22, with extreme values of RMR and Q of 45 and 3, respectively.
- The uncertainties of the average RMR generally vary between ±1% for the competent rock mass and ±3% for the deformation zones. The corresponding uncertainty of the Q values are higher, ±9% and ±50%, respectively, probably due to the fact that Q usually ranges several orders of magnitude for the same rock mass.

Table 6-1. Summary of the results from the investigation.

Borehole	KFM01B		KFM07C		KFM09A		KFM09B	
	Competent rock	Fractured rock	Competent rock	Fractured rock	Competent rock	Fractured rock	Competent rock	Fractured rock
Parameter	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty	Mean/stdev Min – Max Uncertainty
RMR	88.9/5.1 75.2–95.6 ±1%	77.4/7.1 64.2–93,6 ±5%	89.8/3.9 72.8–95.6 ±1%	87.1/4.7 70.0–93,6 ±2%	83.3/5.8 68.5–93.6 ±2%	78.7/5.3 69.6–92,6 ±4%	87.5/5.9 73.7–95.6 ±1%	80.3/4.6 70.5–90,9 ±3%
Q	380.3/424.1 20.2–2133.3 ±8%	69.2/87.6 3.2–400.0 ±89%	307.8/303.9 26.7–1066.7 ±14%	123.4/163.7 7.1–800.0 ±44%	120.5/194.8 2.2–800.0 ±41%	22.1/28.1 2.3–135.0 ±76%	416.1/561.2 22.5–2133.3 ±12%	76.8/70.3 3.2–300.0 ±30%
Young's modulus (GPa)	72.2/7.6 42.8–76.0 ±3%	48.8/15.3 22.6–76.0 ±21%	74.4/5.2 37.2–76.0 ±2%	71.8/9.7 31.6–76.0 ±7%	63.5/12.8 29.0–81.0 ±6%	52.0/12.7 30.8–76.0 ±13%	70.4/9.6 39.0–76.0 ±4%	56.8/12.3 32.6–76.0 ±8%
Uniaxial compressive strength using Hoek & Brown's Criterion (MPa)	96.5/24.6 43.5–134.7 ±8%	53/23.3 23.5–120.5 ±30%	98.1/21.0 38.0–134.7 ±7%	85.2/19.7 32.1–119.4 ±17%	68.8/25.7 18.0–120.5 ±10%	54.2/18.2 28.9–113.0 ±21%	90.4/28.2 22.9–134.7 ±8%	58.5/15.1 33.4–103.9 ±15%
Uniaxial compressive strength using the Mohr-Colomb criterion (MPa)	150.5/21.4 103.0–183.4	111.3/21.4 81.1–171.3	151.2/20.6 72.5–183.9	140.6/18.0 92.5–171.9	125.4/24.5 67.7–171.3	112.0/20.0 50.7–166.4	144.7/26.4 44.3–183.4	117.2/13.6 92.7–157.0
Cohesion (MPa)	27.2/3.1 20.4–32.0 ±3%	21.6/3.1 17.3–30.2 ±8%	27.3/2.8 18.6–32.0 ±3%	25.7/2.6 18.9–30.1 ±7%	23.6/3.5 15.5–30.2 ±2%	21.6/2.7 13.7–29.3 ±5%	26.3/3.8 12.4–32.0 ±3%	22.4/1.9 18.9–28.1 ±4%
Friction angle (°)	50.1/1.1 46.8–51.5 ±1%	47.3/1.8 43.7–51.1 ±3%	50.0/2.1 35.6–51.7 ±1%	49.6/1.3 45.6–51.4 ±3%	48.4/2.2 40.8–51.5 ±1%	47.3/3.0 33.1–51.2 ±3%	49.6/2.5 31.5–51.5 ±1%	48.1/1.1 45.6–50.6 ±2%

- The average deformation modulus of the boreholes KFM01B, KFM07C and KFM09B for the competent rock mass ranges between 70 and 74 GPa compared to borehole KFM09A for which the average deformation modulus is only 64 GPa. The average deformation modulus of the deformation zones rather indicate that borehole KFM01B, with an average deformation modulus of about 49 GPa, has lower modulus than that generally found for boreholes KFM07C, KFM09A and KFM09B, which show deformation modulus values of about 51–72 GPa.
- The uncertainty of the average deformation modulus derived from RMR seems to be about ±4% for the competent rock mass, whereas the uncertainty for the deformation zones has a range twice as large (about ±10%).
- RMR was chosen as a main empirical method because RMR is provided with a more complete set of empirical relations to estimate the mechanical properties of the rock mass seen as a continuous and elastic medium (e.g. parameters of the Hoek & Brown's and Coulomb's Criterium).
- According to the Hoek & Brown's Criterion, the average uniaxial compressive strength of the rock mass ranges between 66 and 95 MPa for the four boreholes, with the highest values to be assigned to KFM07C. In the deformation zones, the average strength drops to 53 to 85 MPa.
- By extrapolating the Mohr-Coulomb Criterion outside the range 10 to 30 MPa confining pressure, the uniaxial compressive strength can also be determined. The values so obtained are much higher that those from the Hoek & Brown's Criterion. This is due to the curvilinearity of the Hoek & Brown's Criterion that must provide lower UCS values. The average UCS_{M-C} for the four boreholes in this report varies between 125 and 151 MPa for the competent rock mass, while it varies between 111 and 141 MPa for the deformation zones.
- The uncertainty of the average uniaxial compressive strength derived through the Hoek & Brown's Criterion, is about ±8% for the competent rock mass and about ±20% for the deformation zones, respectively.
- The equivalent cohesion of the competent rock mass in the boreholes varies, on average, between 23 and 27 MPa, for confinement stresses between 10 and 30 MPa. For the deformation zones, the variation is between 22 and 26 MPa.
- The uncertainty of the average cohesion reported in Section 5.5.5 is about ±3% for the competent rock mass and about ±6% for the deformation zones, respectively.
- The equivalent friction angle of the rock mass in each borehole ranges between 48° and 50°, for the competent rock mass, and between 47° and 50°, for the deformation zones, respectively. Also the friction angle is estimated for confinement stresses between 10 and 30 MPa.
- The uncertainty of the equivalent average friction angle is around ±1% for the competent rock mass, and about three times as large for the deformation zones.
- The use of a threshold to identify deformation zones could identify the most damaged rock in the upper part of the boreholes. The characterization system that generally indicates deformation zones is the Q system. In borehole KFM07C a deformation zone was identified in the RMR system using 1 m sections.
- All of the deformation zones identified with the signature used are found within the deformation zones identified in the single-hole interpretation. The deformation zones identified with the signature coincide with areas within the deformation zones from the single-hole interpretation that are commented on as showing strong indications of larger fracture frequency, or crushed zones. This is perhaps a way to identify the core of the deformation zone which has a large significance in engineering.
- Generally, the uncertainty of the Q values is larger than that for RMR due to the logarithmic nature of the Q system.

The values of Q can be plotted against the values of RMR to derive a site-specific correlation equation. In Figure 6-1 these correlations are plotted together with some of the relations reported in the literature. In the literature, the relations reported apply for the "classification" of the rock mass, where the effect of the boundary conditions is regarded. For "characterisation", as in this report, the effects of the boundary conditions are disregarded and will be added to the parameters in the modelling phase of the Site Descriptive Modelling Project for Forsmark version 2.2. The relations between RMR and Q obtained for the five boreholes can be summarised as follows:

KFM01B: $RMR = 4.62 \cdot \ln(Q) + 63$ (9)

KFM07C: $RMR = 2.52 \cdot \ln(Q) + 77$ (10)

KFM09A: $RMR = 2.64 \cdot \ln(Q) + 73$ (11)

KFM09B: $RMR = 4.02 \cdot \ln(Q) + 66$ (12)

The data contained in the Appendices are delivered to SKB's database Sicada to complete the single-hole interpretation. The Appendices also contain 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.

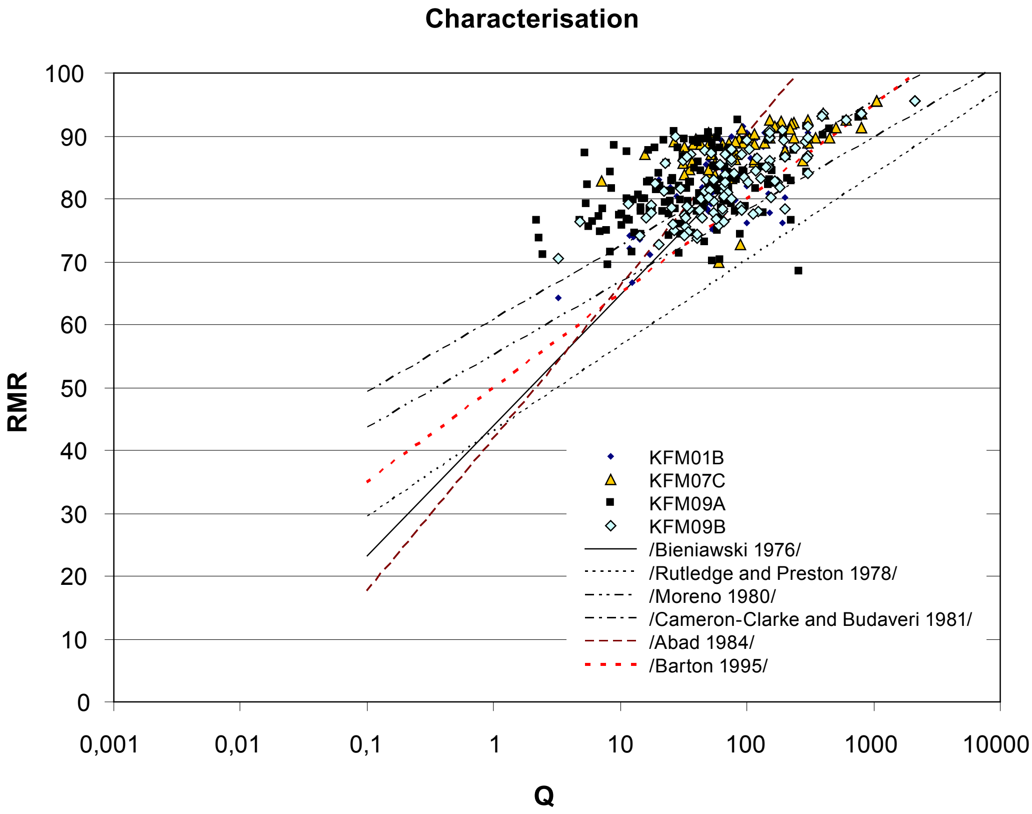

Figure 6-1. *Correlation between RMR and Q for the characterisation of the rock mass along boreholes KFM01B, KFM07C, KFM09A and KFM09B (core sections of 5 m). The characterisation results are compared with some classification/design relations from the literature.*

7 Data delivery to Sicada

The results of the rock mass characterisation are delivered to SKB's database Sicada, where they are traceable by the SKB's order number SKB 15112. 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 the drill-core/borehole and of 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 (Em) 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 the minimum, average and maximum deformation modulus of the rock mass. Before storage into the database, quality assessment routines were performed on the methods and delivered data.

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Appendix 1

KFM01B – Characterisation of the rock mass

1.1 Fracture orientation

Set identification from the fracture orientation mapped for borehole KFM01B (Sicada data delivery – 06_134_1). The orientations are given as strike/dip (right-hand rule).

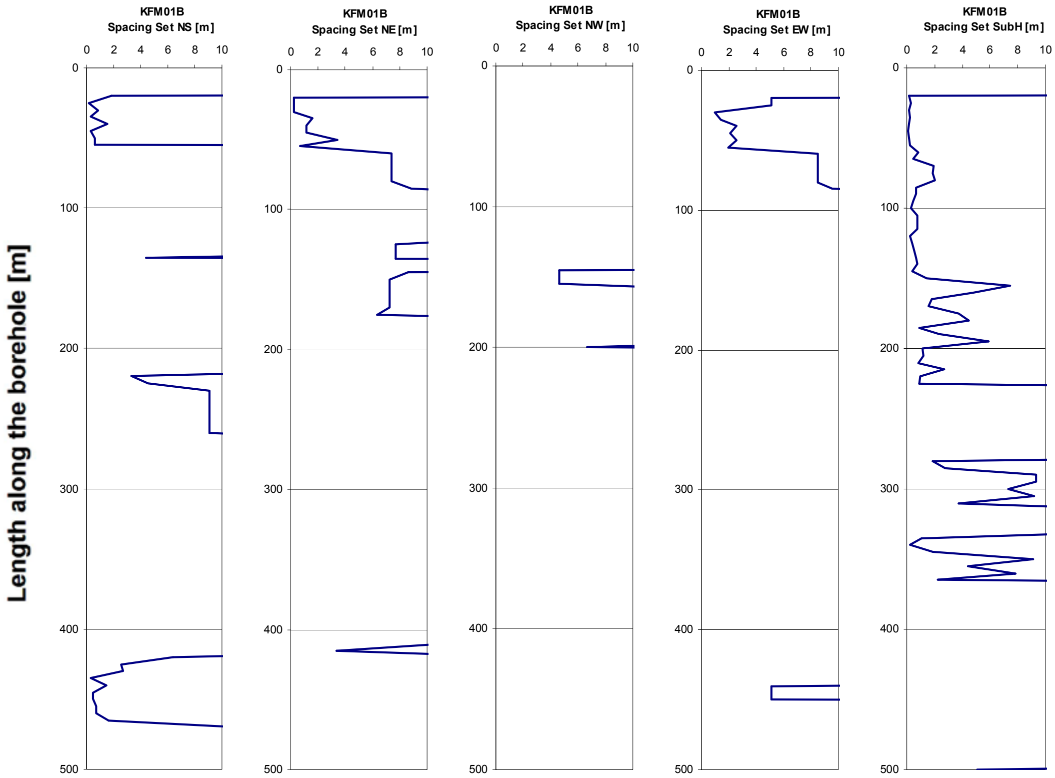
Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
15–53	314	180/88	226/84		301/76	121/03
53–107	76		214/63	115/72	301/76	131/08
107–135	75	153/69	051/69		274/62	130/07
135–141	14					118/07
141–415	113	160/88	038/87	130/72	317/76	106/09
415–454	31	348/85	047/69	130/60	309/85	041/06
454–500	5	354/83				150/17

Fisher's constant of the fracture sets identified along borehole KFM01B (Sicada data delivery – 06_134_1).

Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
15–53	314	17.2	7.5		30.7	40.3
53–107	76		10000*	10000*	10000*	86.9
107–135	75	14.9	10000*		10000*	69.0
135–141	14					157.4
141–415	113	13.4	42.3	24.7	10000*	43.2
415–454	31	32.0	10000*	10000*	10000*	94.1
454–500	5	63.3				10000*

* Derived from one fracture.

Fracture spacing with length along borehole for the four facture sets in borehole KFM01B. The values are averaged for each 5 m length of borehole.

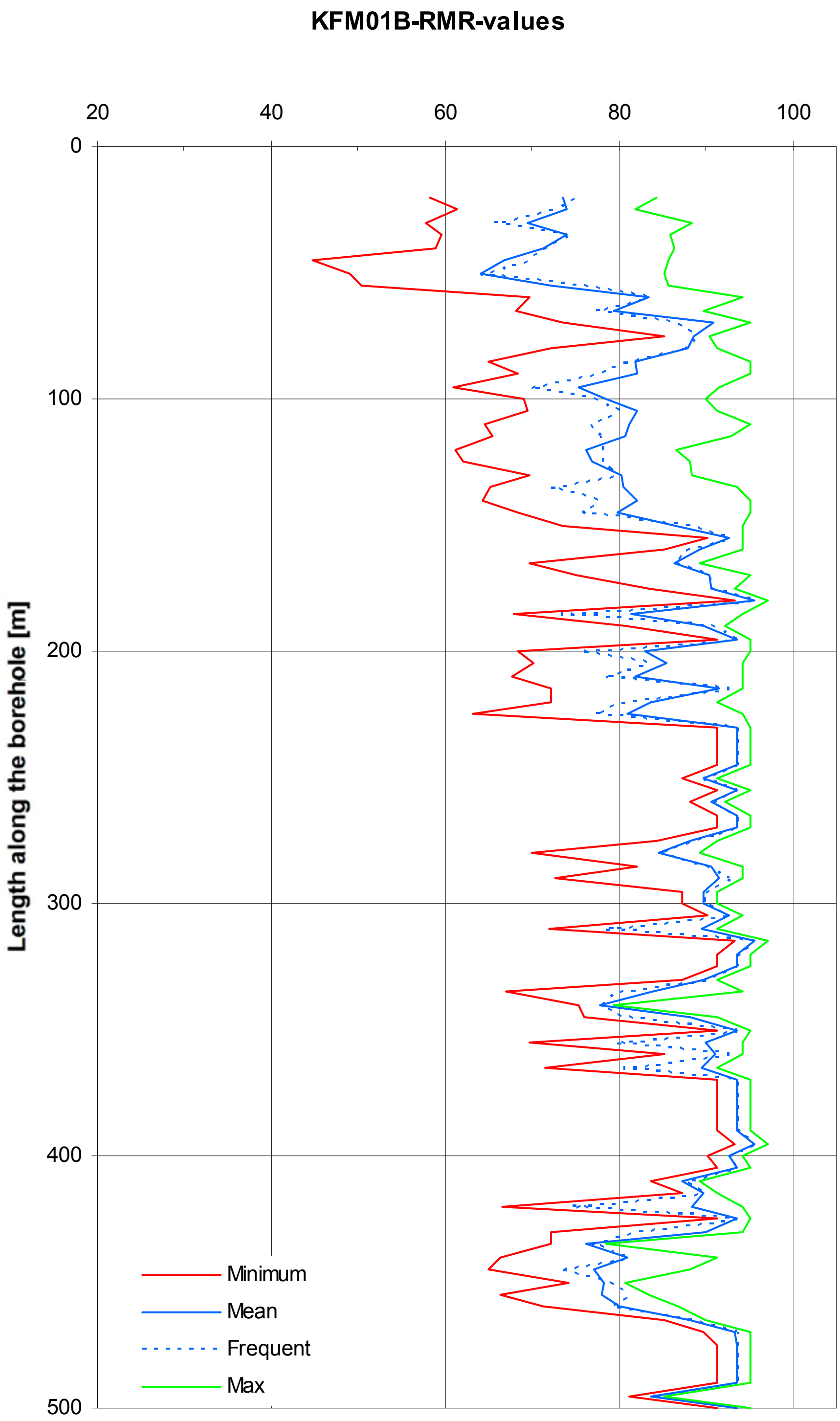


1.2 RMR

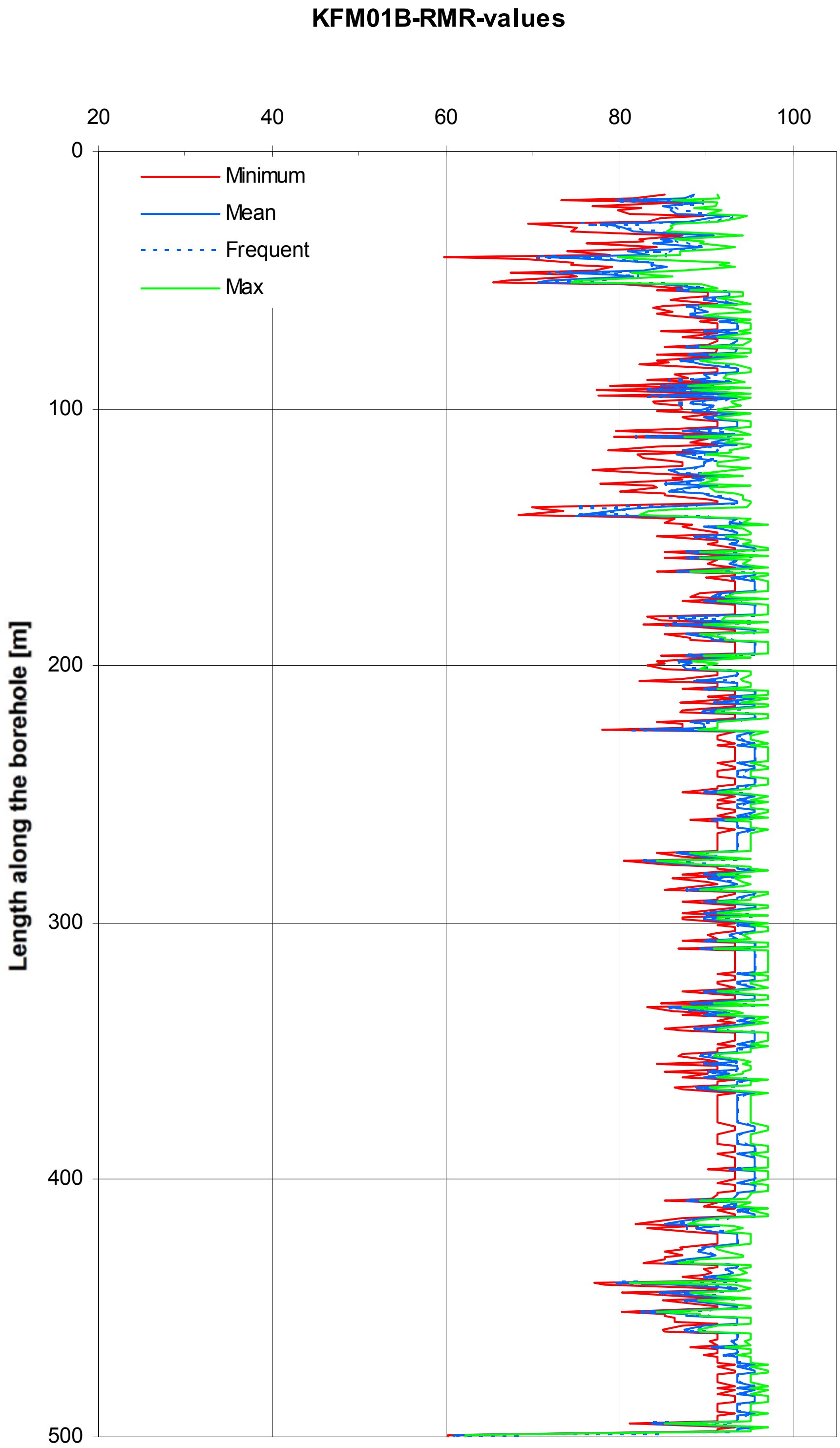
RMR values along borehole KFM01B (core sections of 5 m).

Rock unit length along borehole [m]	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
DZ1, 16-55	64.2	70.7	71.7	74	3.6	44.8	88.4
RU1, 55-105	75.2	83	82.1	90.7	4.9	61	95.2
DZ2, 105-135	76.2	79.3	80.4	81.2	2.1	61.12	95.2
RU1, 135-140	82	82	82	82	–	64.3	95.2
RU2, 140-415	77.7	89.9	90.6	95.6	4.4	63.1	97.2
DZ3, 415-455	76.1	82.8	79.6	93.6	6.8	65	95.2
RU2, 455-500	80.1	90.4	93.6	93.6	5.2	71.3	95.2
Rock mass	75.2	88.9	89.9	95.6	5.1	61.0	97.2
Deformation zones	64.2	77.4	77.0	93.6	7.1	44.8	95.2
Whole borehole	64.2	86.3	89.3	95.6	7.4	44.8	97.2

Variation of RMR along borehole KFM01B. The values are given every 5 m.



Variation of RMR along borehole KFM01B. The values are given every 1 m.

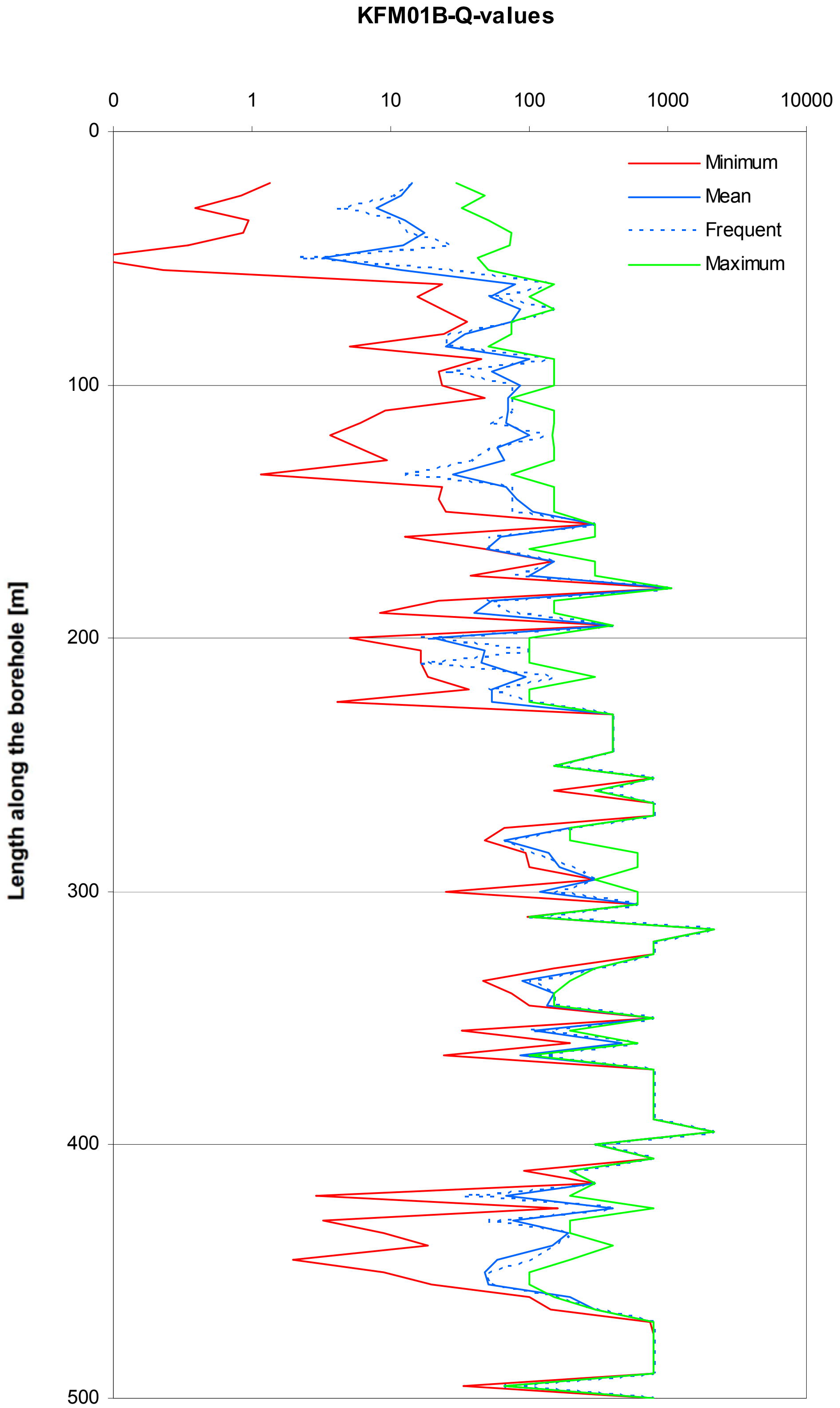


1.3 Q

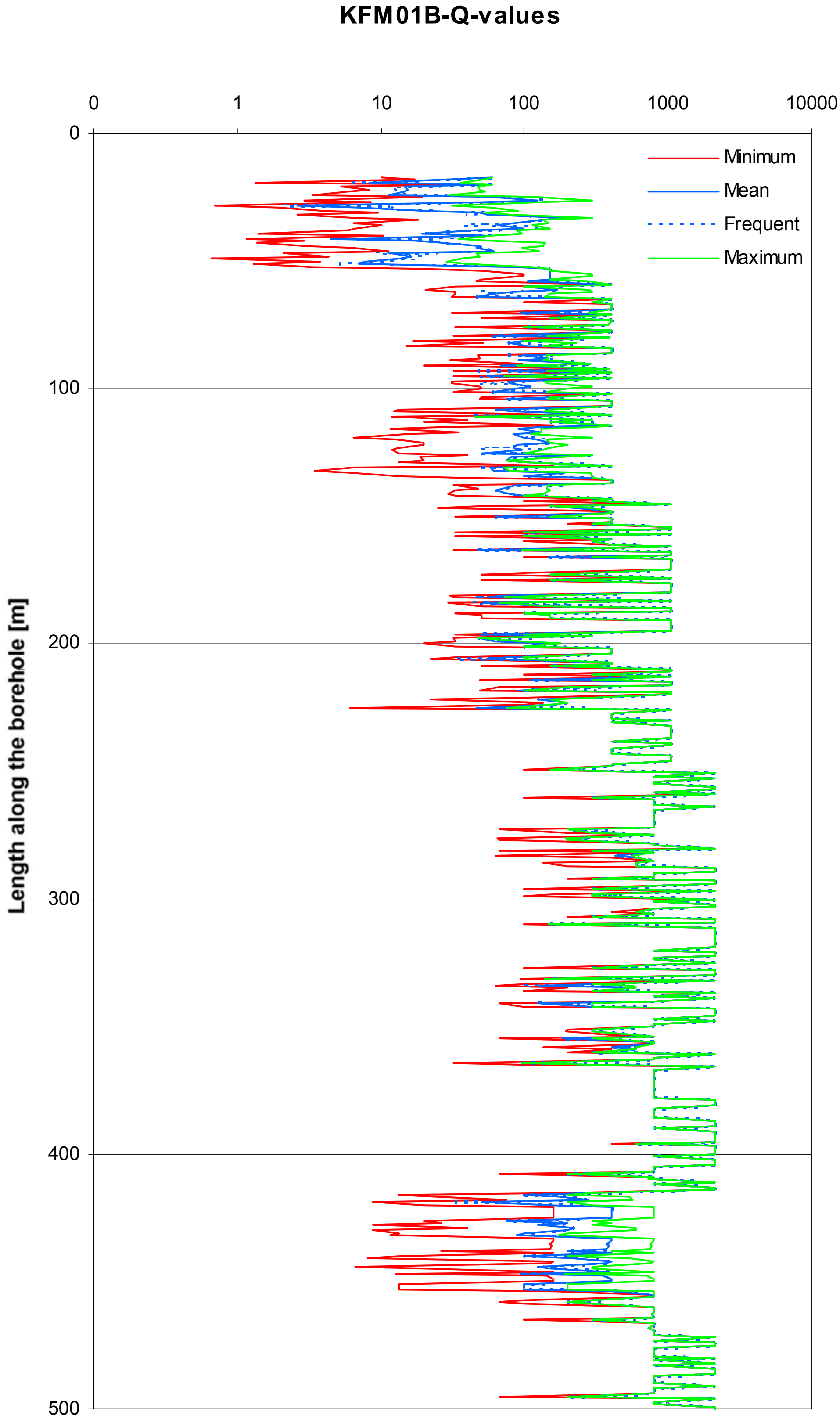
Q values along borehole KFM01B (core sections of 5 m).

Rock Unit Length along borehole [m]	Minimum Q	Average Q	Frequent Q	Maximum Q	Standard deviation	Min possible Q	Max possible Q
DZ1, 16–55	3.2	11.5	12.1	17.3	4.2	0.06	75
RU1, 55–105	25	65.8	71.8	98.9	24	5.13	150
DZ2, 105–135	28	65	67	99	22.9	1.17	150
RU1, 135–140	67.5	65	67	99	–	23.5	150
RU2, 140–415	20.2	408.2	300	2133.3	451.2	4.1	2133.3
DZ3, 415–455	48.1	130.1	72.2	400	120.7	2	800
RU2, 455–500	66.7	594.6	800	800	310.4	33.3	800
Rock mass	20.2	380.3	195.6	2133.3	424.1	4.1	2133.3
Deformation zones	3.2	69.2	54	400	87.6	0.1	800
Whole borehole	3.2	309.8	107.9	2133.3	396.8	0.1	2133.3

Variation of Q along borehole KFM01B. The values are given every 5 m.



Variation of Q along borehole KFM01B. The values are given every 1 m.



Rock mass properties

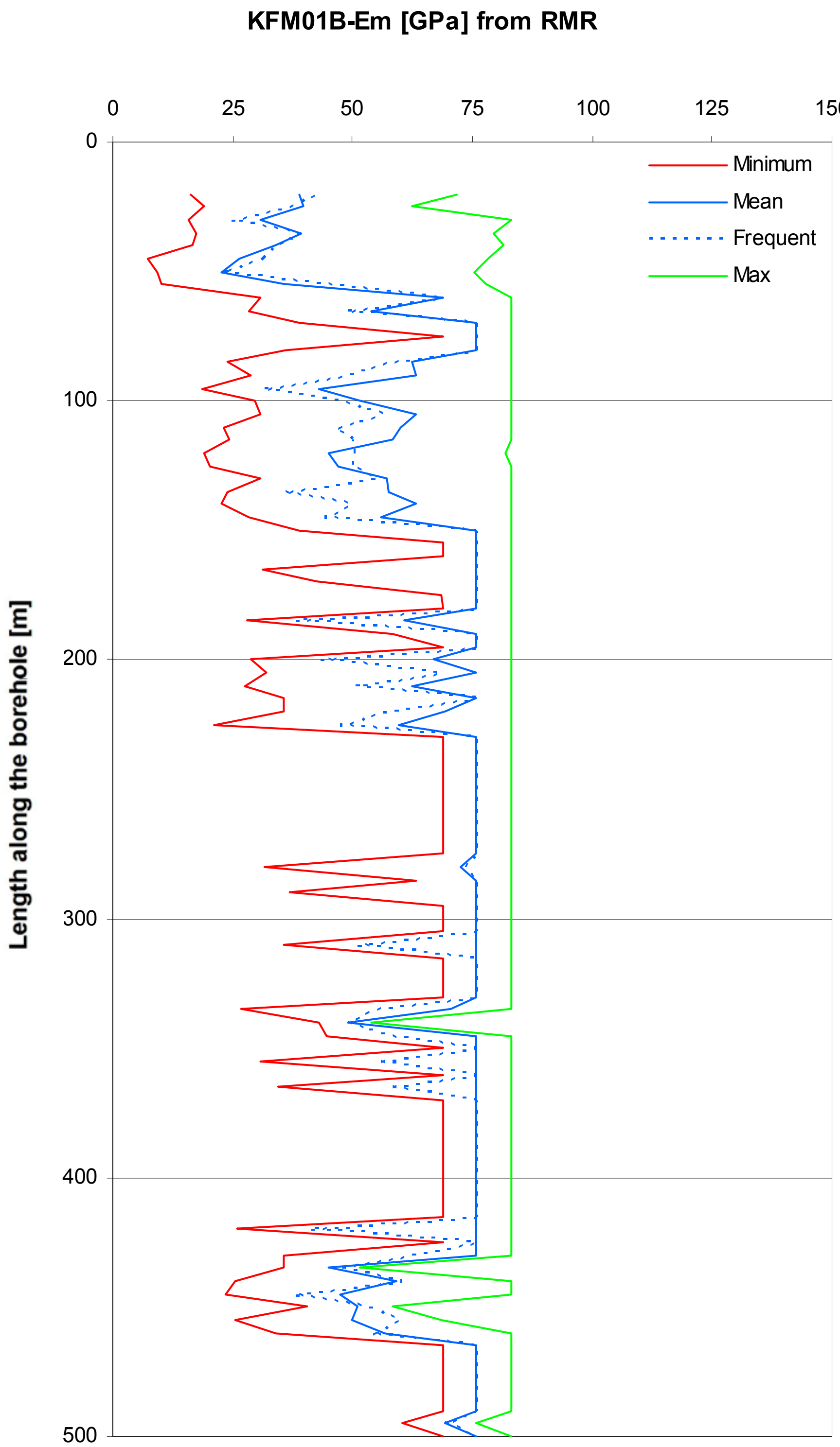
1.4 Deformation modulus

1.4.1 RMR

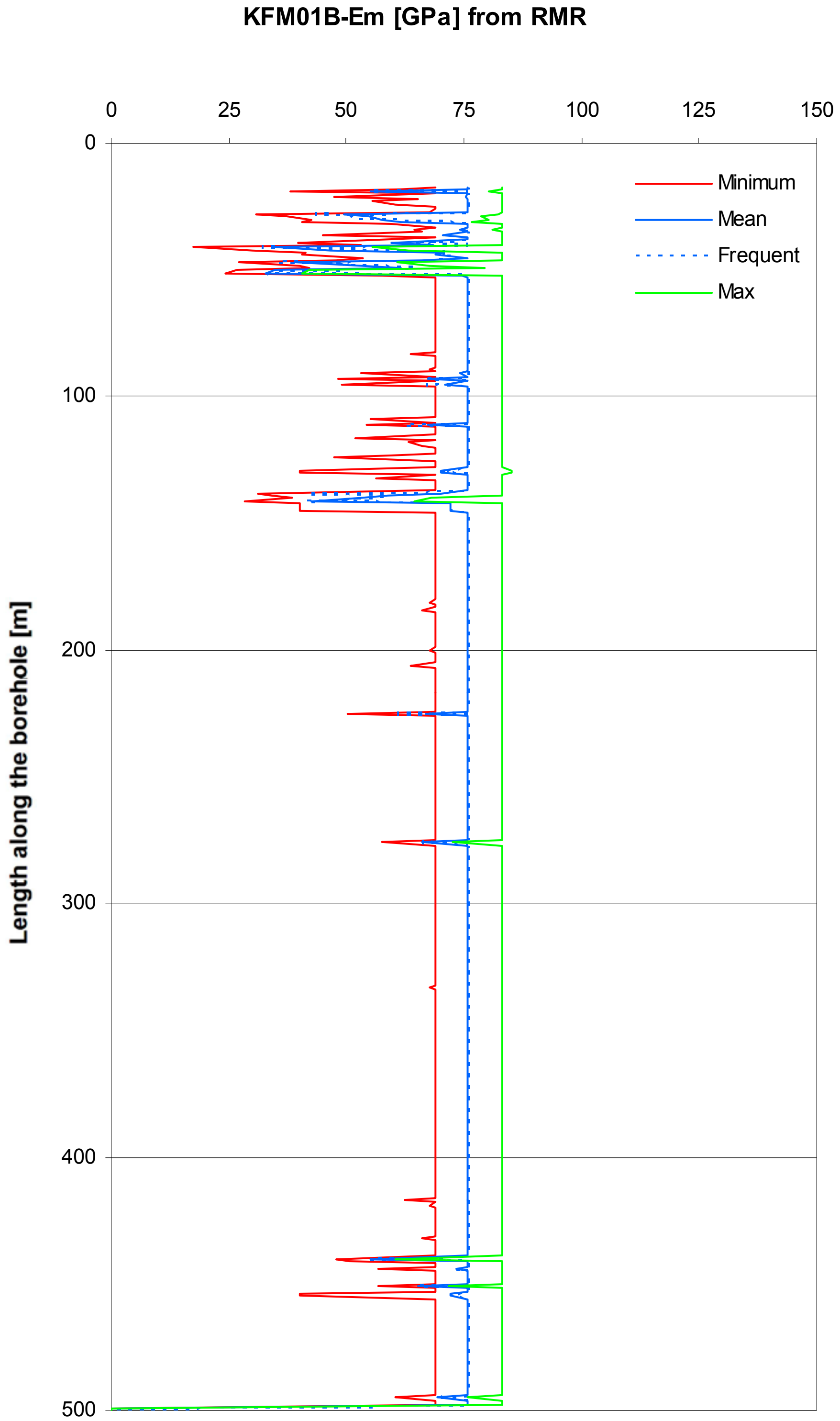
Deformation modulus Em derived from RMR along borehole KFM01B (core sections of 5 m).

Rock unit length along borehole [m]	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation	Min possible Em [GPa]	Max possible Em [GPa]
DZ1, 16–55	22.6	33.4	34.8	39.9	6.4	7.41	83
RU1, 55–105	42.8	63.4	63.3	76	114	18.84	83
DZ2, 105–135	45.2	54.3	57.4	60.1	6.4	18.97	83
RU1, 135–140	63.2	54.3	57.4	60.1	–	22.8	83
RU2, 140–415	49.2	73.9	76	76	5.7	21.3	83
DZ3, 415–455	45	60.1	55.1	76	13.8	23.7	83
RU2, 455–500	56.7	73.1	76	76	6.5	34.1	83
Rock mass	42.8	72.2	76	76	7.6	18.8	83
Deformation zones	22.6	48.8	47.7	76	15.3	7.4	83
Whole borehole	22.6	66.9	76	76	13.9	7.4	83

Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM01B. The values are given every 5 m.

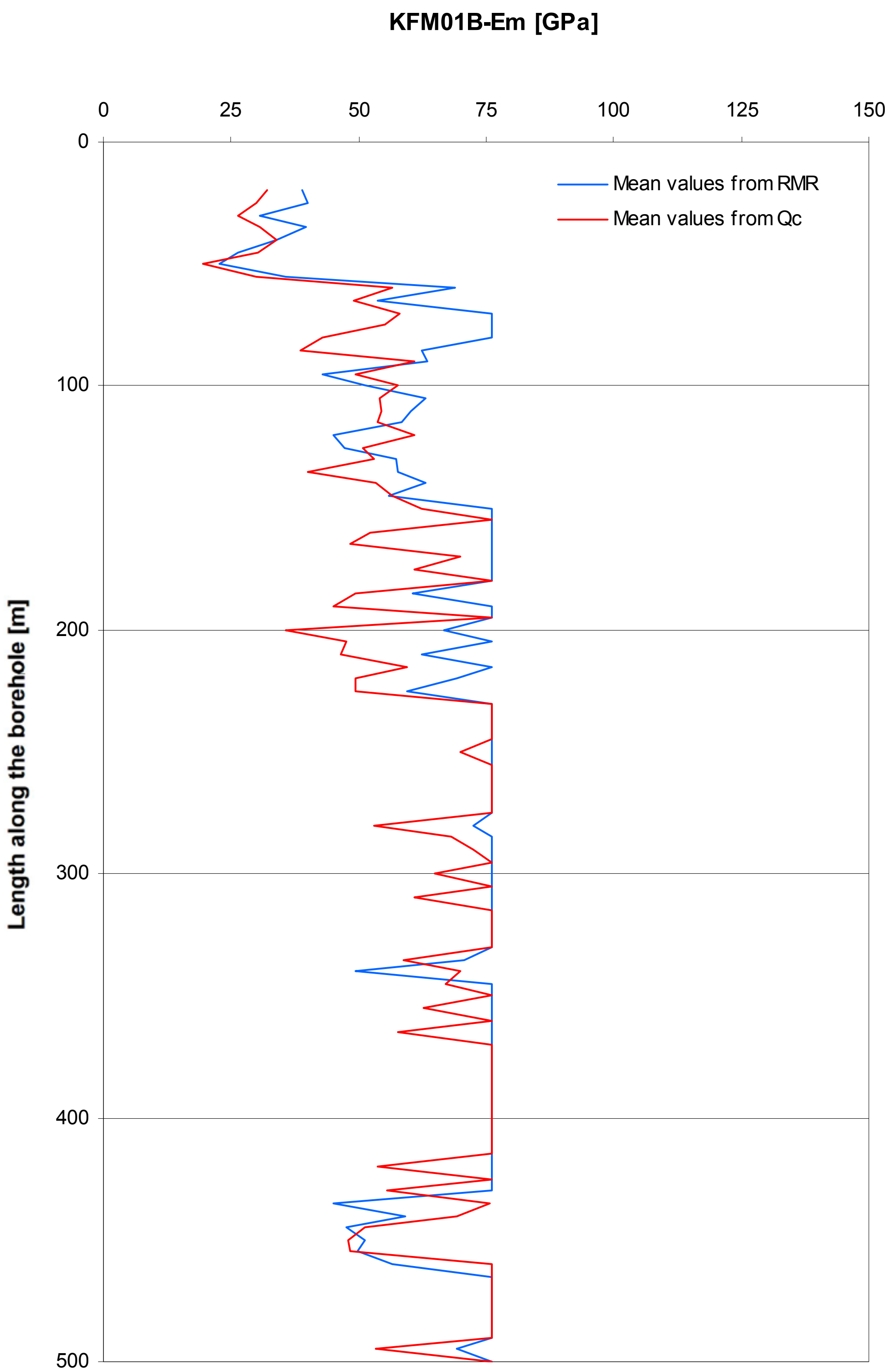


Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM01B. The values are given every 1 m.

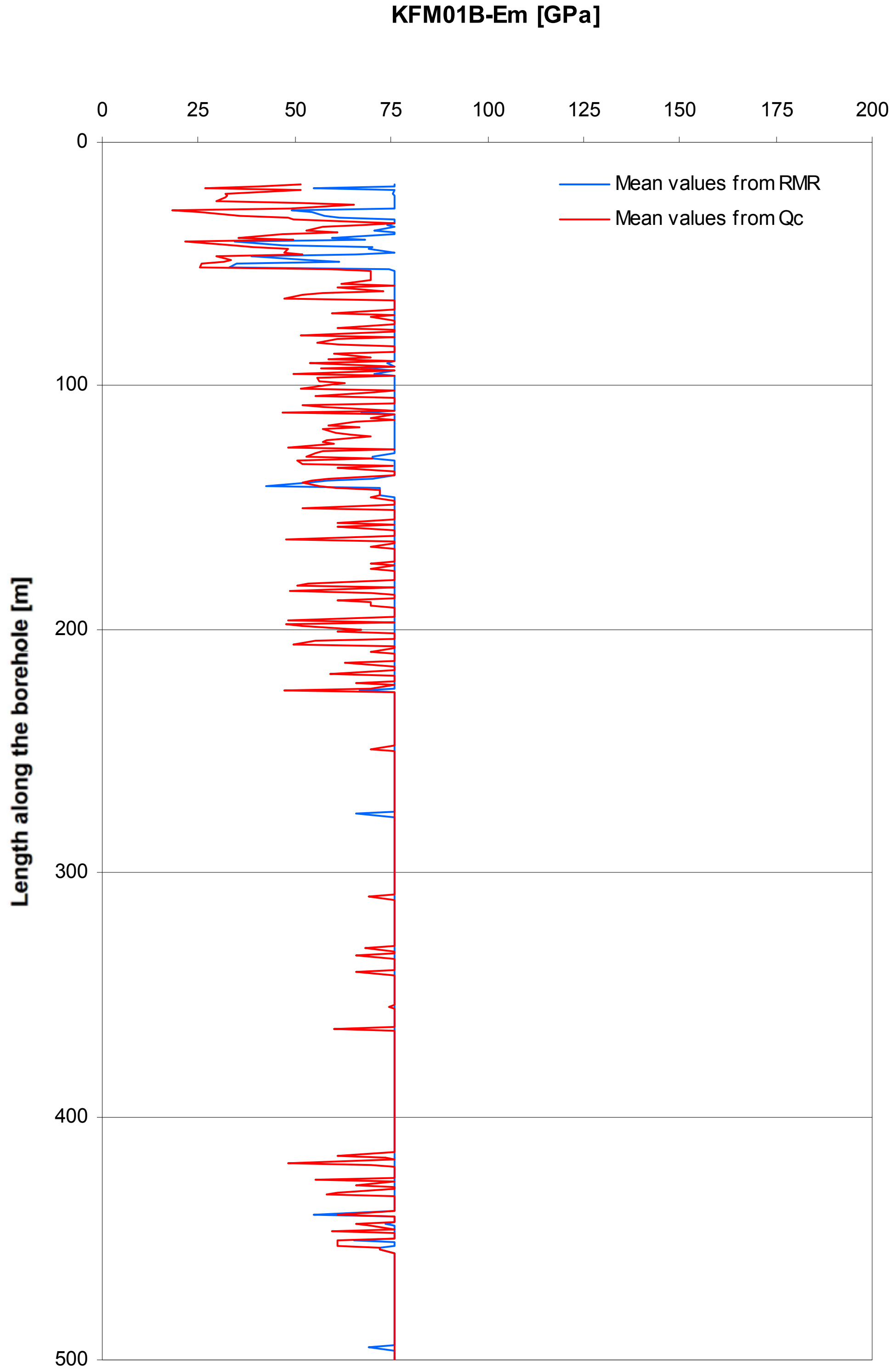


1.4.2 Comparison

Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM01B. The values are given every 5 m.



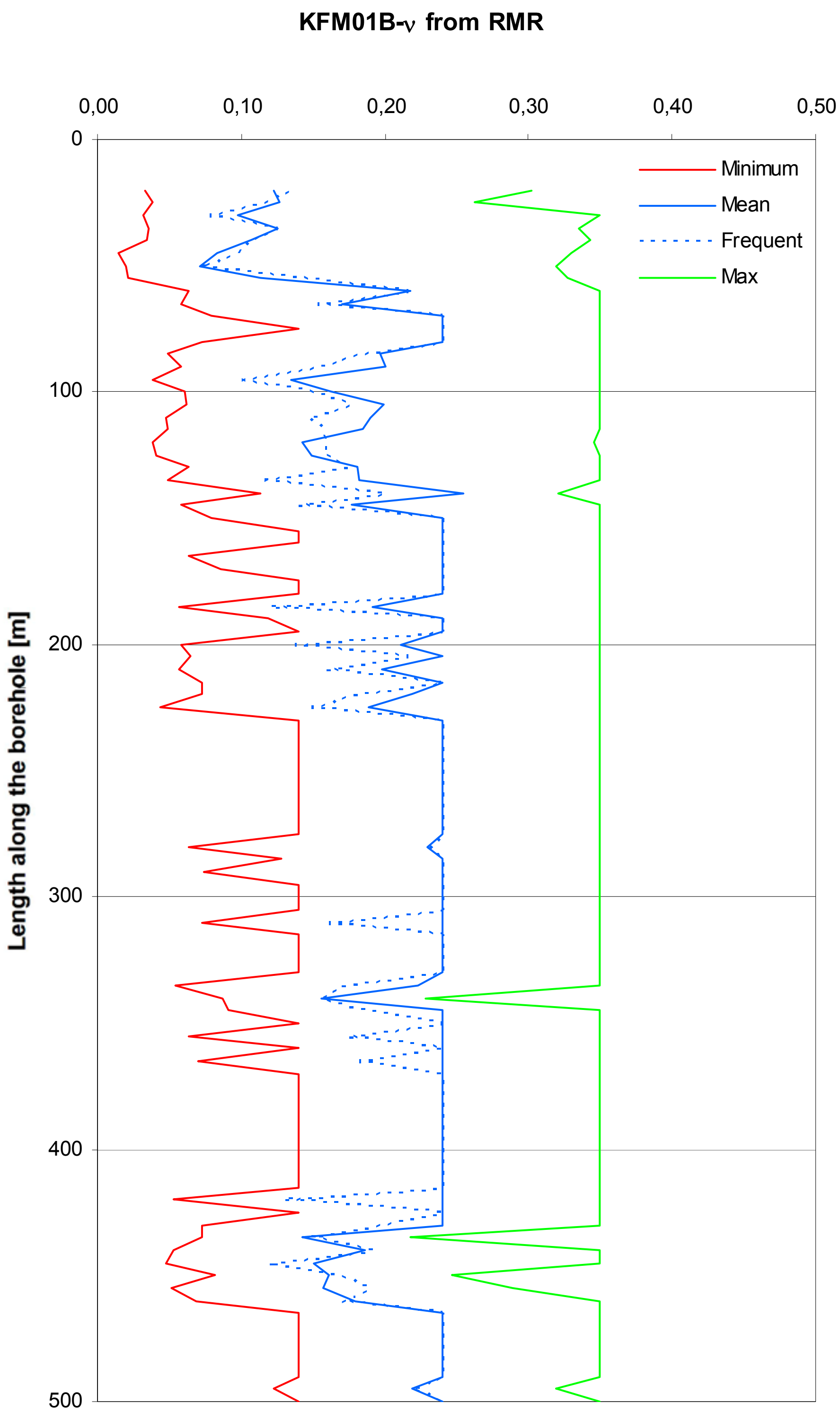
Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM01B. The values are given every 1 m.



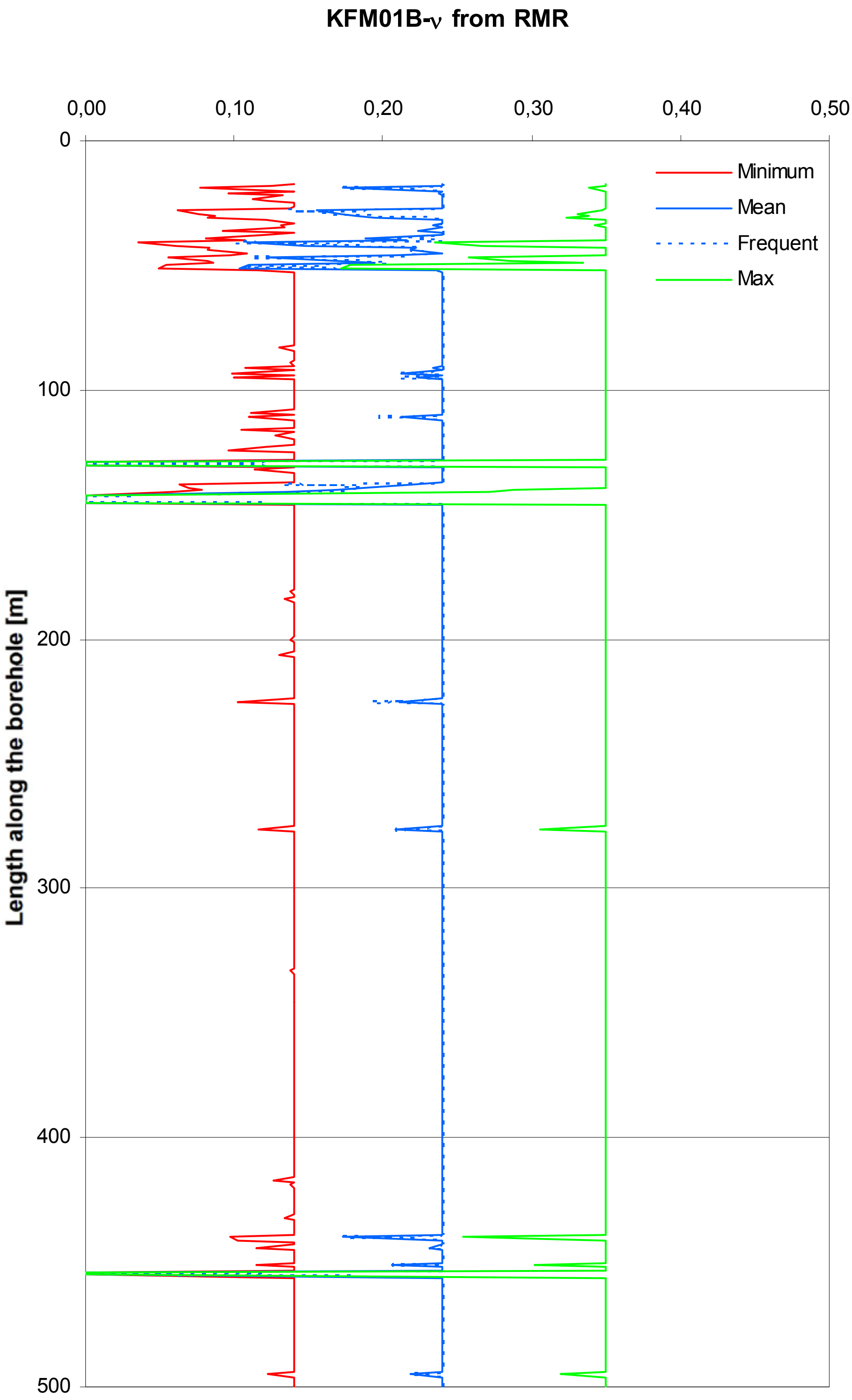
1.5 Poisson's ratio

1.5.1 RMR

Variation of Poisson's ratio (ν) along borehole KFM01B (Hoek & Brown's a=0.5). The values are given every 5 m.



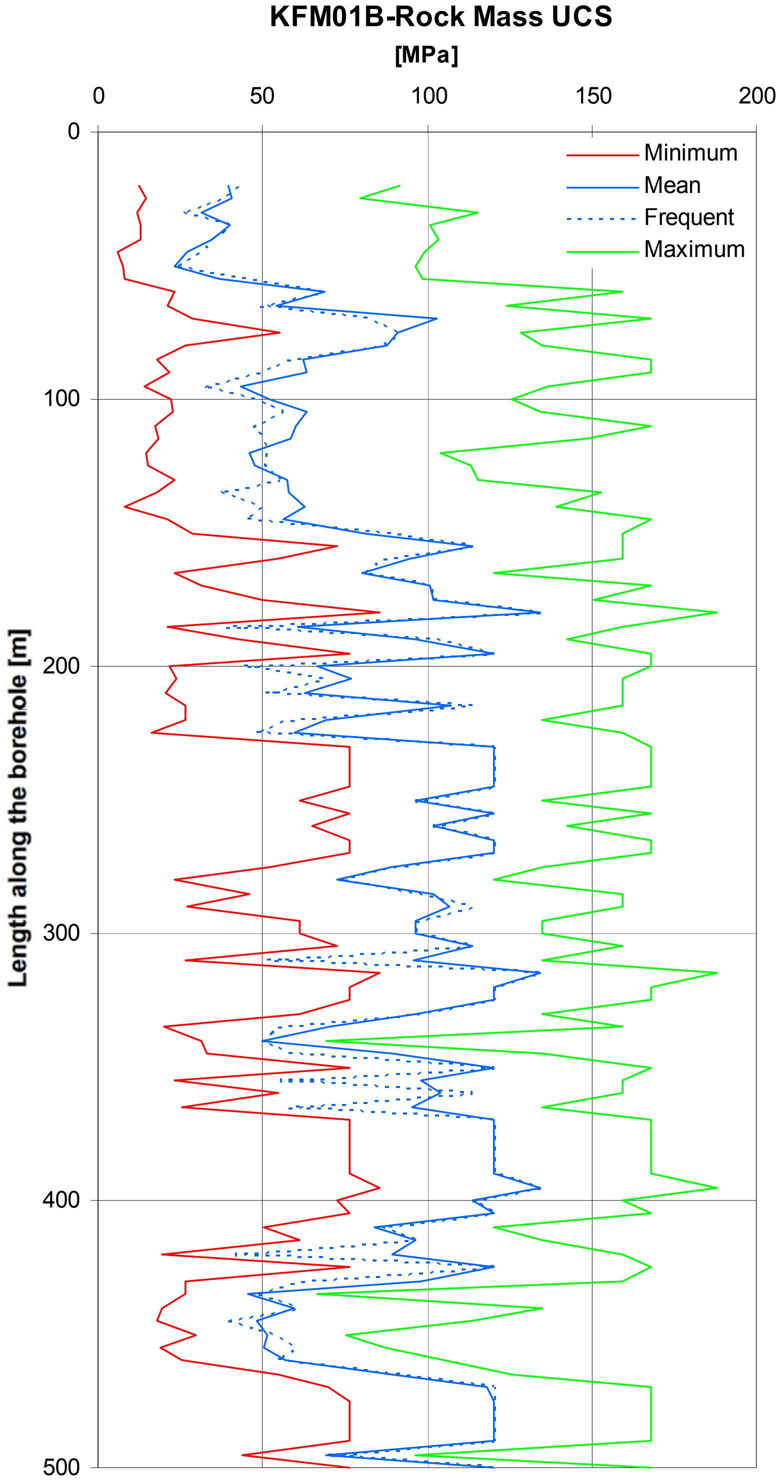
Variation of Poisson's ratio (ν) along borehole KFM01B (Hoek & Brown's a=0.5). The values are given every 1 m.



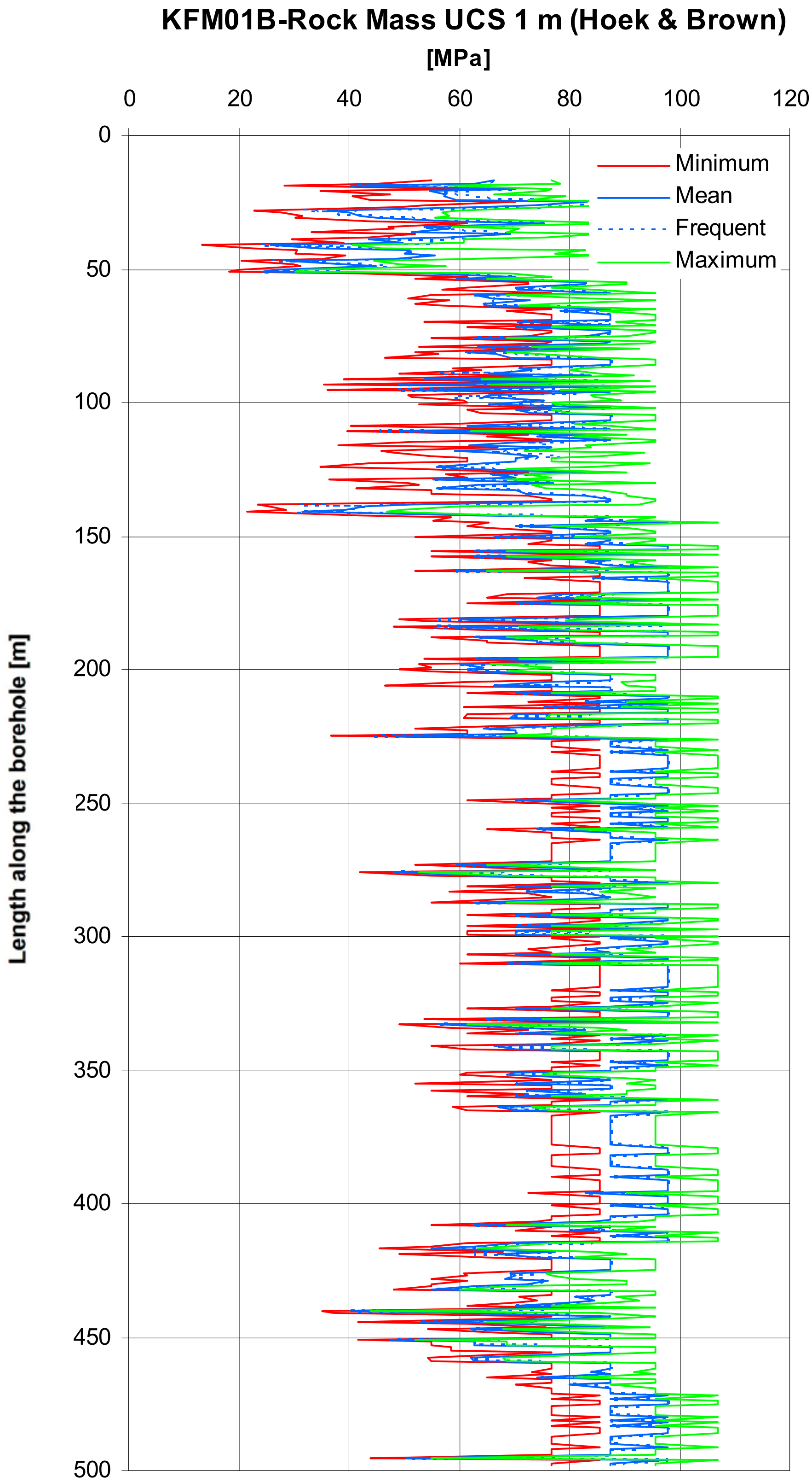
1.6 Uniaxial compressive strength

1.6.1 RMR

Variation of the uniaxial compressive strength of the rock mass along borehole KFM01B (Hoek & Brown's a=0.5). The values are given every 5 m.



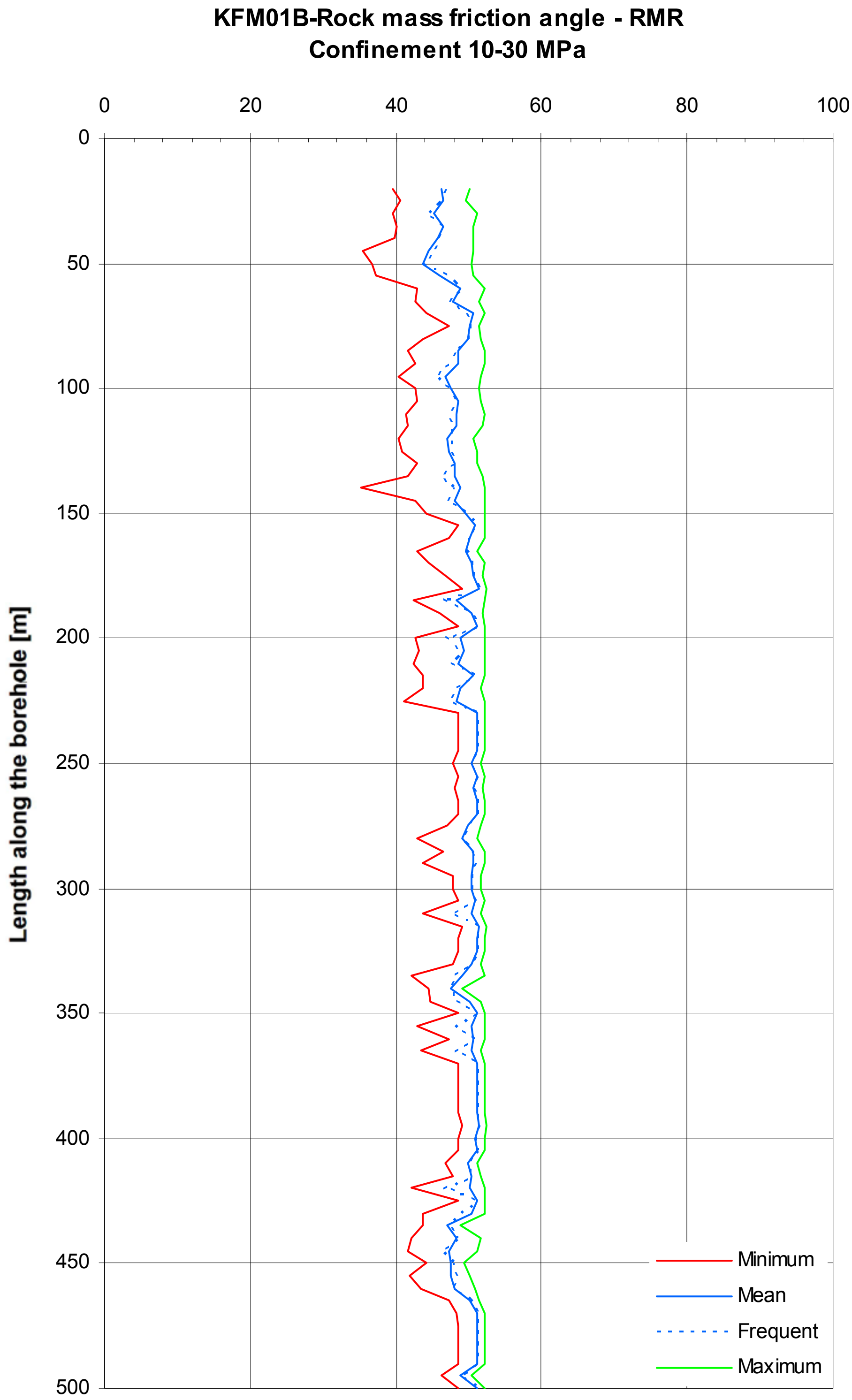
Variation of the uniaxial compressive strength of the rock mass along borehole KFM01B (Hoek & Brown's a=0.5). The values are given every 1 m.



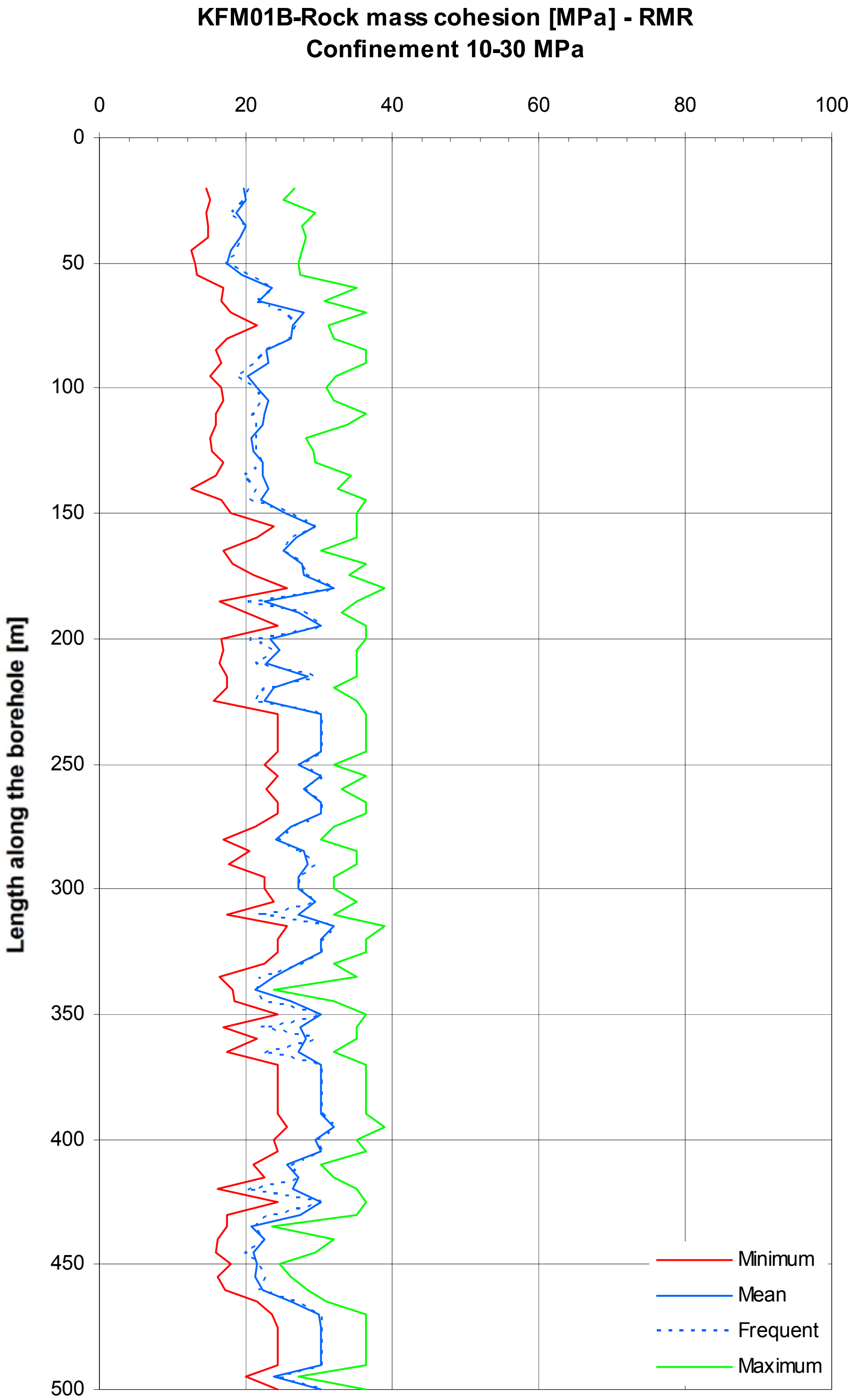
1.7 Friction angle and cohesion and of the rock mass

1.7.1 RMR

Variation of the rock mass friction angle ϕ' from RMR along borehole KFM01B under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Variation of the rock mass cohesion c' from RMR along borehole KFM01B under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Appendix 2

KFM07C – Characterisation of the rock mass

2.1 Fracture orientation

Set identification from the open fracture orientation mapped for borehole KFM07C (Sicada data delivery - 07_002). The orientations are given as strike/dip (right-hand rule).

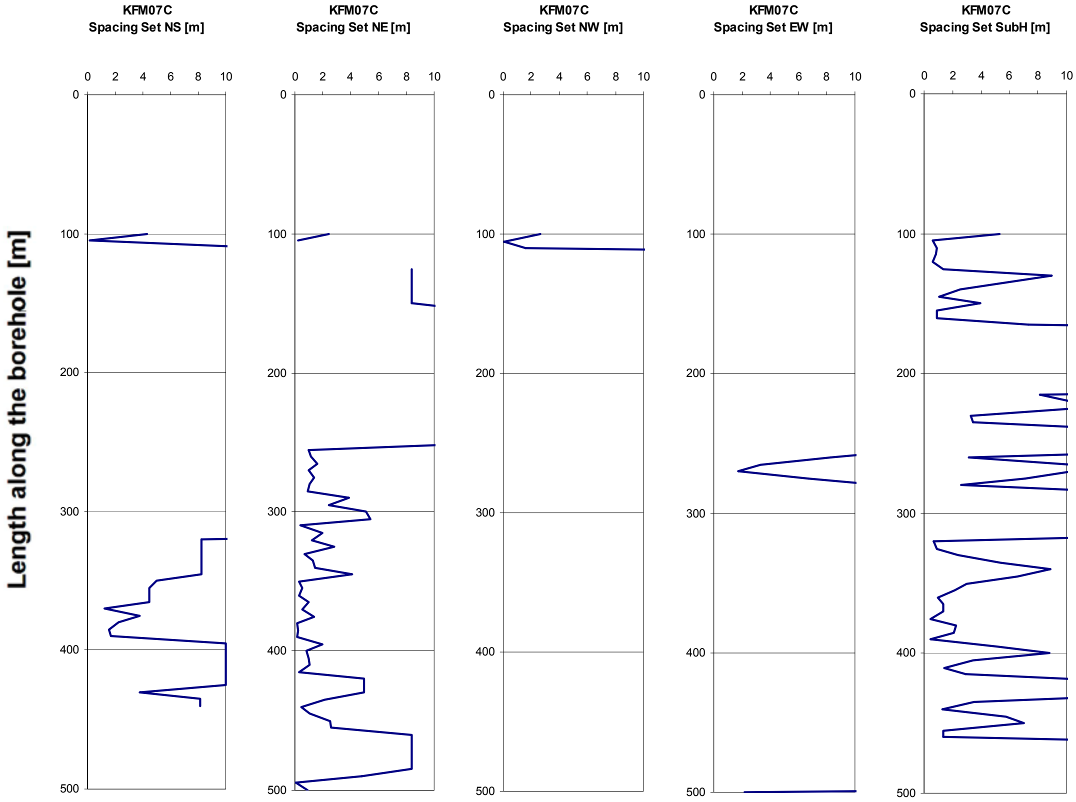
Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
98–103	17	143/75	227/66	133/70		1/9
103–123	24	144/74		140/67		189/4
123–308	61	329/80	231/82	132/75	293/83	247/10
308–388	115	348/82	236/80	111/66		359/0
388–429	24	160/85	242/72			110/3
429–439	17	146/84	55/80			73/14
439–496	28		222/89		270/82	144/2

Fisher's constant of the fracture sets identified for borehole KFM07C (Sicada data delivery- 07_002).

Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
98–103	17	10000*	3.3	181		11
103–123	24	10000*		10000*		15
123–308	61	10000*	13	10000*	10000*	43
308–388	115	14	25	10000*		28
388–429	24	1648	17			17
429–439	17	10000*	22			21
439–496	28		23		10000*	52

* Derived from one fracture.

Fracture spacing along the borehole for the four facture sets in borehole KFM07C. The values are averaged for each 5 m length of borehole.

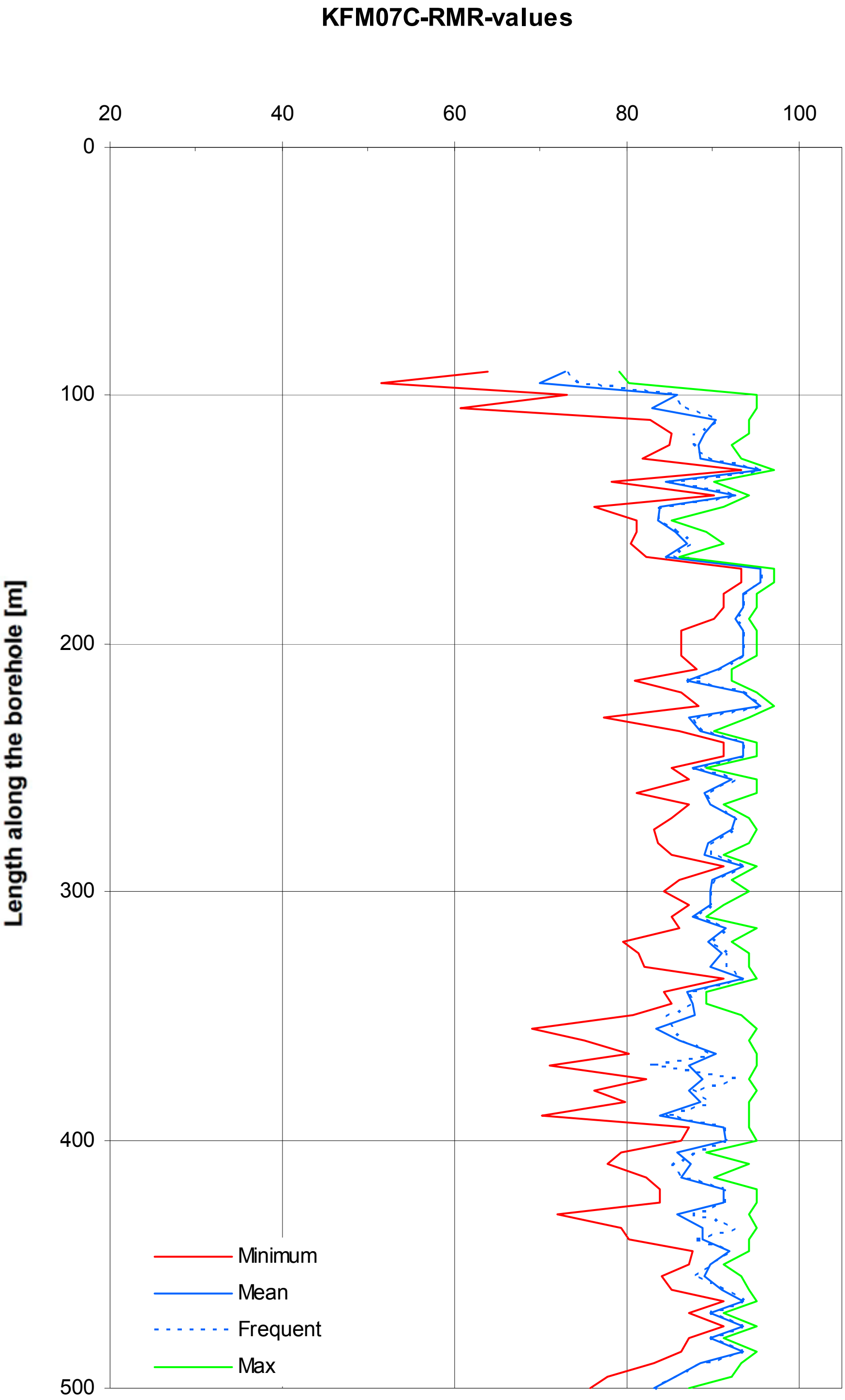


2.2 RMR

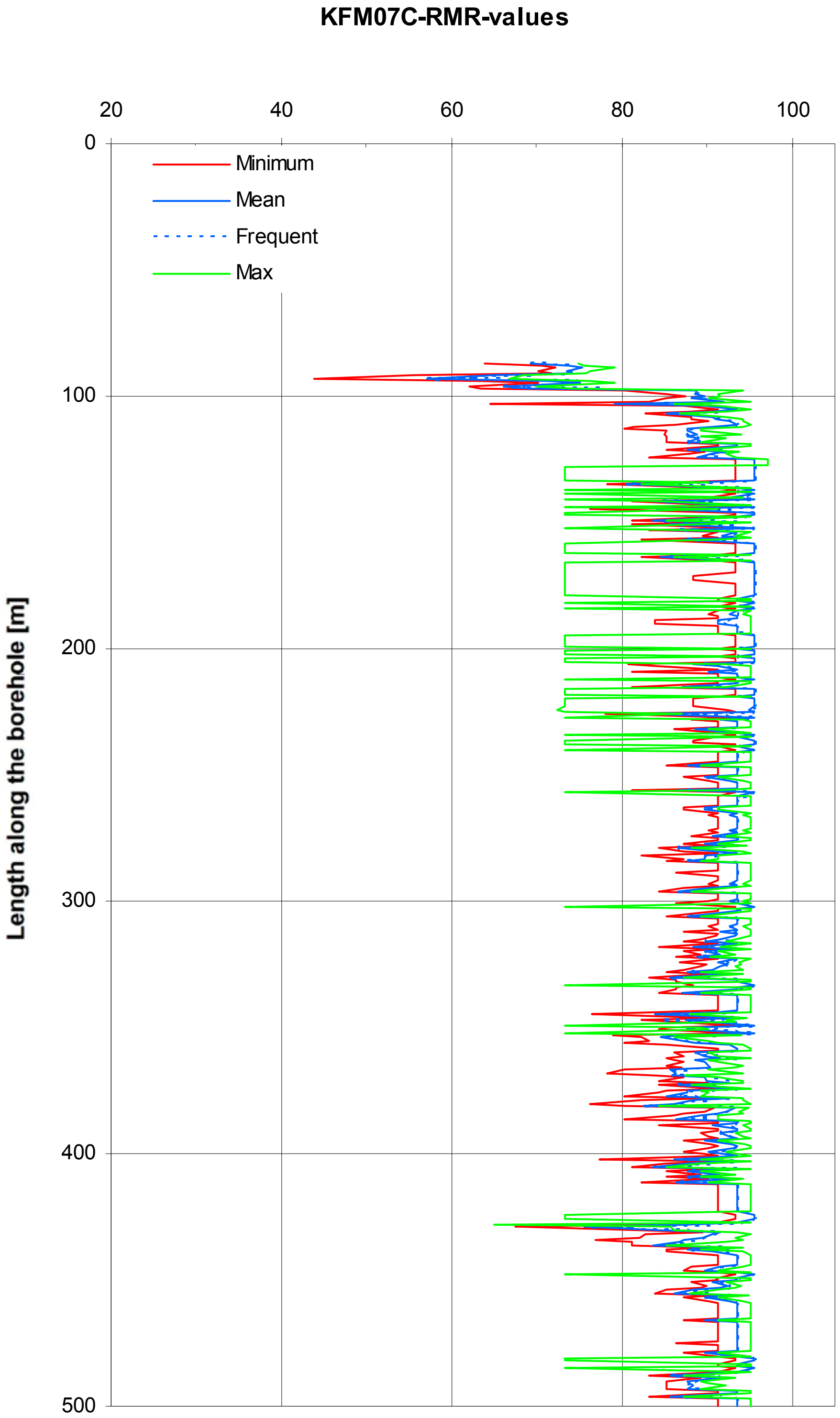
RMR values along borehole KFM07C (core sections of 5 m).

Rock unit length along borehole [m]	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
RU1, 85–90	72.8	72.8	72.8	72.8	–	63.8	79.2
DZ1, 90–105	70	79.6	82.9	86	8.5	51.4	95.2
RU1, 105–125	88.3	89.1	88.9	90.4	0.9	81.8	94.2
RU2, 125–310	83.6	90.6	90.6	95.6	3.6	76.2	97.2
DZ2, 310–390	83.4	88.3	88.3	93.6	2.7	69	95.2
RU2, 390–430	85.8	88.9	89.4	91.4	2.7	73	95.2
DZ3, 430–440	88.7	88.8	88.8	88.9	0.1	79.4	95.2
RU2, 440–500	83.3	90.0	89.6	93.6	3.2	75.8	95.2
Rock mass	72.8	89.8	89.6	95.6	3.9	63.8	97.2
Deformation zones	70	87.1	87.9	93.6	4.7	51.4	95.2
Whole borehole	70	89.2	89.5	95.6	4.3	51.4	97.2

Variation of RMR along borehole KFM07C. The values are given every 5 m.



Variation of RMR along borehole KFM07C. The values are given every 1 m.

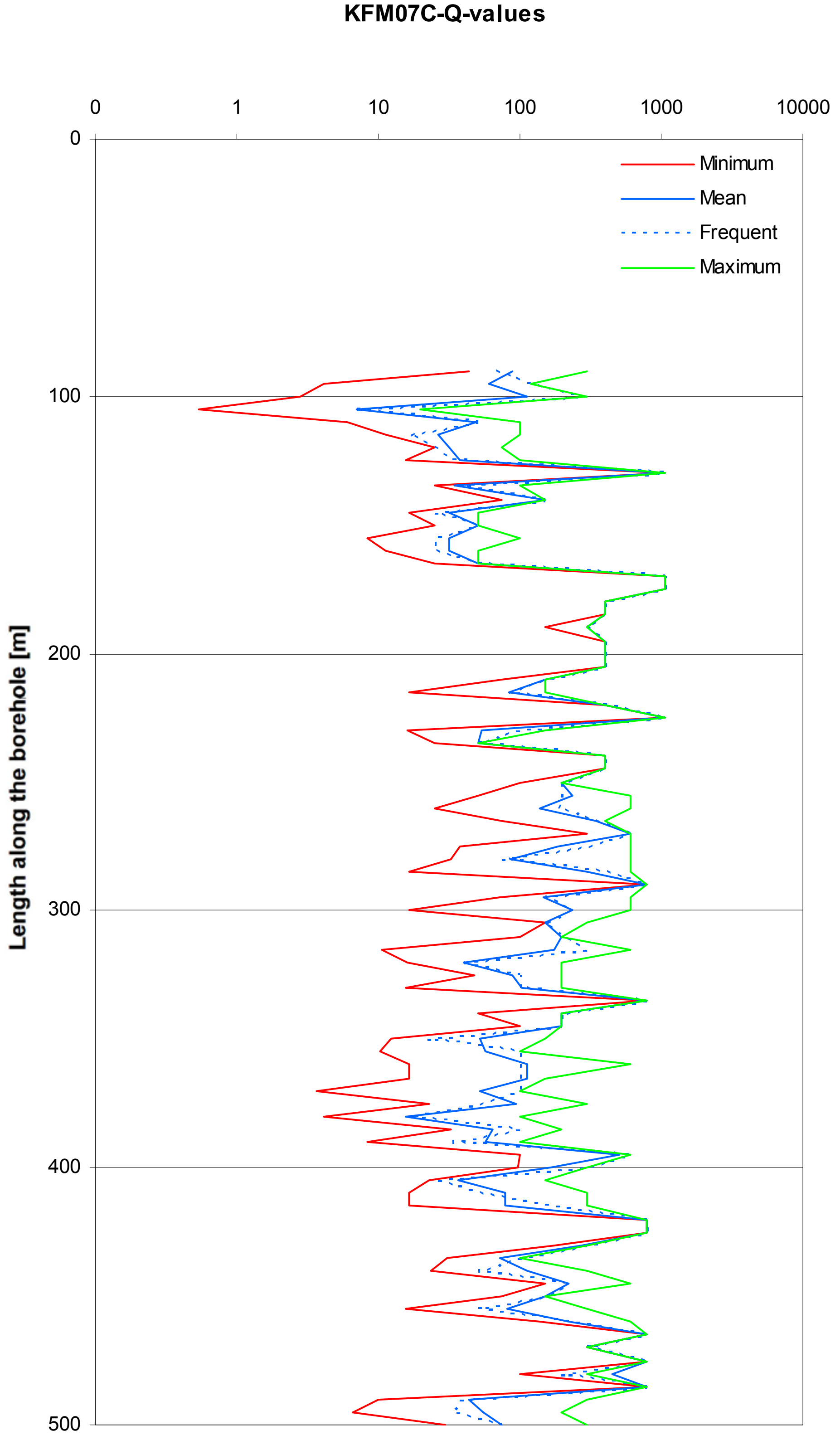


2.3 Q

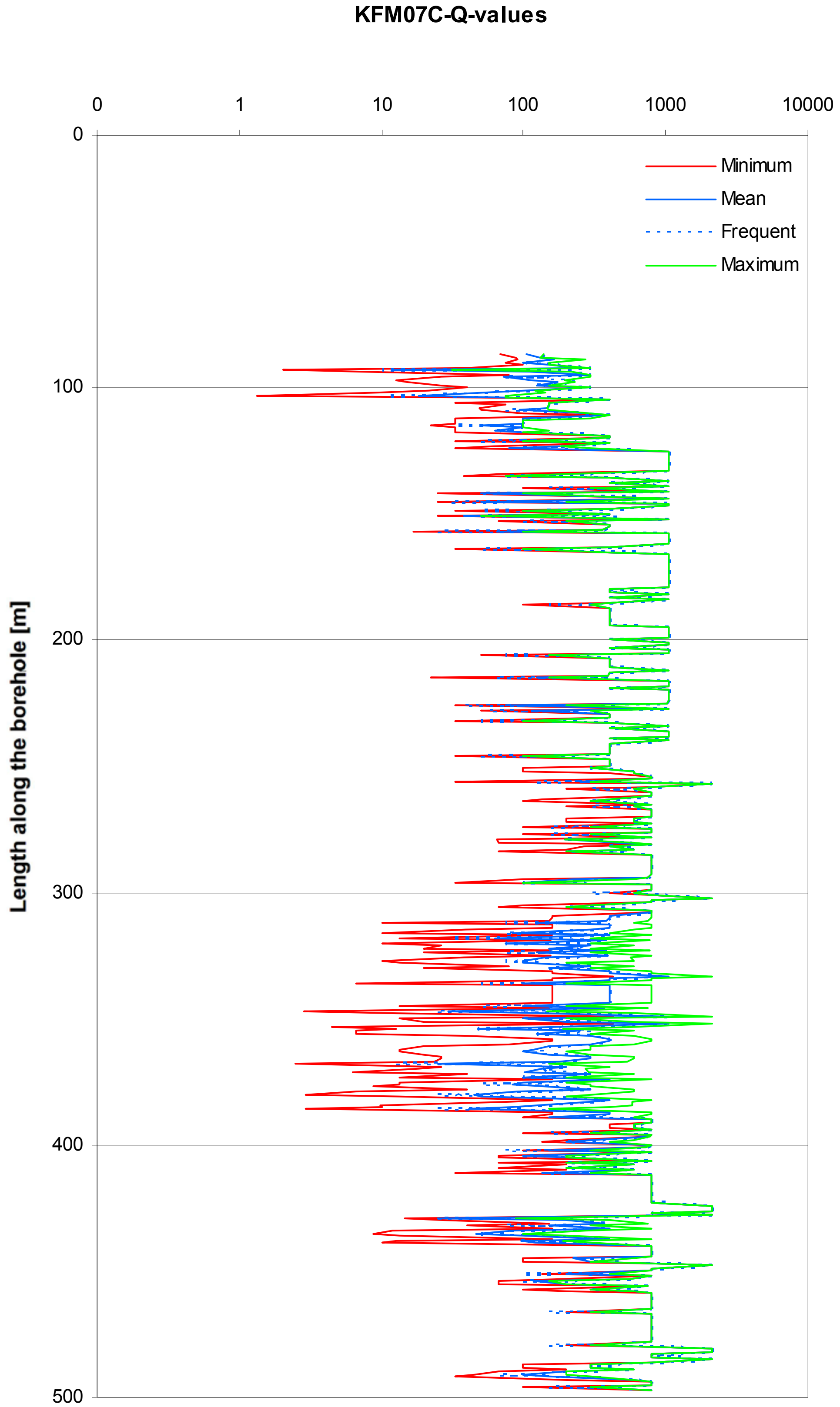
Q values along borehole KFM07C (core sections of 5 m).

Rock unit length along borehole [m]	Minimum Q	Average Q	Frequent Q	Maximum Q	Standard deviation	Min possible Q	Max possible Q
RU1, 85–90	88.8	88.8	88.8	88.8	–	44	300
DZ1, 90–105	7.1	60.4	60.4	113.6	53.2	0.54	300
RU1, 105–125	26.7	36.5	34.7	49.8	9.9	6.13	100
RU2, 125–310	31.3	327.3	233.3	1066.7	313.2	8.3	1066.7
DZ2, 310–390	15.8	139.1	92	800	184.7	3.7	800
RU2, 390–430	36.8	342.2	220.4	800	318.6	16.7	800
DZ3, 430–440	71.7	92.8	92.8	113.9	29.8	23.8	300
RU2, 440–500	43.8	333.4	223	800	304.1	6.7	800
Rock mass	26.7	307.8	200	1066.7	303.9	6.1	1066.7
Deformation zones	7.1	123.4	90.2	800	163.7	0.5	800
Whole borehole	7.1	261.1	150	1066.7	285.9	0.5	1066.7

Variation of Q along borehole KFM07C. The values are given every 5 m.



Variation of Q along borehole KFM07C. The values are given every 1 m.



Rock mass properties

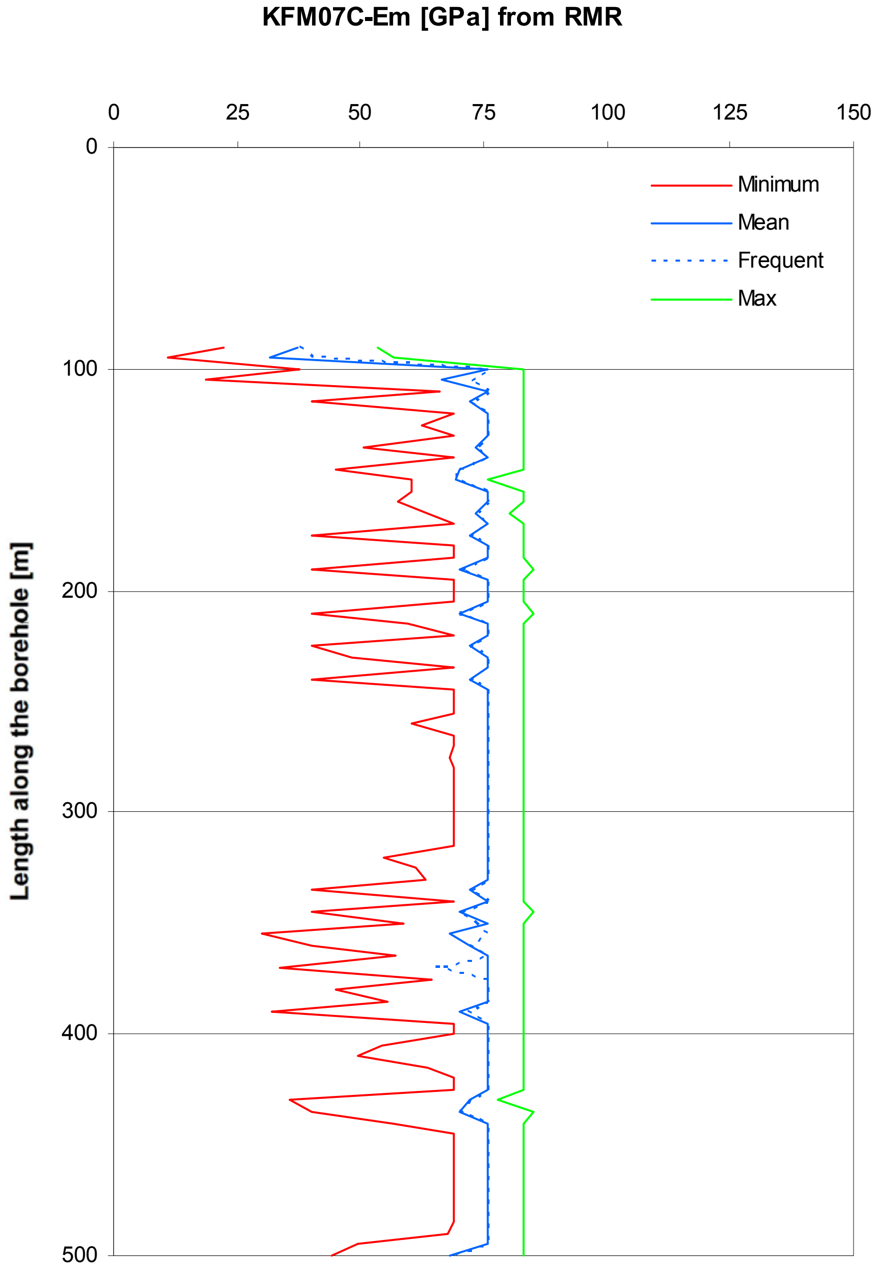
2.4 Deformation modulus

2.4.1 RMR

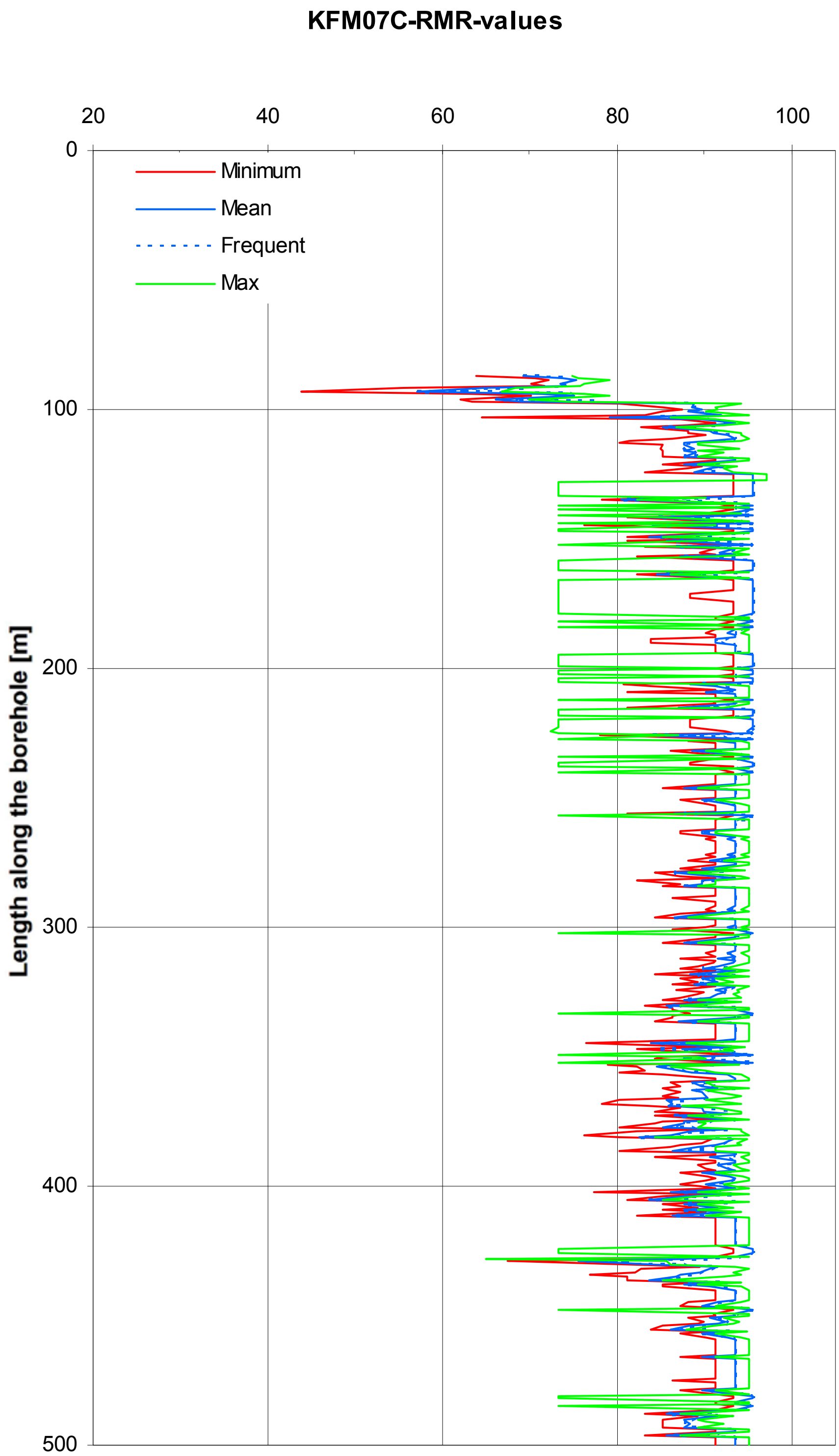
Deformation modulus Em derived from RMR along for borehole KFM07C (core sections of 5 m).

Rock unit length along borehole [m]	Minimum EmRMR [GPa]	Average EmRMR [GPa]	Frequent EmRMR [GPa]	Maximum EmRMR [GPa]	Standard deviation [GPa]	Min possible EmRMR [GPa]	Max possible EmRMR [GPa]
RU1, 85–90	37.2	37.2	37.2	37.2	–	22.1	53.7
DZ1, 90–105	31.6	58	66.5	76	23.4	10.8	83
RU1, 105–125	72	75	76	76	2	40	83
RU2, 125–310	69.2	74.9	76	76	2.2	40	85
DZ2, 310–390	68.2	74.3	76	76	2.8	29.9	85
RU2, 390–430	72	75.5	76	76	1.4	35.5	83
DZ3, 430–440	70	73	73	76	4.2	40	85
RU2, 440–500	68	75.3	76	76	2.3	44.2	83
Rock mass	37.2	74.4	76	76	5.2	21.1	85
Deformation zones	31.6	71.8	76	76	9.7	10.8	85
Whole borehole	31.6	73.8	76	76	6.7	10.8	85

Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM07C. The values are given every 5 m.

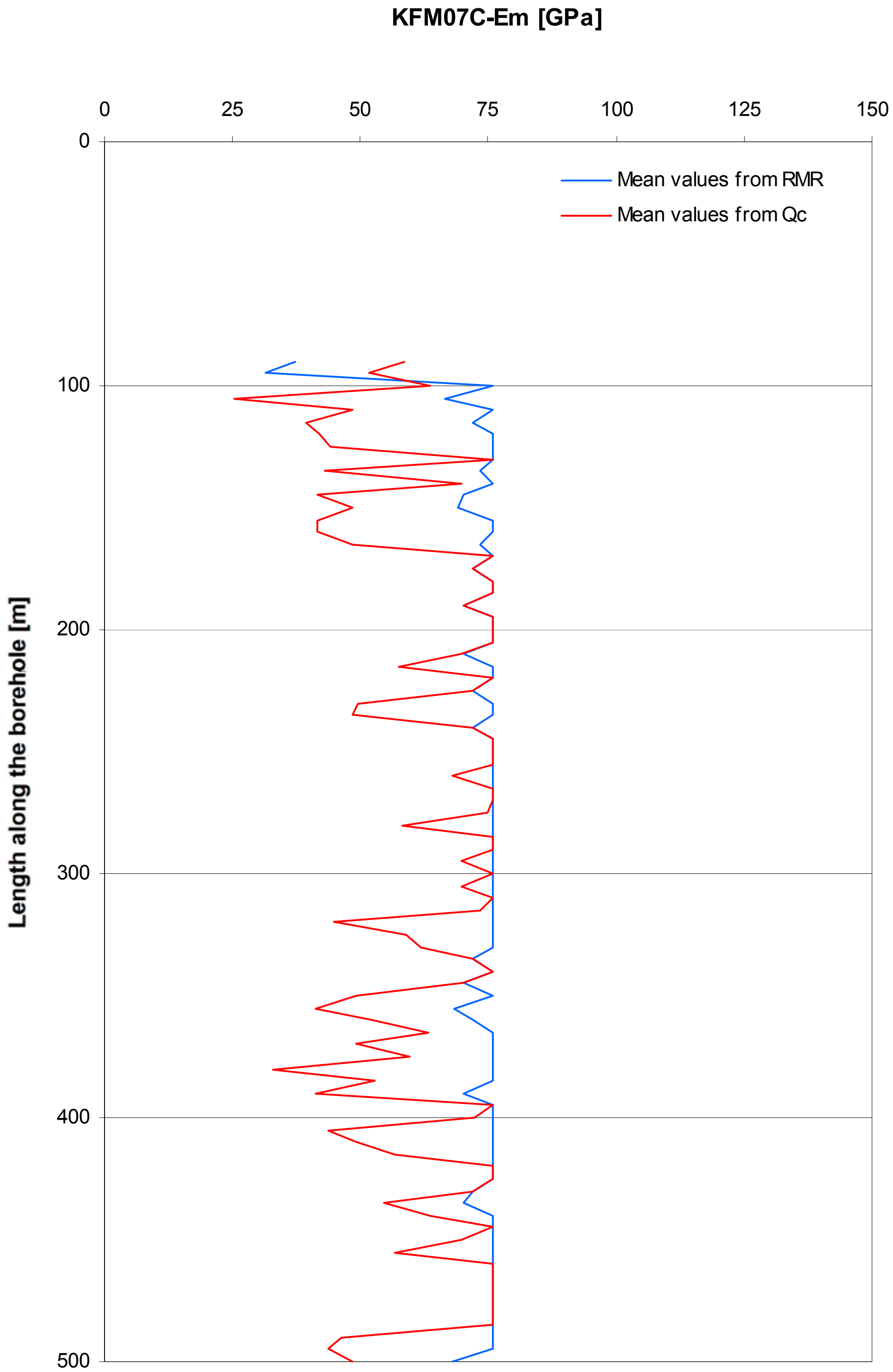


Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM07C. The values are given every 1 m.

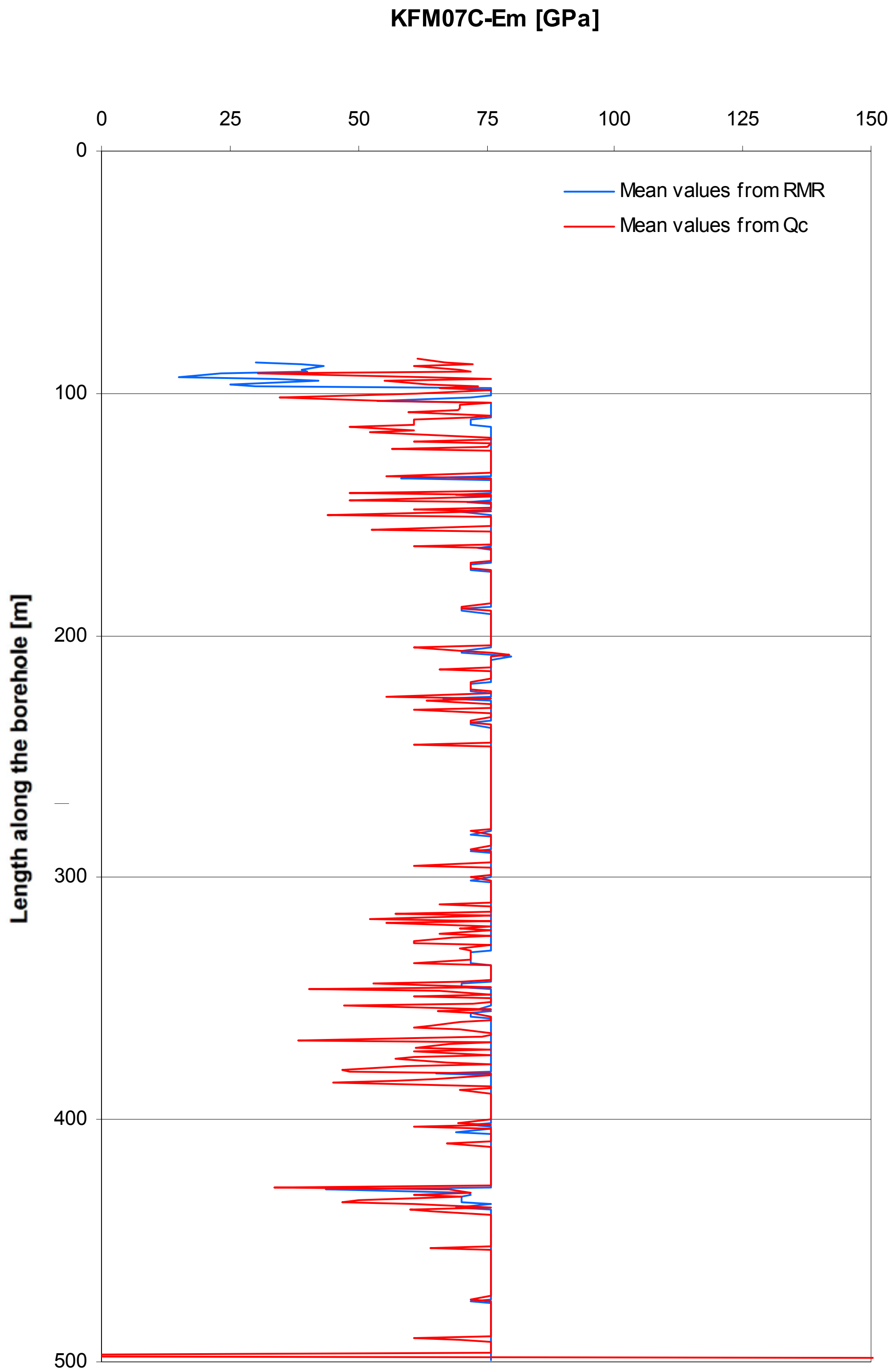


2.4.2 Comparison

Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM07C. The values are given every 5 m.

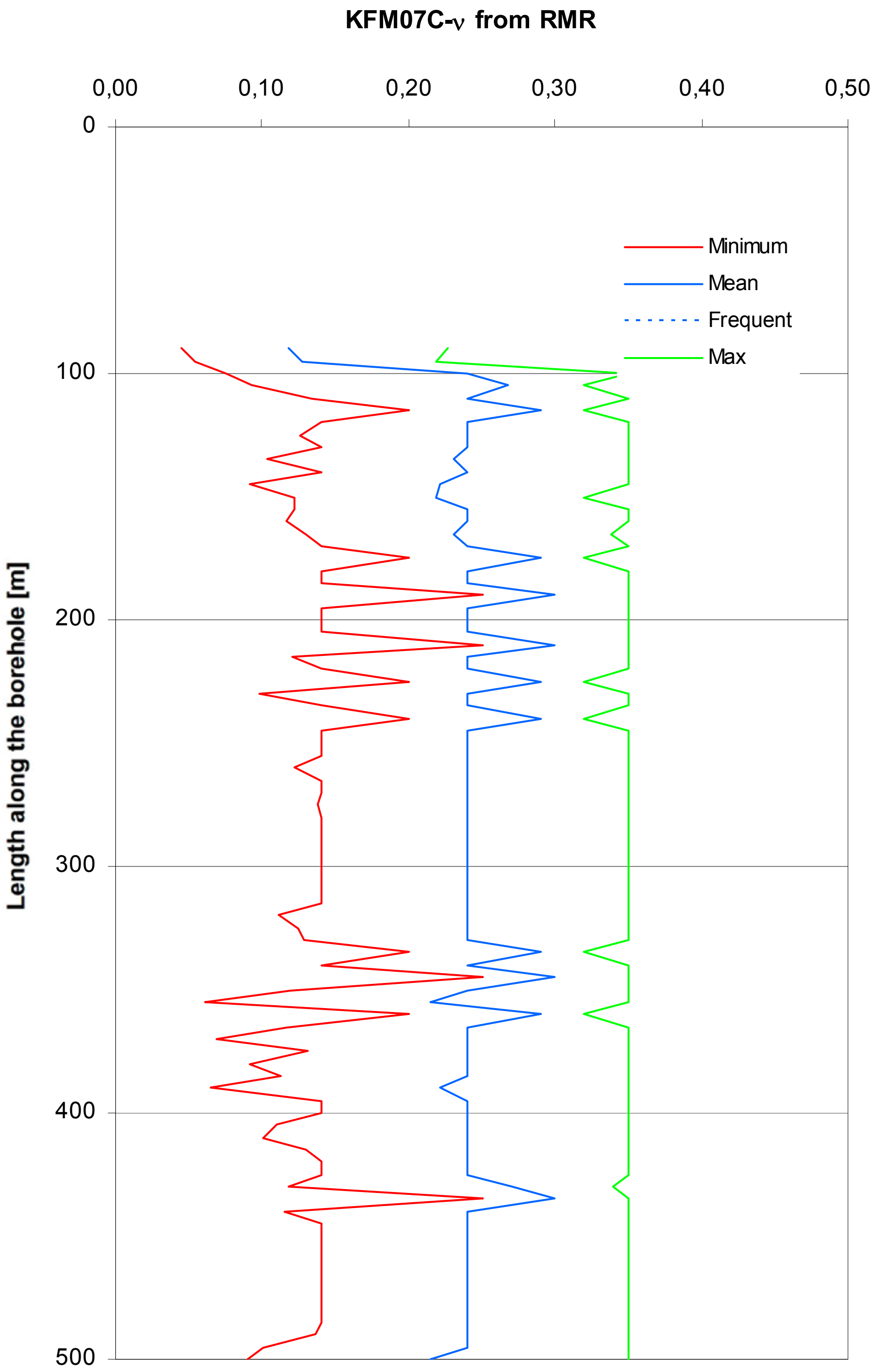


Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM07C. The values are given every 1 m.

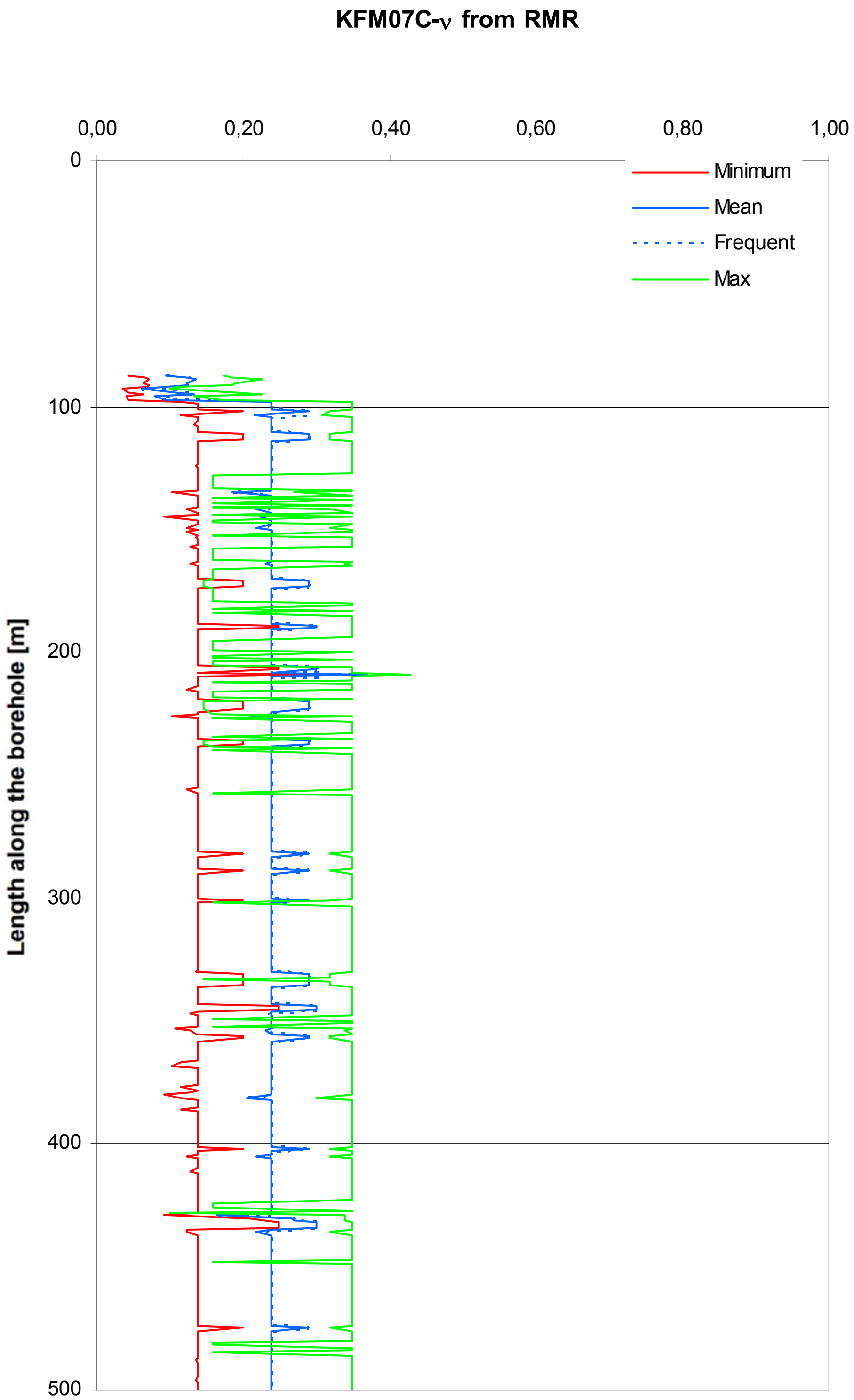


2.5 Poisson's ratio

Variation of Poisson's ratio (ν) with depth for borehole KFM07C (Hoek & Brown's a=0.5). The values are given every 5 m.



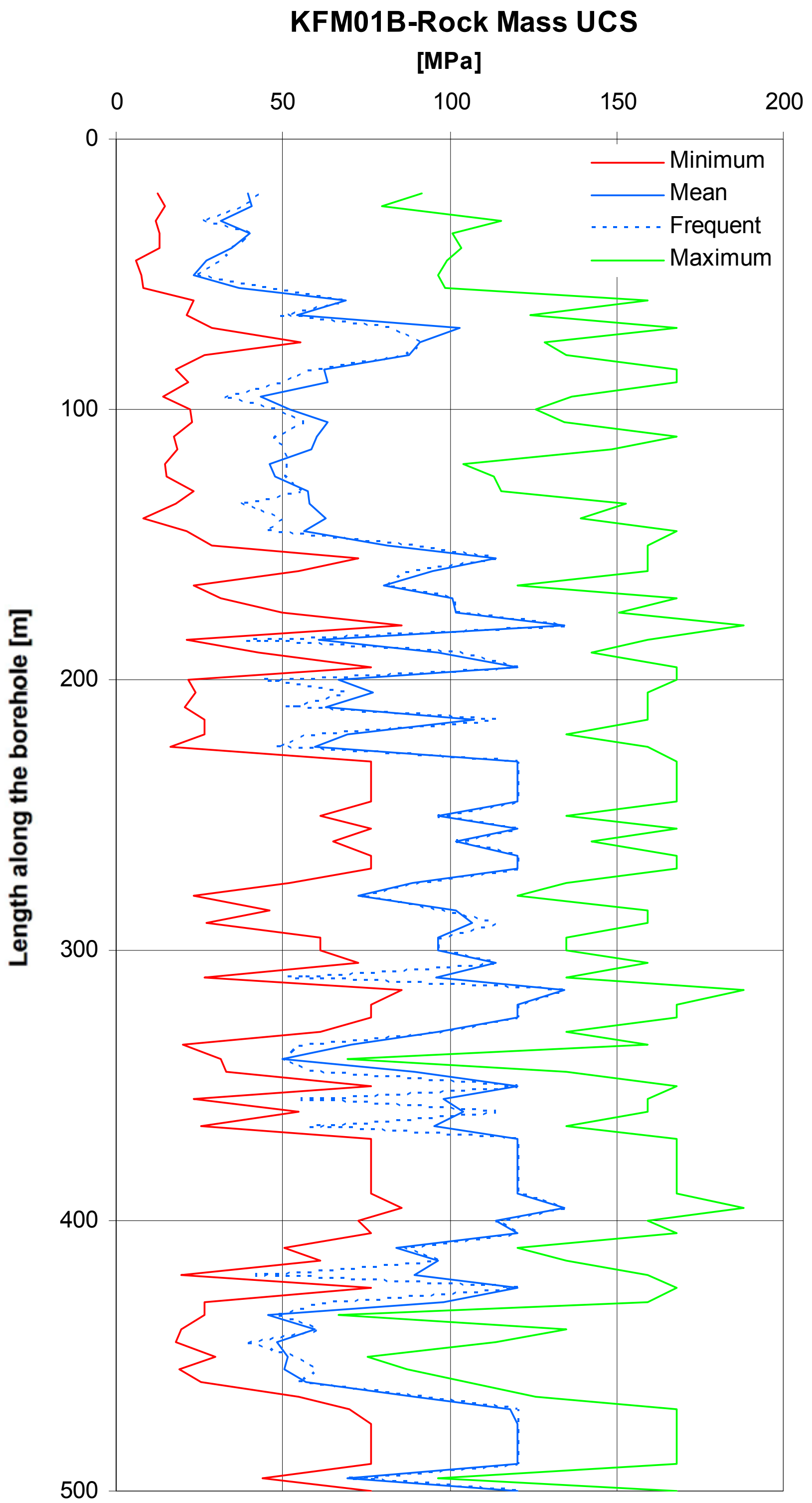
Variation of Poisson's ratio (ν) along borehole KFM07C (Hoek & Brown's a=0.5). The values are given every 1 m.



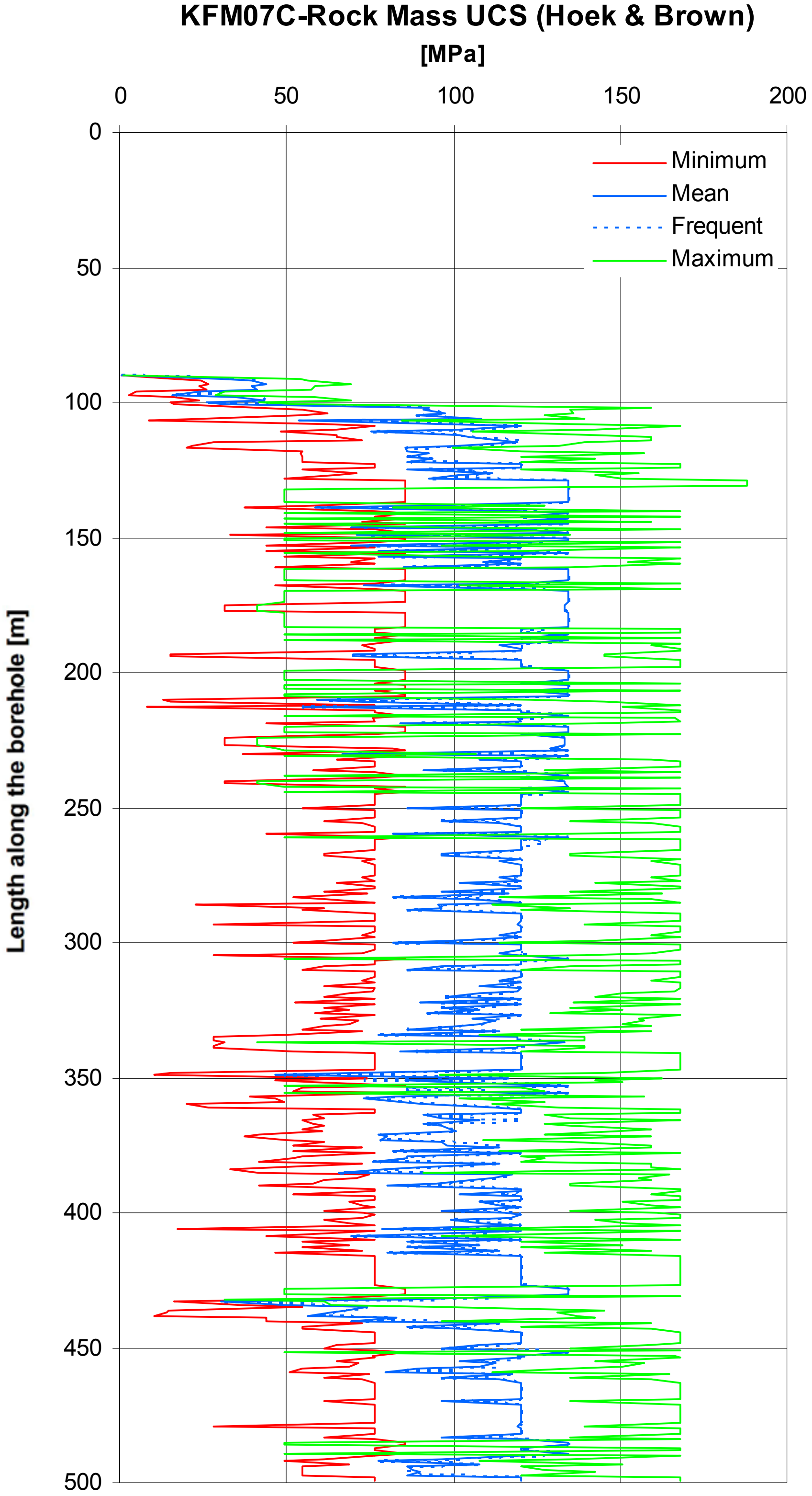
2.6 Uniaxial compressive strength

2.6.1 RMR

Variation of the uniaxial compressive strength of the rock mass along borehole KFM07C (Hoek & Brown's a=0.5). The values are given every 5 m.



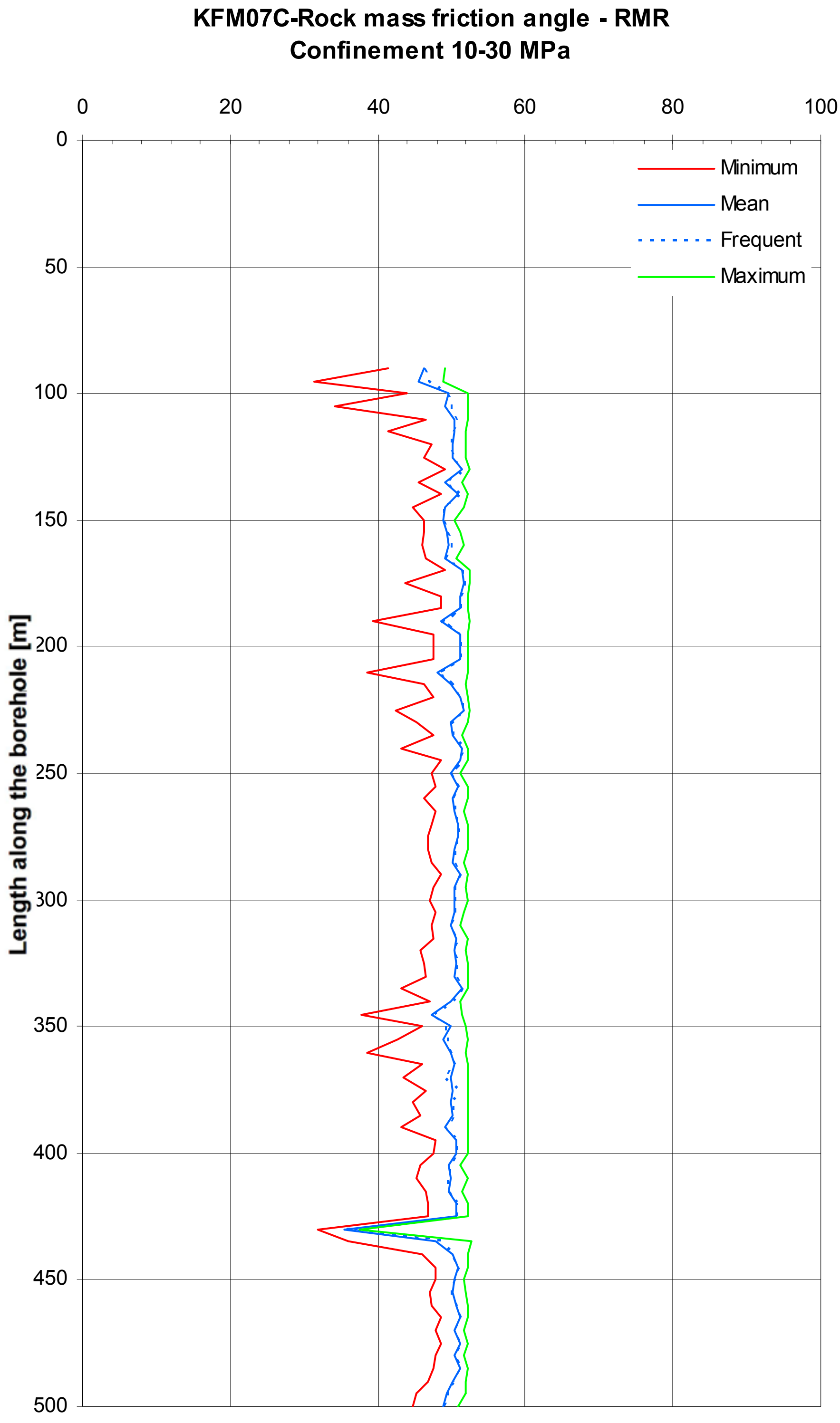
Variation of the uniaxial compressive strength of the rock mass along borehole KFM07C (Hoek & Brown's a=0.5). The values are given every 1 m.



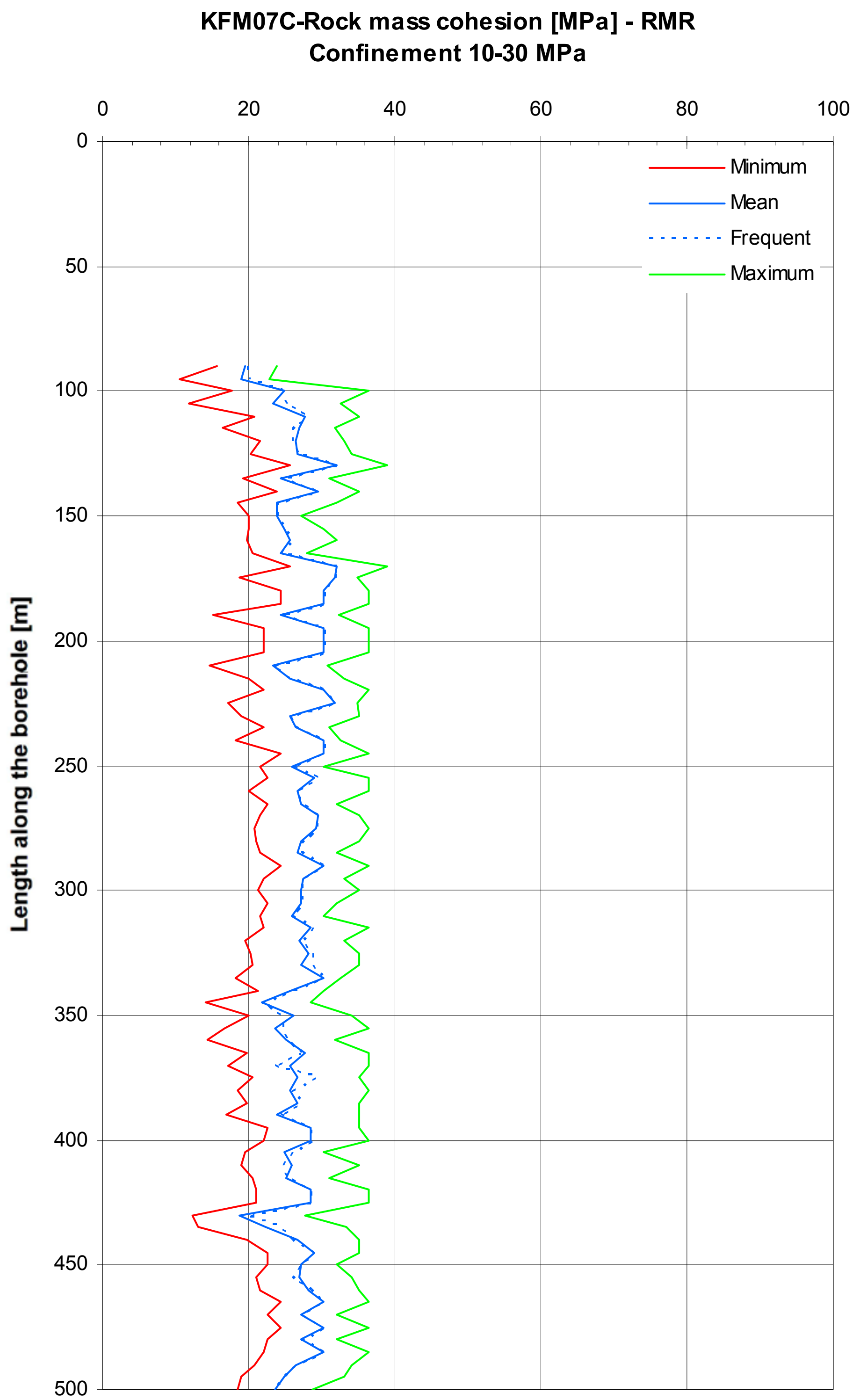
2.7 Friction angle and cohesion and of the rock mass

2.7.1 RMR

Variation of the rock mass friction angle ϕ' from RMR along borehole KFM07C under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Variation of the rock mass cohesion c' from RMR along borehole KFM07C under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Appendix 3

KFM09A – Characterisation of the rock mass

3.1 Fracture orientation

Set identification from the fracture orientation mapped for borehole KFM09A (Sicada data delivery – 06_134_1). The orientations are given as strike/dip (right-hand rule).

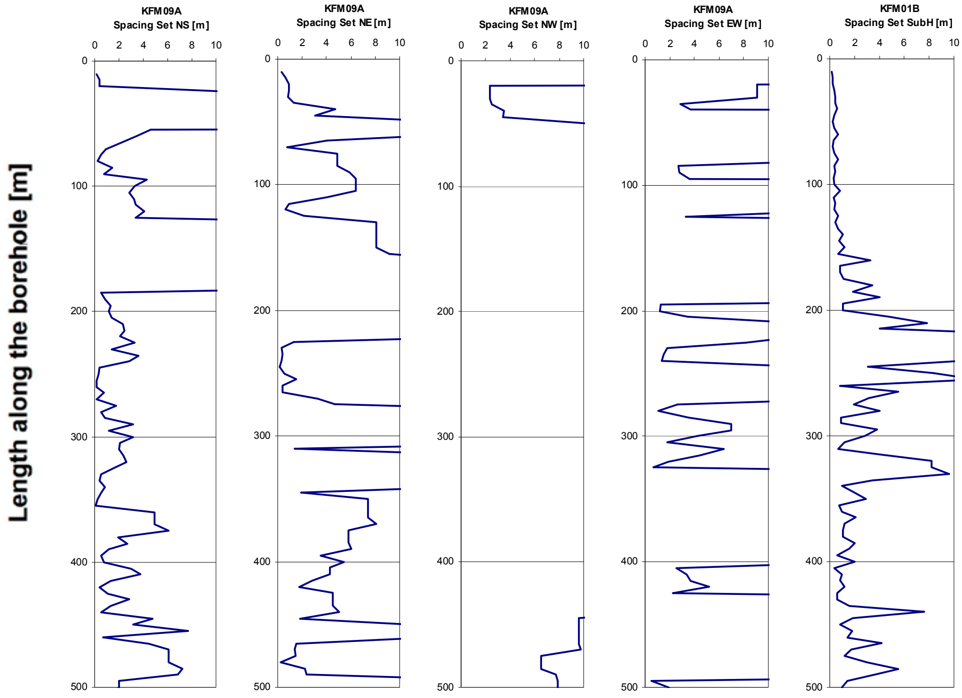
Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
8–15	39	348/88	240/75			110/14
15–40	71	159/83	248/88	119/84	298/84	080/07
40–52	37		256/88	111/89		067/13
52–86	98	167/89	238/81		309/77	095/13
86–116	80	334/83	252/77			064/06
116–124	20	336/85	242/54		298/79	065/07
124–217	77	338/81	221/75		303/79	069/14
217–242	50	358/89	235/81	135/87	306/78	289/10
242–280	92	341/89	234/88		306/79	216/05
280–440	214	155/88	237/85	132/82	304/78	122/04
440–512	88	326/86	243/88	135/82	311/79	287/04
512–522	8	175/89	237/80		302/89	358/13
522–641	80	335/90	240/81	120/79	298/84	130/09
641–723	69	152/85	227/81	137/75	274/87	190/10
723–758	100	147/84	232/87	133/78	300/79	299/08
758–800	66	149/86	229/84	133/84	312/79	226/11

Fisher's constant of the fracture sets identified for borehole KFM09A (Sicada data delivery – 06_134_1).

Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
8–15	39	36.5	17.0			63.8
15–40	71	77.9	64.2	54.0	1460.7	34.4
40–52	37		3285.8	10000*		54.0
52–86	98	51.2	8.2		21.3	48.2
86–116	80	22.9	12.6		10000*	26.2
116–124	20	184.3	48.0		51.7	28.7
124–217	77	34.3	44.0		21.7	67.0
217–242	50	10.6	11.2	10000*	34.7	12.9
242–280	92	23.4	11.2		45.3	21.7
280–440	214	53.3	8.7	55.0	19.2	63.4
440–512	88	38.5	15.6	2665.6	28.1	33.2
512–522	8	5.8	7.3		10000*	27.3
522–641	80	37.8	14.0	40.0	27.4	39.6
641–723	69	39.7	11.3	169.5	10000*	18.7
723–758	100	85.6	9.0	55.0	16.5	17.1
758–800	66	48.5	7.7	61.0	18.7	18.7

* Derived from one fracture.

Fracture spacing for the seven facture sets along the borehole KFM09A. The values are averaged for each 5 m length of borehole.

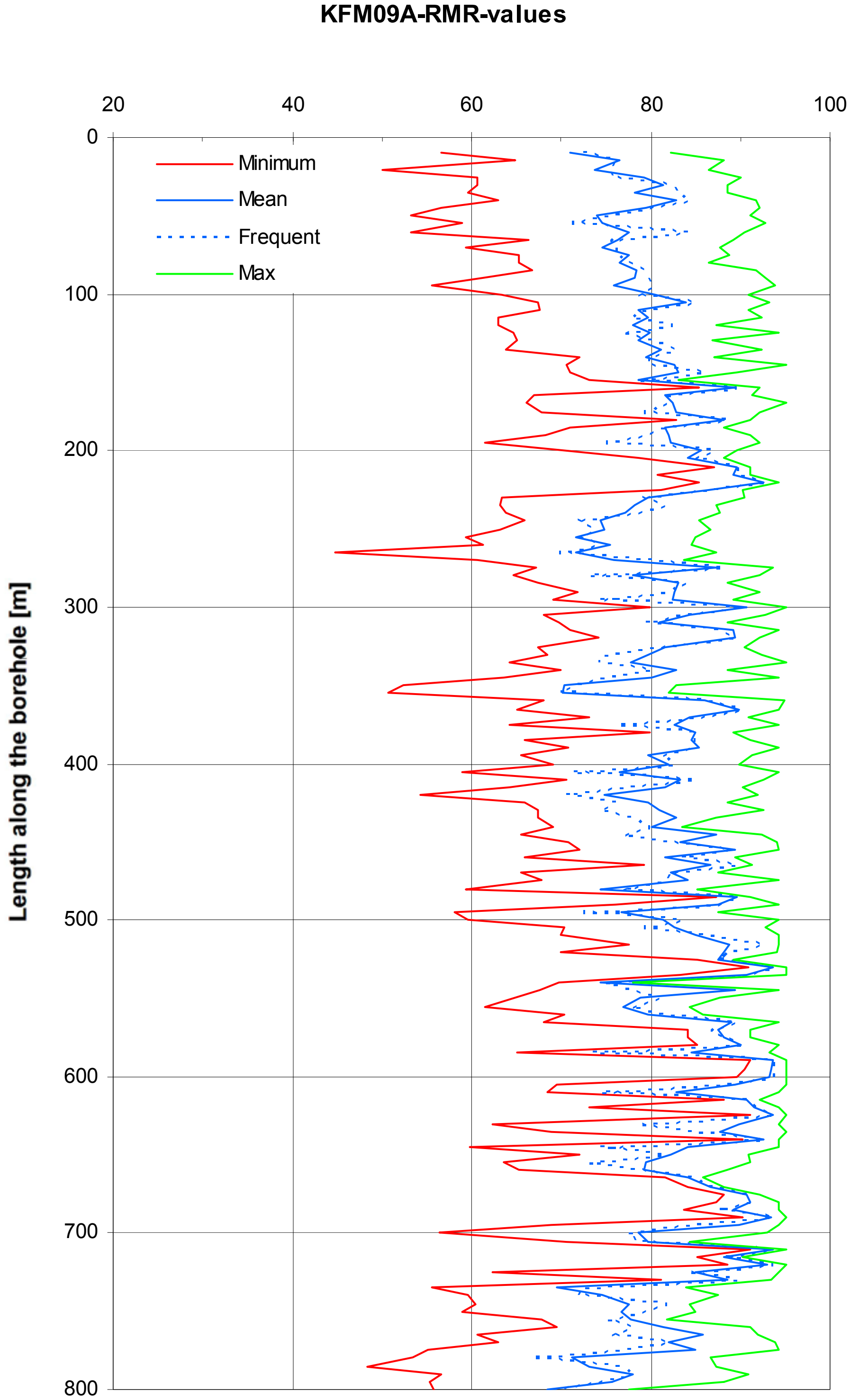


3.2 RMR

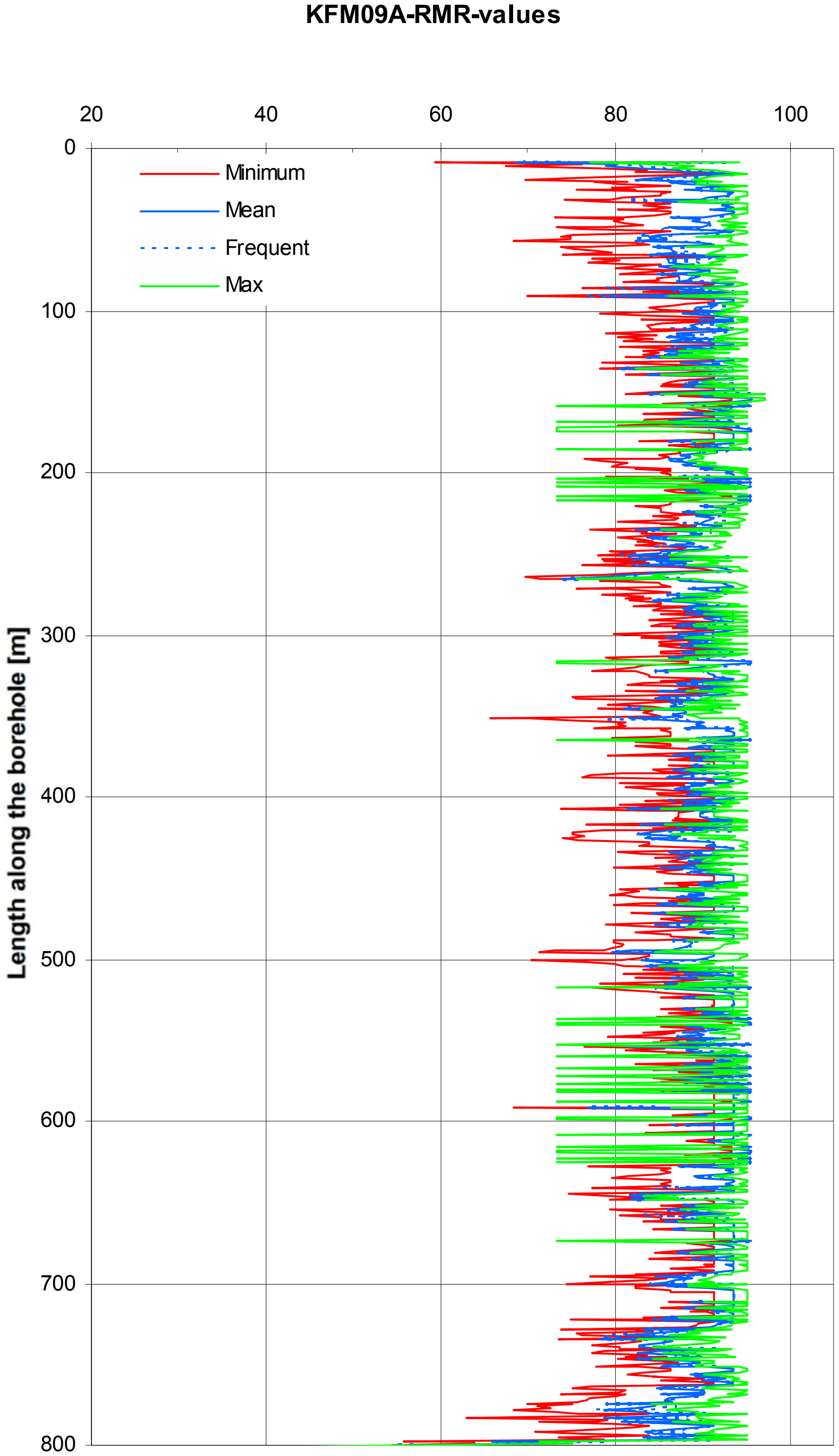
RMR values along borehole KFM09A (core sections of 5 m).

Rock unit length along the borehole [m]	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
8–15	71	73.8	73.8	76.5	3.9	56.53	88.2
15–40	73.7	79	79.2	82.8	3.5	50.09	91.8
40–55	74	76.1	74.6	79.6	3.0	53.29	92.8
55–90	74.6	76.9	77.1	78.4	1.3	53.3	91.8
90–120	75.9	79.4	79.2	84	2.4	55.5	94.2
120–125	79.9	79.9	79.9	79.9	–	64.7	94.2
125–215	78.6	83.5	82.5	89.6	3.6	61.5	95.2
215–280	71.5	78.7	77.1	92.6	6.4	44.8	94.2
280–440	70.1	81	81.6	90.7	5.3	44.8	95.2
440–515	74.4	84	84.1	89.6	4.5	58	94.4
515–525	87.6	87.8	87.8	88.1	0.3	69.8	94.1
525–645	74.4	87.7	89.4	93.6	5.6	59.7	95.2
645–725	78.6	86.5	87.4	93.6	5.4	56.5	95.2
725–755	69.6	77.4	77.1	88.5	6.2	55.5	93.4
755–760	81.3	81.3	81.3	81.3	–	69.6	91
760–800	68.5	77.4	76.8	85.8	6.4	48.3	94.2
Rock mass	68.5	83.3	82.9	93.6	5.8	48.3	95.2
Deformation zones	69.6	78.7	78	92.6	5.25	44.8	94.2
Whole borehole	68.5	82.4	82.2	93.6	6	44.8	95.2

Variation of RMR along borehole KFM09A. The values are given every 5 m.



Variation of RMR along borehole KFM09A. The values are given every 1 m.

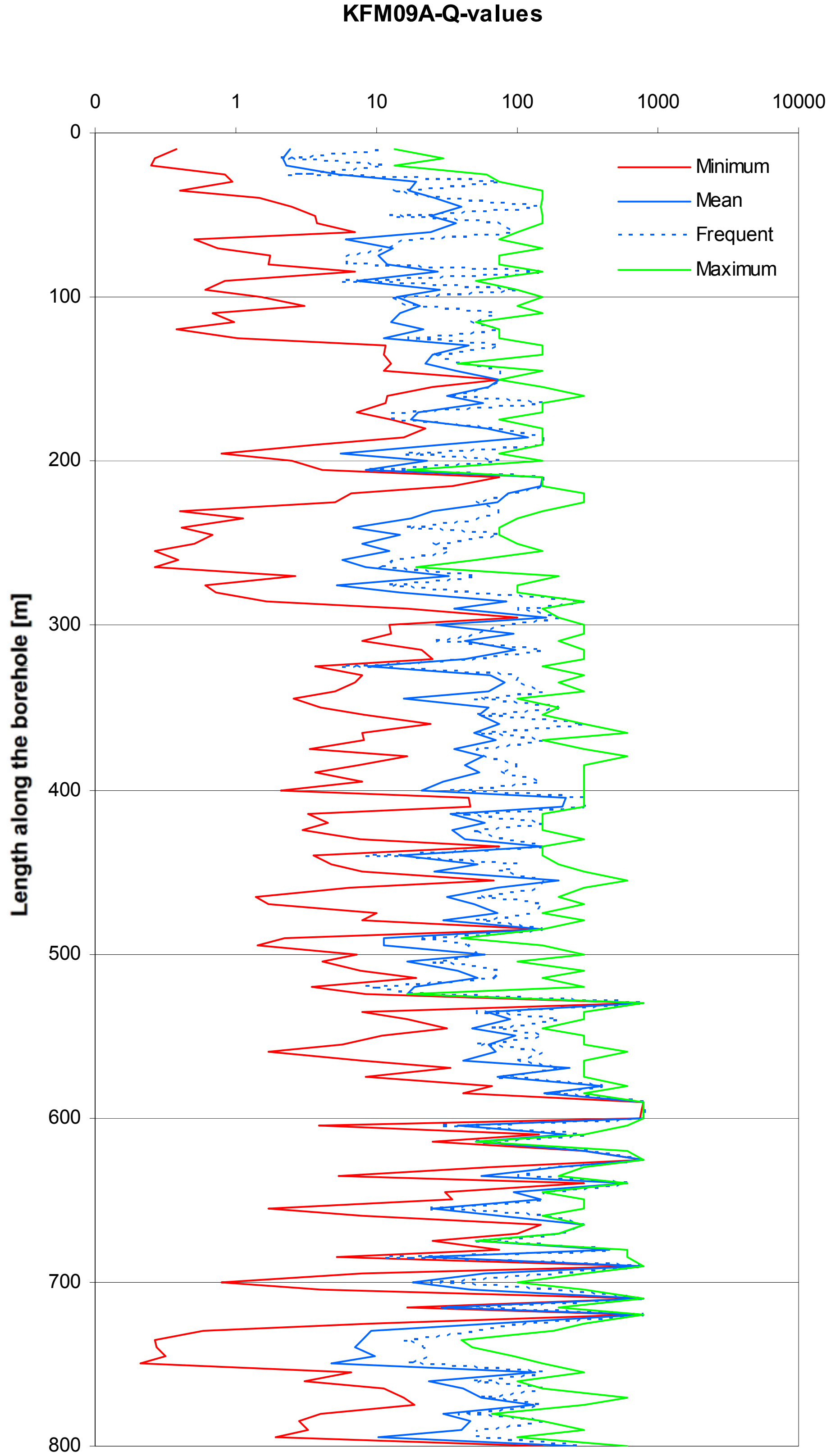


3.3 Q

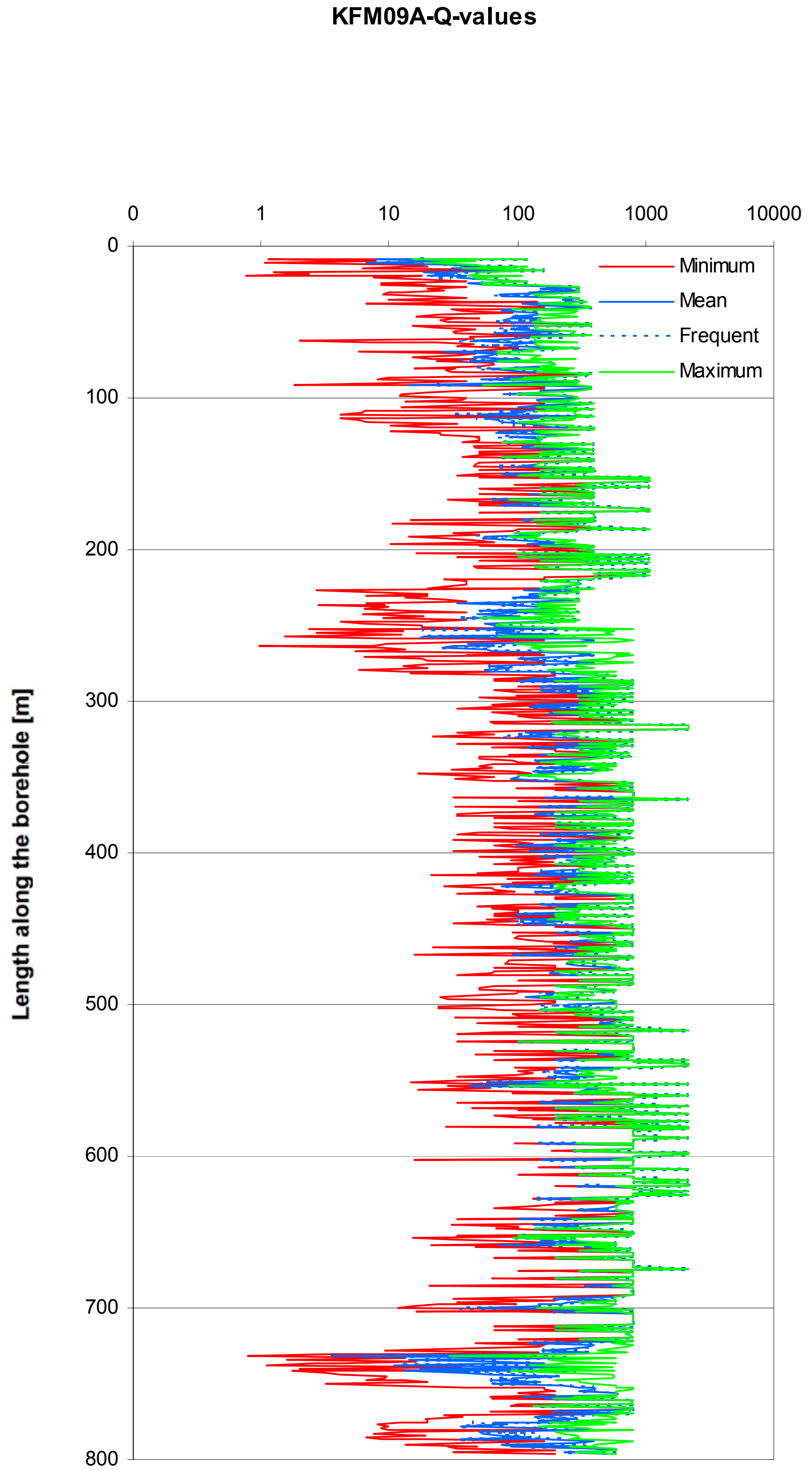
Q values along borehole KFM09A (core sections of 5 m).

Rock unit length along borehole [m]	Minimum Q	Average Q	Frequent Q	Maximum Q	Standard deviation	Min possible Q	Max possible Q
8–15	2.2	2.3	2.3	2.4	0.2	0.26	30
15–40	2.3	13.9	17.1	25.7	9.8	0.25	150
40–55	24.5	33.7	36.5	40.1	8.2	2.53	150
55–90	6	14.3	11.8	27.5	8.3	0.5	150
90–120	12.8	18.6	17.3	28.5	6	0.4	150
120–125	11.4	11.4	11.4	11.4	–	1	75
125–215	5.5	52	34.1	149.7	44.6	0.8	300
215–280	5.2	23.8	14.7	85.7	26.1	0.3	300
280–440	5.2	56.8	42.9	222	51.5	0.3	600
440–515	11.3	58	49.3	196.8	51.6	1.4	600
515–525	16.7	17.7	17.7	18.7	1.5	3.4	300
525–645	37.9	286	126.9	800	297.4	1.7	800
645–725	17.9	240.7	70.9	800	295.7	0.8	800
725–755	4.8	28.9	8.5	135	52	0.2	300
755–760	23.8	23.8	23.8	23.8	–	3	100
760–800	10.2	76.4	43.9	257.1	81.2	1.9	600
Rock mass	2.2	120.5	50	800	194.8	0.3	800
Deformation zones	2.3	22.1	4.2	135	28.1	0.2	300
Whole borehole	2.2	101.9	41.5	800	180	0.21	800

Variation of Q along borehole KFM09A. The values are given every 5 m.



Variation of Q along borehole KFM09A. The values are given every 1 m.



Rock mass properties

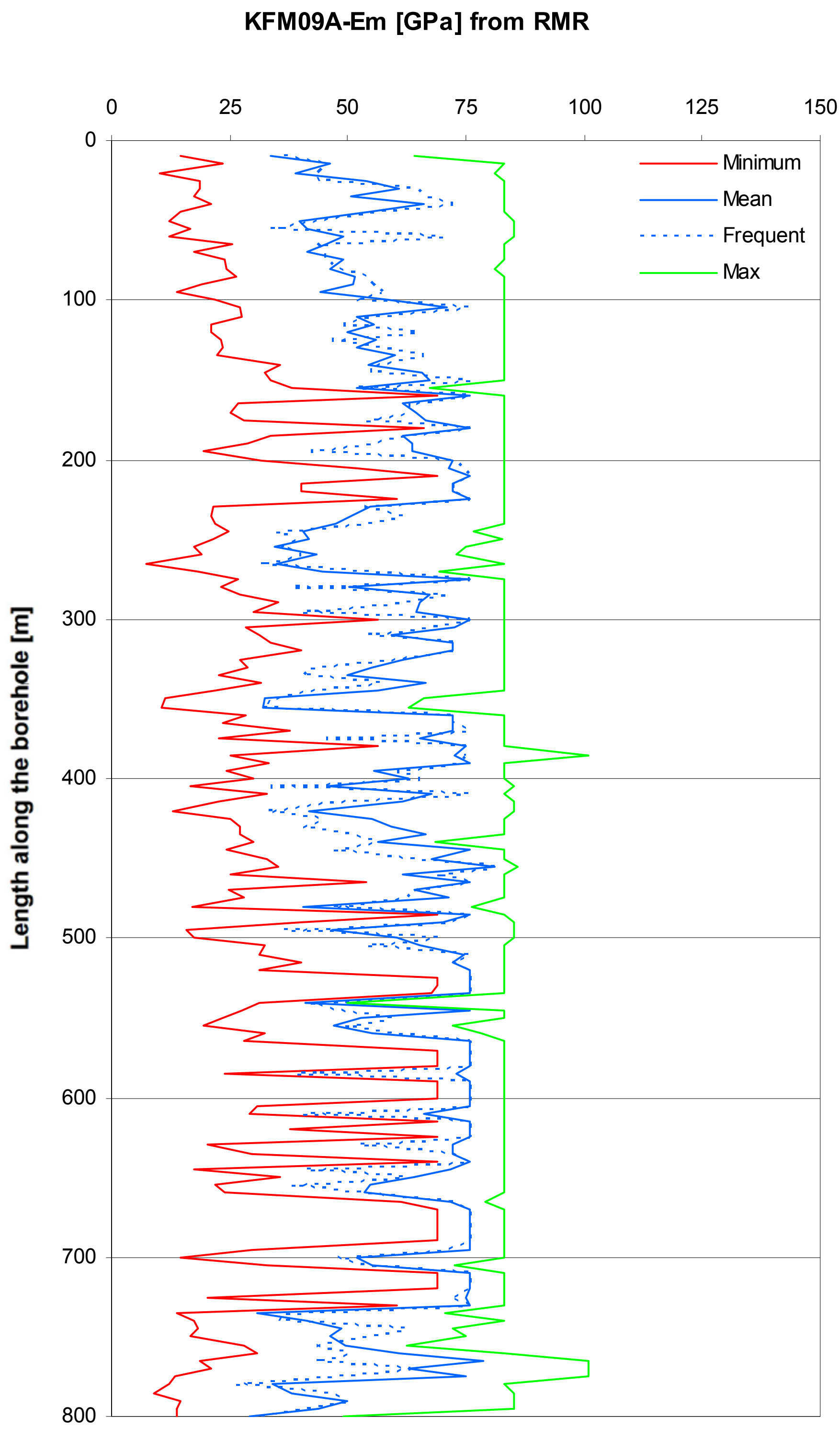
3.4 Deformation modulus

3.4.1 RMR

Deformation modulus Em derived from RMR along borehole KFM09A (core sections of 5 m).

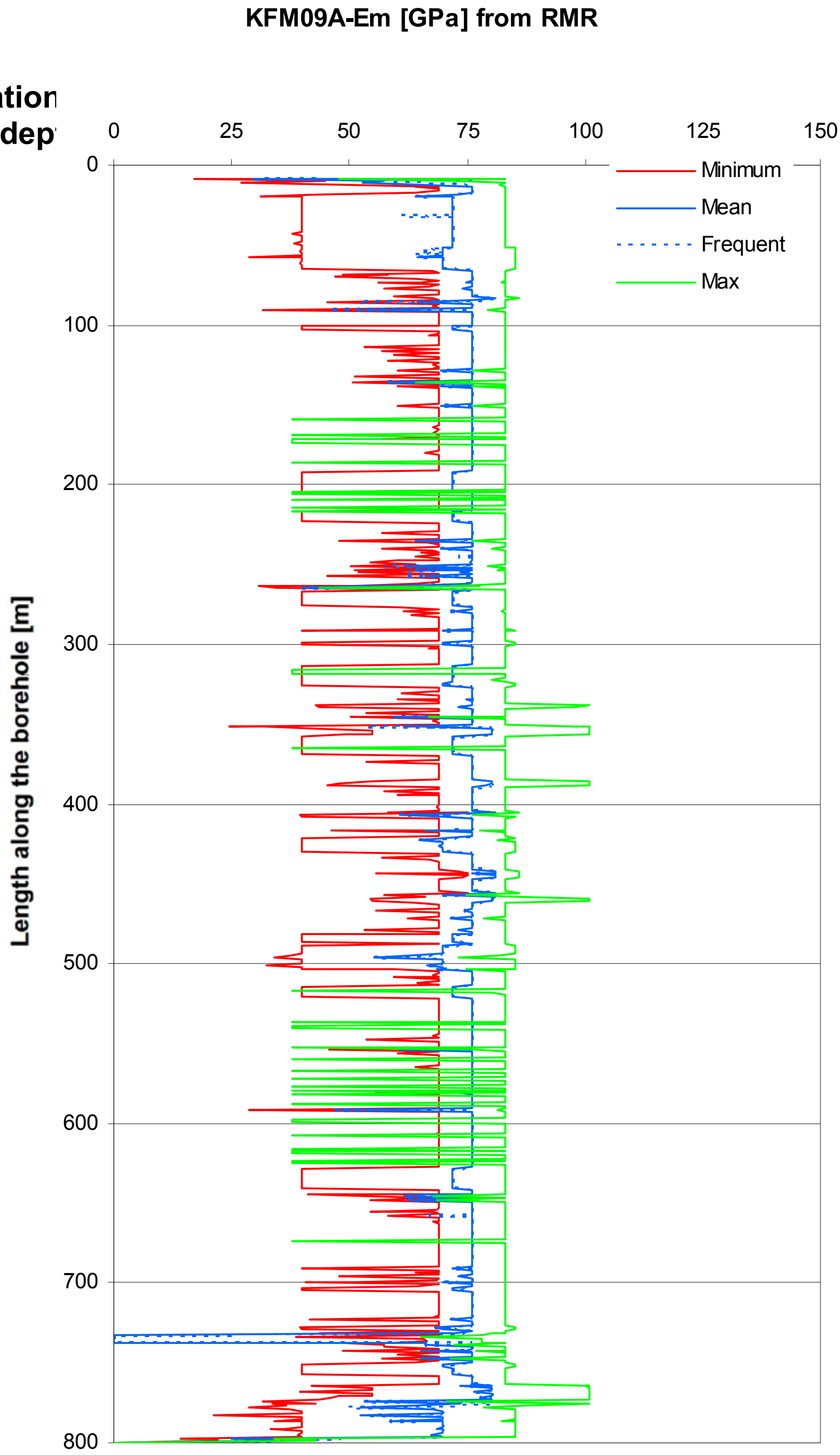
Rock unit length along borehole [m]	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation [GPa]	Min possible Em [GPa]	Max possible Em [GPa]
8–15	33.6	39.8	39.8	46.1	8.8	14.56	83
15–40	39	54	33.8	65.9	10.3	10.05	83
40–55	39.9	45.3	53.8	65.9	8.3	12.08	85
55–90	41.3	47.1	47.6	51.3	3.5	12.1	85
90–120	44.3	54.7	53.8	70.8	7.8	13.7	83
120–125	56.1	56.1	56.1	56.1	–	23.3	83
125–215	51.8	65.3	65	76	7.7	19.4	83
215–280	34.6	51.3	47.5	76	14.8	7.4	83
280–440	31.8	59.1	61.7	76	13.4	7.4	101
440–515	40.6	66.9	70	81	11.1	15.8	86
515–525	76	76	76	76	–	31.3	83
525–645	40.8	70.4	76	76	10.4	17.5	83
645–725	51.7	69.3	76	76	9.8	14.5	83
725–755	30.8	48.8	47.5	76	15	13.8	83
755–760	60.6	60.6	60.6	60.6	–	30.9	83
760–800	29	51.4	46.9	78.6	18.8	9.1	101
Rock mass	29	63.5	66.5	81	12.8	9.1	101
Deformation zones	30.8	52	50.1	76	12.7	7.4	83
Whole borehole	29	61.3	63.9	81	13.5	7.4	101

Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM09A. The values are given every 5 m.



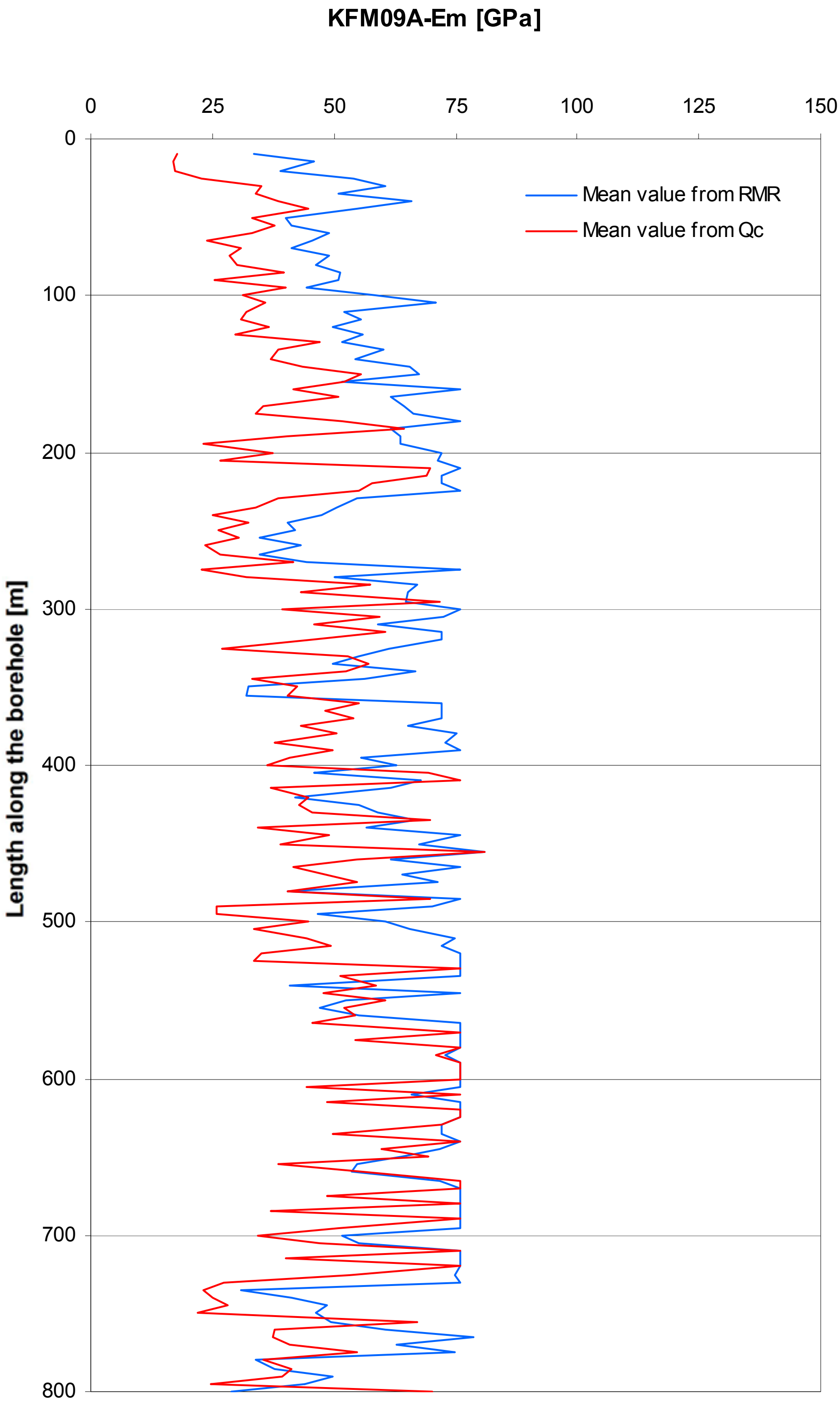
Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM09A. The values are given every 1 m.

Variation ... from Q_C
with dep...

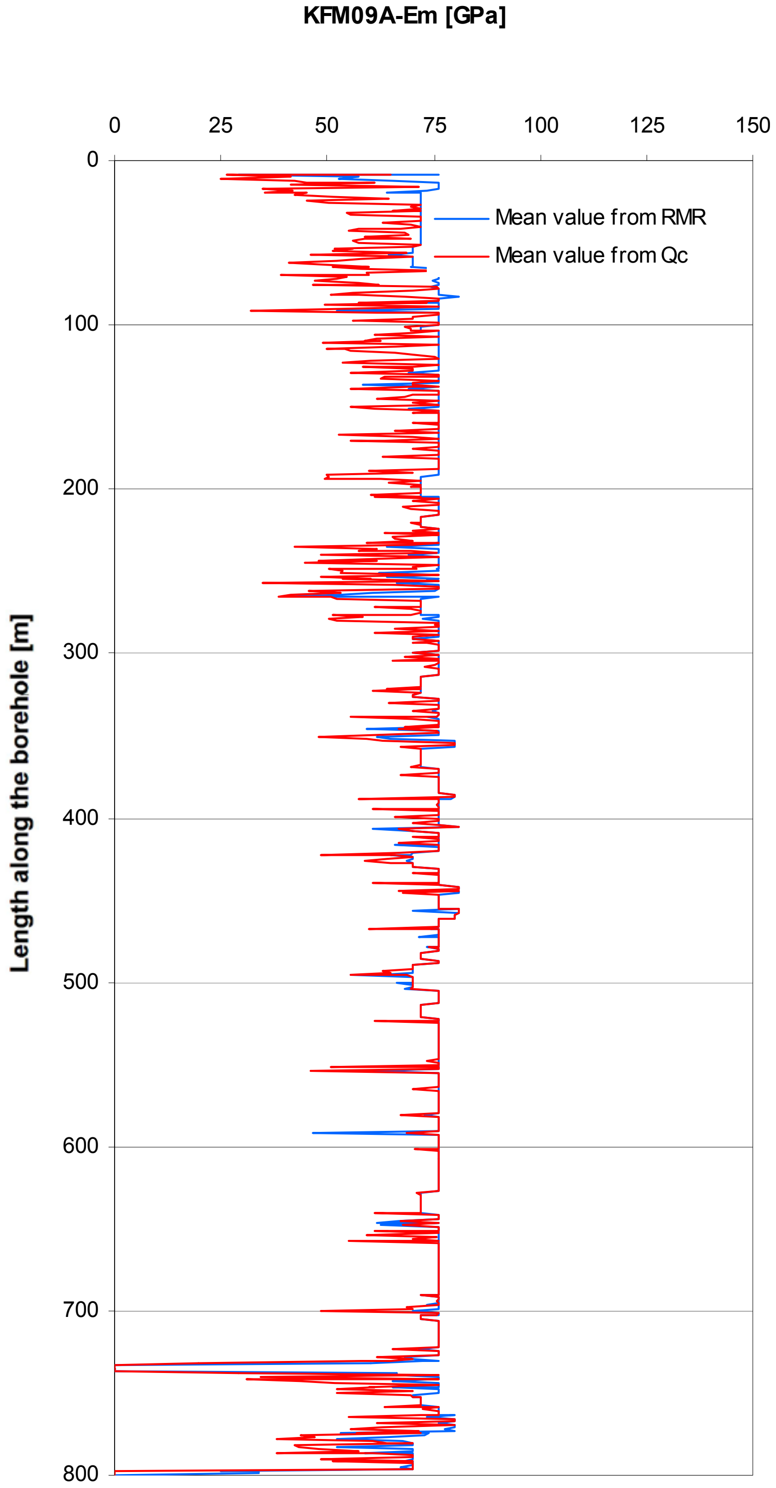


3.4.2 Comparison

Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM09A. The values are given every 5 m.



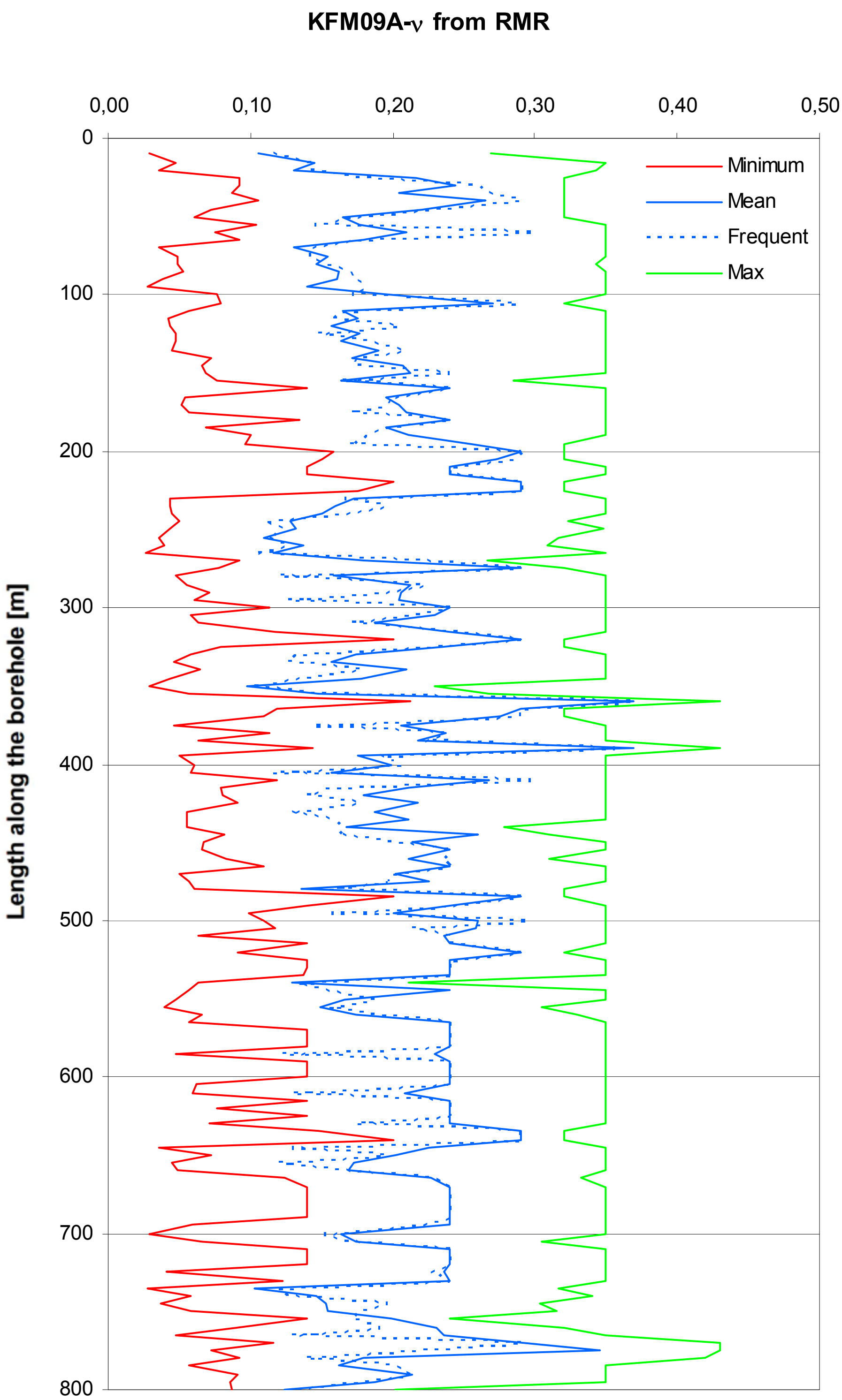
Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM09A. The values are given every 1 m.



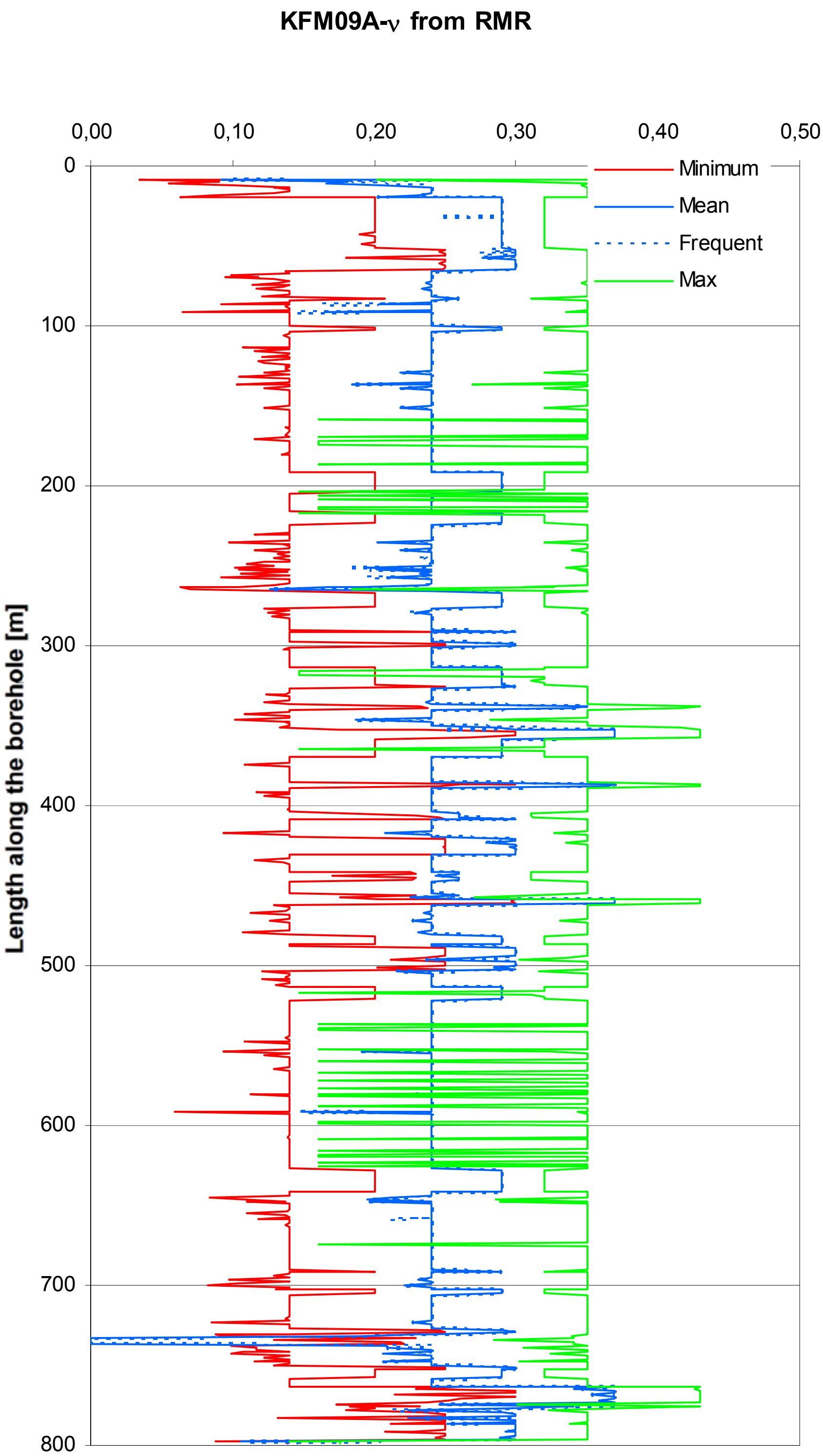
3.5 Poisson's ratio

3.5.1 RMR

Variation of Poisson's ratio (ν) along borehole KFM09A (Hoek & Brown's a=0.5). The values are given every 5 m.



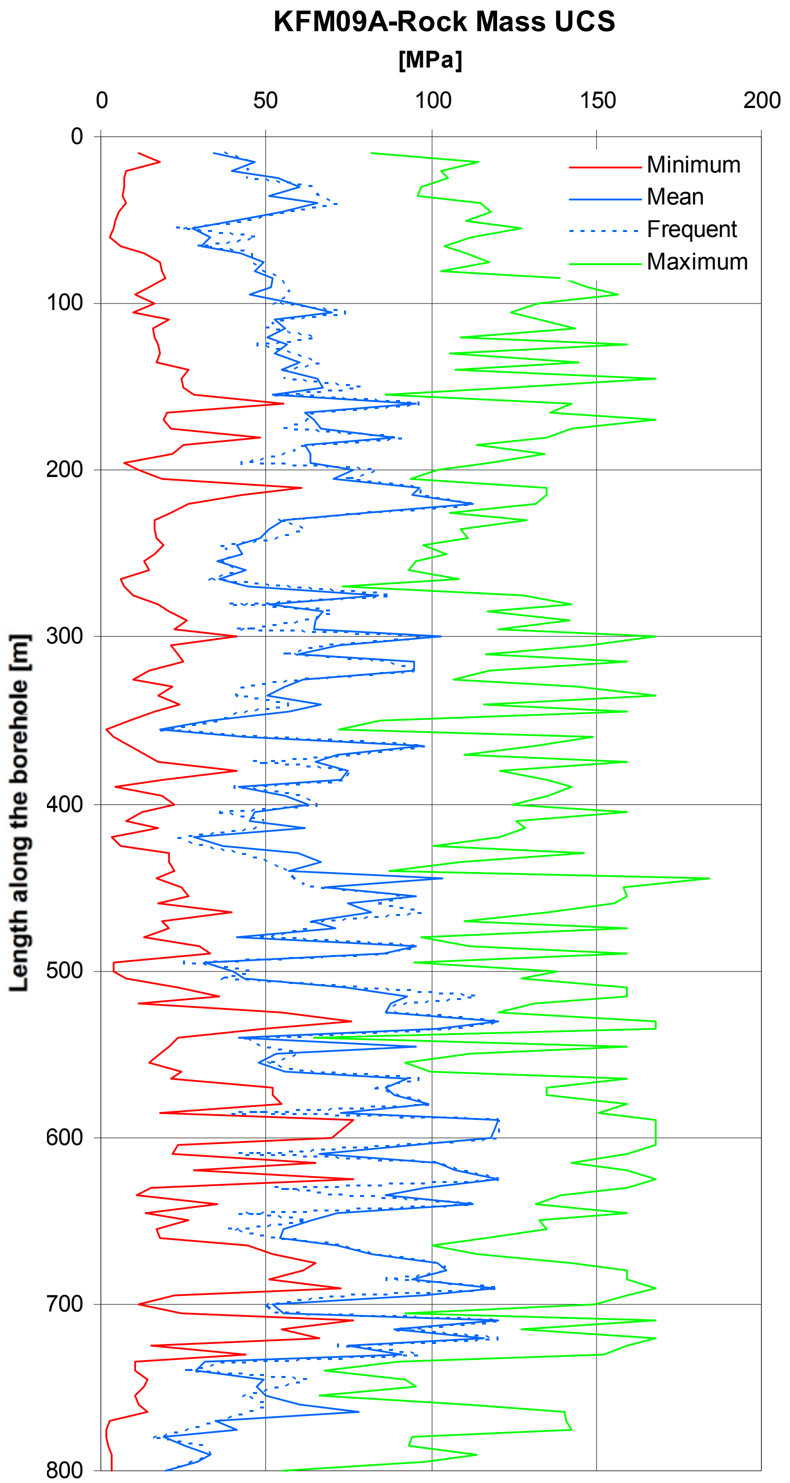
Variation of Poisson's ratio (ν) along borehole KFM09A (Hoek & Brown's a=0.5). The values are given every 1 m.



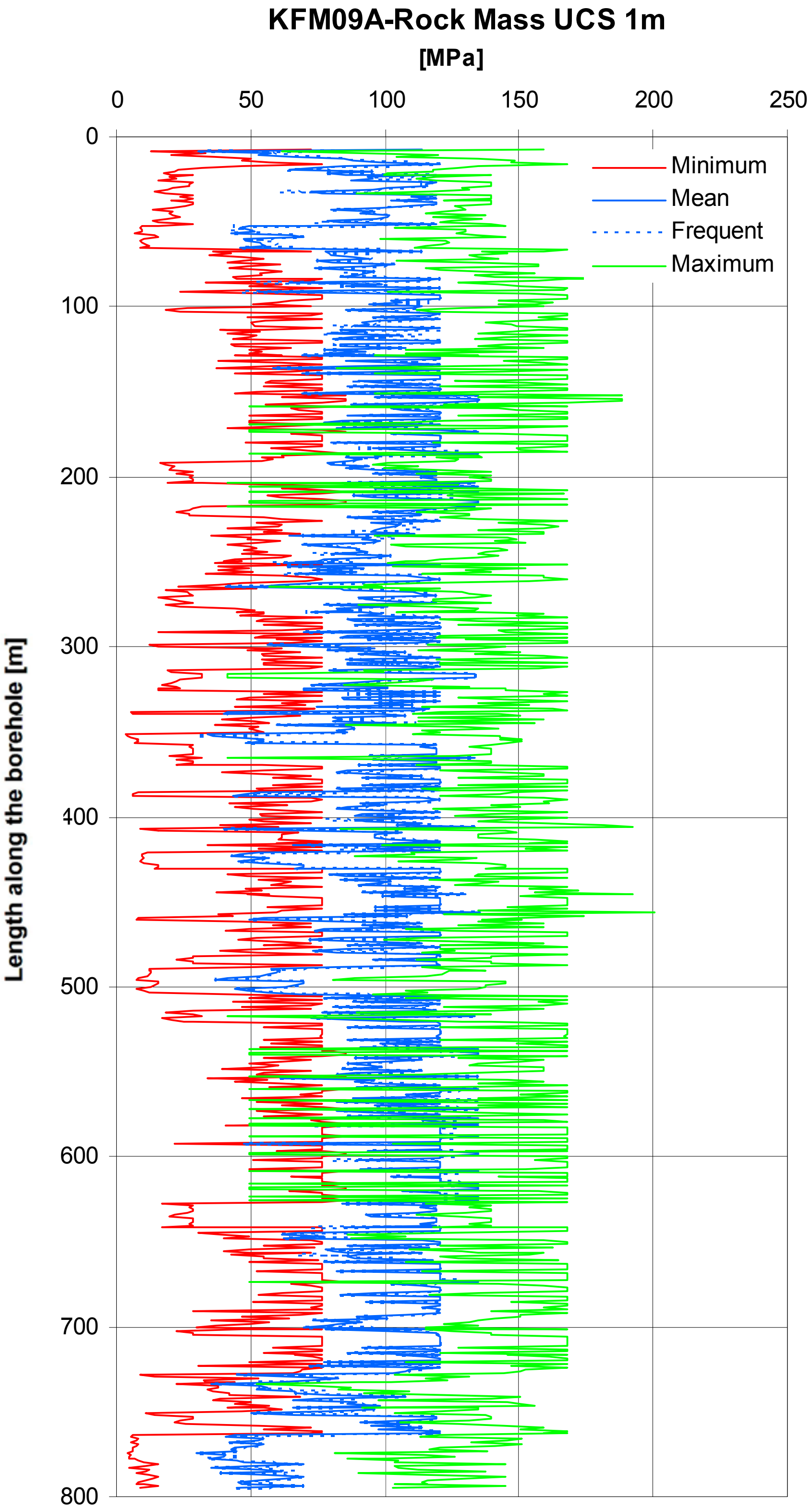
3.6 Uniaxial compressive strength

3.6.1 RMR

Variation of the uniaxial compressive strength of the rock mass along borehole KFM09A (Hoek & Brown's a=0.5). The values are given every 5 m.



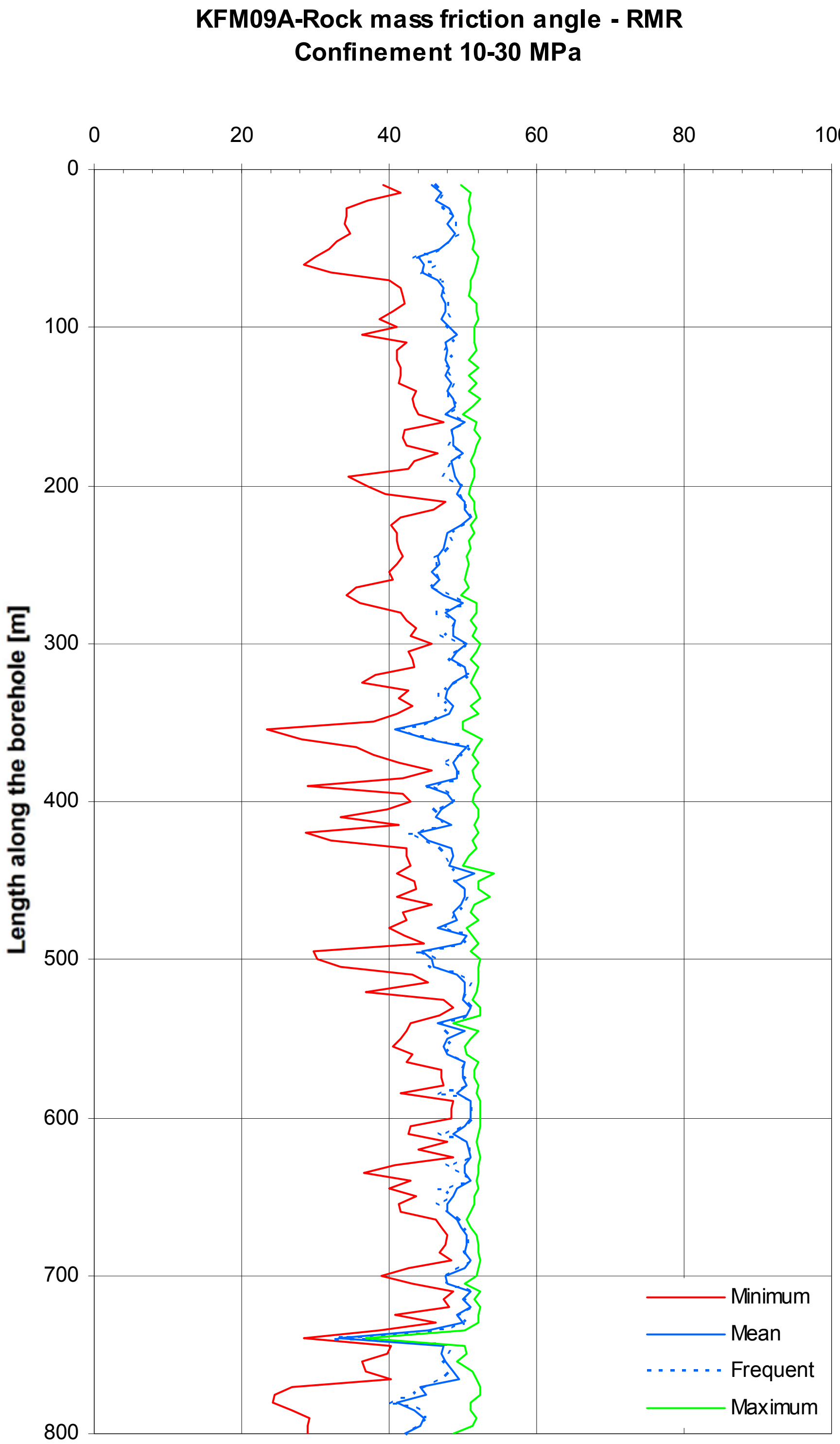
Variation of the uniaxial compressive strength of the rock mass along borehole KFM09A (Hoek & Brown's a=0.5). The values are given every 1 m.



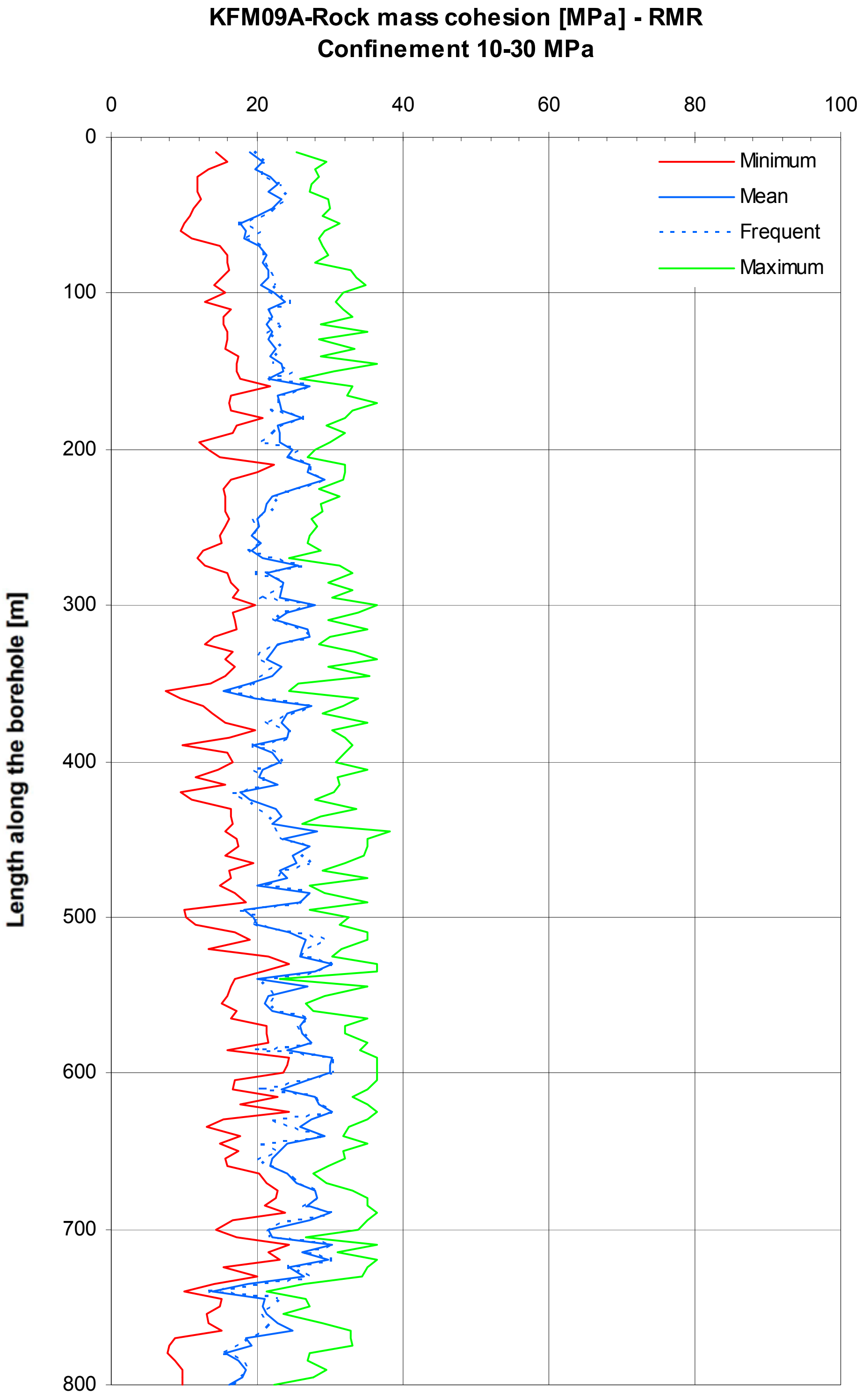
3.7 Friction angle and cohesion and of the rock mass

3.7.1 RMR

Variation of the rock mass friction angle ϕ' from RMR along borehole KFM09A under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Variation of the rock mass cohesion c' from RMR along borehole KFM09A under stress confinement 10-30 MPa (Hoek & Brown's a=0.5).



Appendix 4

KFM09B – Characterisation of the rock mass

4.1 Fracture orientation

Set identification from the fracture orientation mapped along borehole KFM09B (Sicada data delivery – 06_134_1). The orientations are given as strike/dip (right-hand rule).

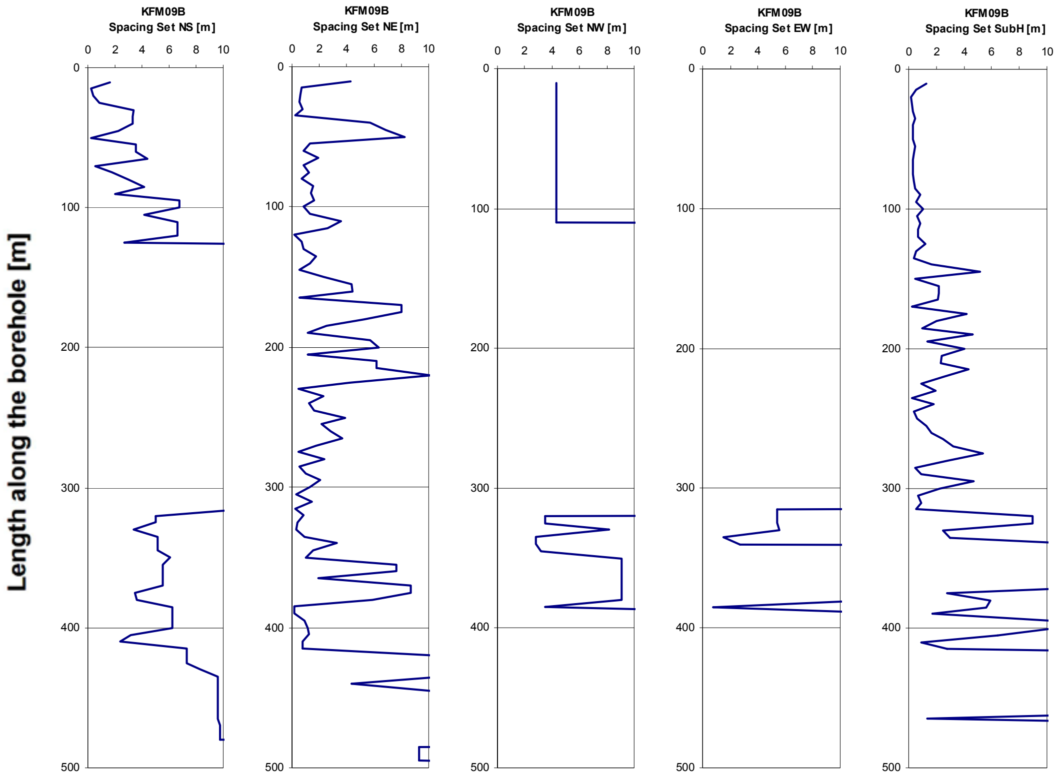
Length along borehole [m]	No. of fractures	NS	NE	NW	EW	SubH
9.2–110	287	166/83	238/84	138/77	277/72	82/09
110–132	47	181/81	227/81			76/11
132–169	49		233/87			155/03
169–259	86	177/64	241/78			91/09
259–308	51	13/86	53/85	105/88		67/07
308–318	20	178/79	62/88		272/79	89/15
318–340	28	16/86	63/87	105/79	291/86	317/04
340–363	12	175/89	235/88	116/89		111/15
363–413	76	359/83	235/81	119/83	299/86	241/04
413–445	5	175/86	236/89			63/08
445–480	5	324/78			314/81	157/15
480–520	8		212/88		312/85	135/07
520–550	38	171/80	239/88	138/65	287/80	
550–561	5	321/76	242/81		286/83	
561–574	43	163/80	65/86	115/83	293/87	343/08
574–616	1		31/82			

Fisher's constant of the fracture sets identified along borehole KFM09B (Sicada data delivery – 06_134_1).

Depth [m]	No. of fractures	NS	NE	NW	EW	SubH
9.2–110	287	26.5	21.2	10000*	41.4	44.7
110–132	47	24.0	18.1			34.1
132–169	49		11.8			9.2
169–259	86	10000*	18.6			75.0
259–308	51	10000*	20.8	10000*		60.0
308–318	20	10000*	30.2		10000*	79.3
318–340	28	13190	63.2	10000*	49.8	19.8
340–363	12	10000*	35.1	10000*		10000*
363–413	76	16.3	11.2	70.6	186.3	19.0
413–445	5	10000*	133.3			10000*
445–480	5	10000*			10000*	144.1
480–520	8		89.0		10000*	12.3
520–550	38	14.7	8.5	10000*	45.9	
550–561	5	10000*	11.6		109.1	
561–574	43	27.9	32.4	154.9	143.5	10000*
574–616	1		10000*			

* Derived from one fracture.

Fracture spacing with depth for the five facture sets in borehole KFM09B. The values are averaged for each 5 m length of borehole.

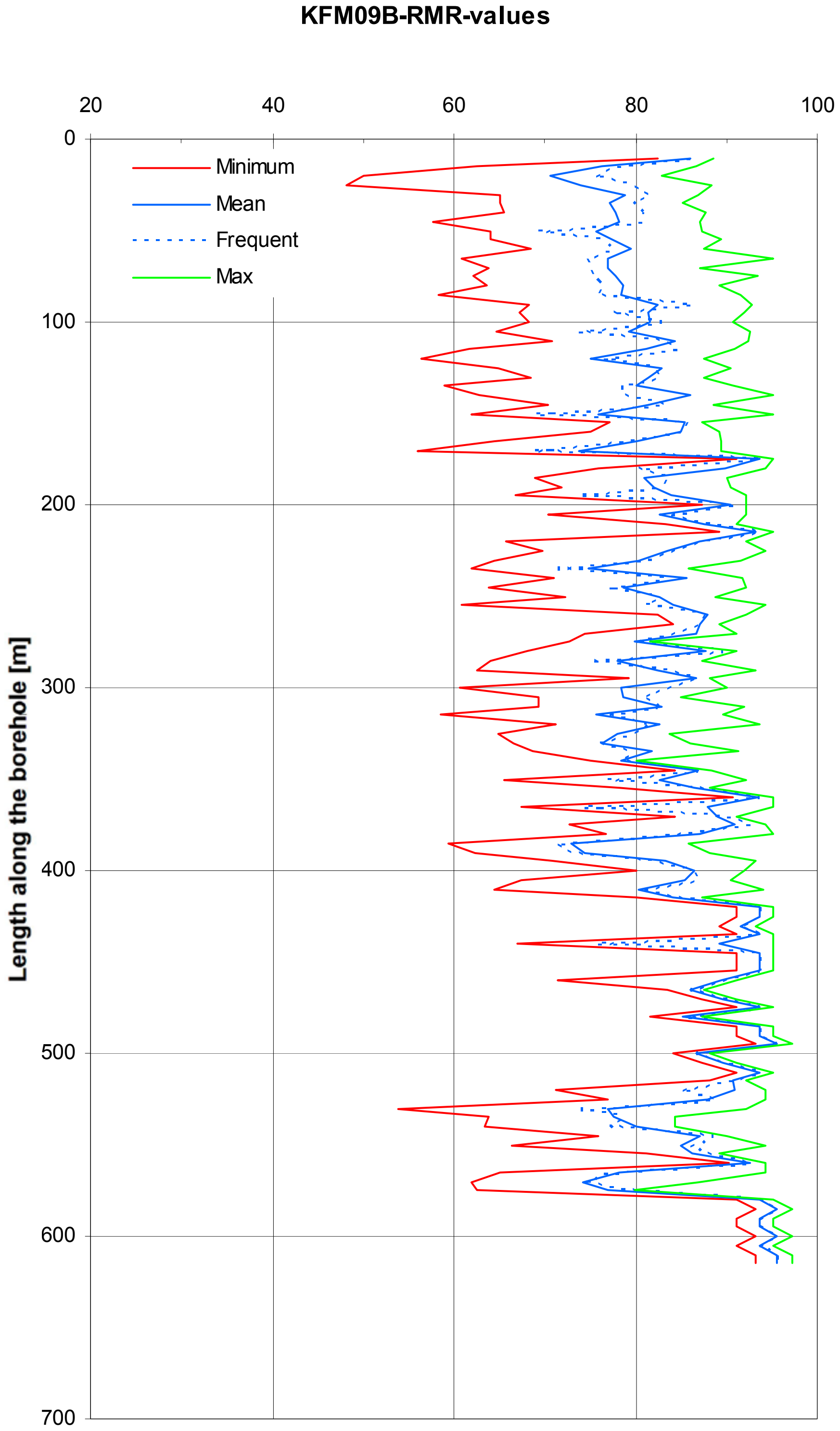


4.2 RMR

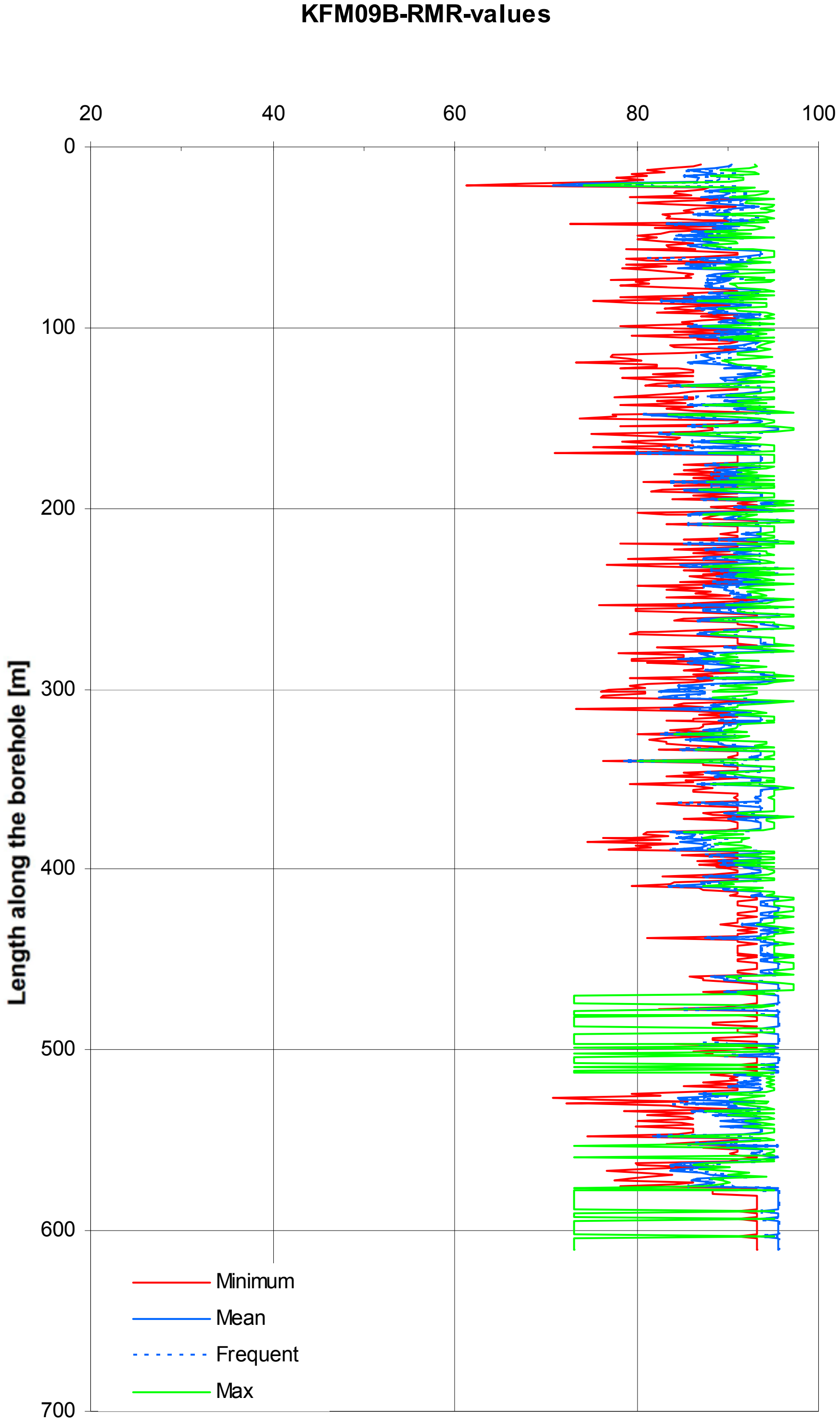
RMR values along borehole KFM09B (core sections of 5 m).

Rock unit length along borehole [m]	Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
5–110	70.5	78.5	78.2	85.9	3.4	48.16	95.2
110–135	75	80.2	81.3	83	3.0	56.45	91
135–170	73.7	81.1	81.3	86	4.9	56	95.2
170–260	74.8	85	84	93.6	5	60.95	95.2
260–305	78	82.9	82.5	87.8	4.2	60.6	93.3
305–320	75.7	80.4	82.6	82.9	4.1	58.5	93.6
320–340	76.3	78.6	78.2	81.8	2.3	64.9	91.4
340–360	82.8	87.4	86.6	93.5	4.5	65.6	95.2
360–415	72.8	83.8	85.4	90.9	5.8	59.5	95.2
415–445	89.2	92.5	93.6	93.6	1.8	67	95.2
445–485	85.1	90.6	91.6	93.6	3.6	71.5	95.2
485–520	86.6	91.5	91	95.6	3	71.2	97.2
520–550	76.9	82.4	82.5	88	4.9	53.8	94.2
550–565	78.2	85.7	86.2	92.6	7.2	65.1	94.2
565–575	74.2	75.5	75.5	76.8	1.9	61.9	87
575–615	93.6	94.6	94.6	95.6	1.1	91.2	97.2
Rock mass	73.7	87.5	87.4	95.6	5.9	56	97.2
Deformation zones	70.5	80.3	79.4	90.9	4.6	48.2	95.2
Whole borehole	70.5	84.4	84.1	95.6	6.4	48.2	97.2

Variation of RMR with depth for borehole KFM09B. The values are given every 5 m.



Variation of RMR along borehole KFM09B. The values are given every 1 m.

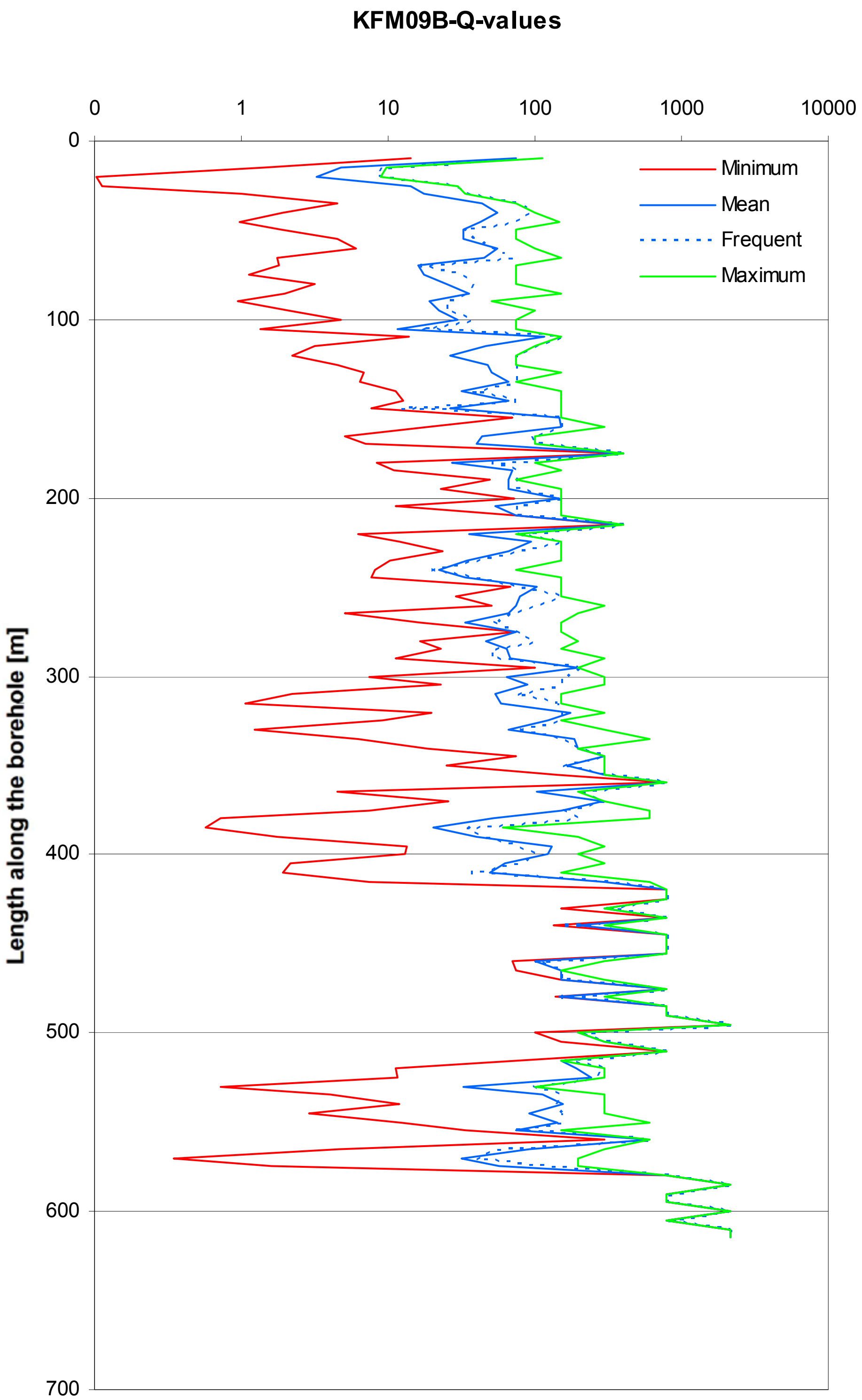


4.3 Q

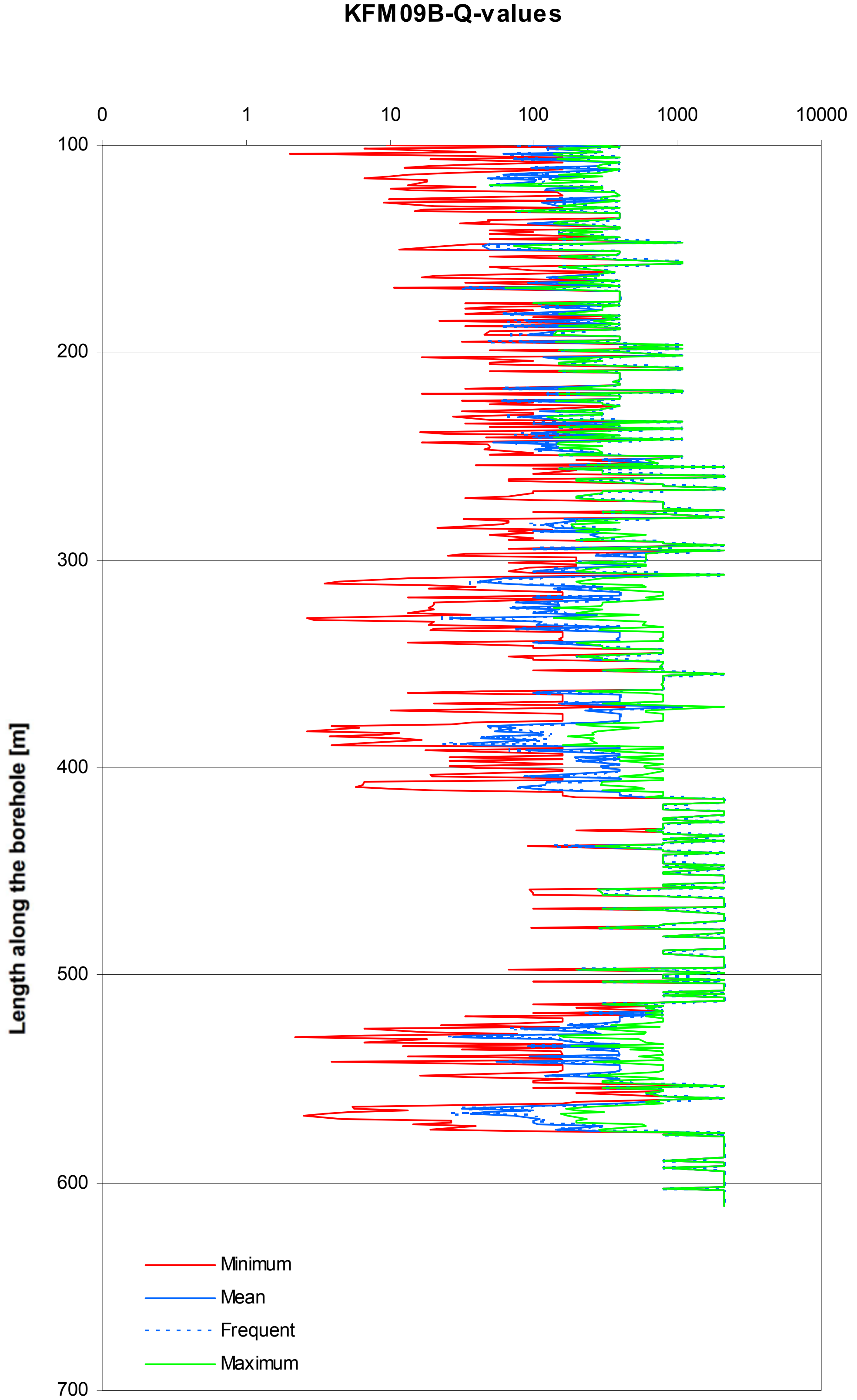
Q values along borehole KFM09B (core sections of 5 m).

Rock unit length along borehole [m]	Minimum Q [–]	Average Q [–]	Frequent Q [–]	Maximum Q [–]	Standard deviation	Min possible Q [–]	Max possible Q [–]
5–110	7.3	77.1	67.8	266.4	59.7	0.17	435
110–135	59.9	106.5	107.2	147	31.2	1.8	435
135–170	26.2	72.1	43.5	149.7	53.9	5.11	300
170–260	22.5	102.4	68.5	400	111.1	6.25	400
260–305	33.3	78.3	66.7	200	48.3	5	300
305–320	123	218.5	135.2	397.3	155	1.7	870
320–340	148	322.9	347.6	448.6	138.1	2.0	1740
340–360	166.7	389.7	298.5	795.2	277.4	25	800
360–415	20.2	120.1	104.2	300	96	0.6	600
415–445	196	616	800	800	286.9	135	800
445–485	98.6	468.1	475	800	355.2	69.8	800
485–520	150	653.6	300	2133.3	710.7	11.1	2133.3
520–550	33	128.9	127.2	240	69.3	0.7	600
550–565	75	255.1	90.3	600	298.8	4.6	600
565–575	31.7	44.8	44.8	57.8	18.5	0.3	200
575–615	800	1466.7	1466.7	2133.3	712.7	800	2133.3
Rock mass	22.5	416.1	149.9	2133.3	561.2	4.6	2133.3
Deformation zones	3.2	76.8	51.6	300	70.3	0.1	600
Whole borehole	3.2	271.5	76.8	2133.3	458.3	0.1	2133.3

Variation of Q along borehole KFM09B. The values are given every 5 m.



Variation of Q along borehole KFM09B. The values are given every 1 m.



Rock mass properties

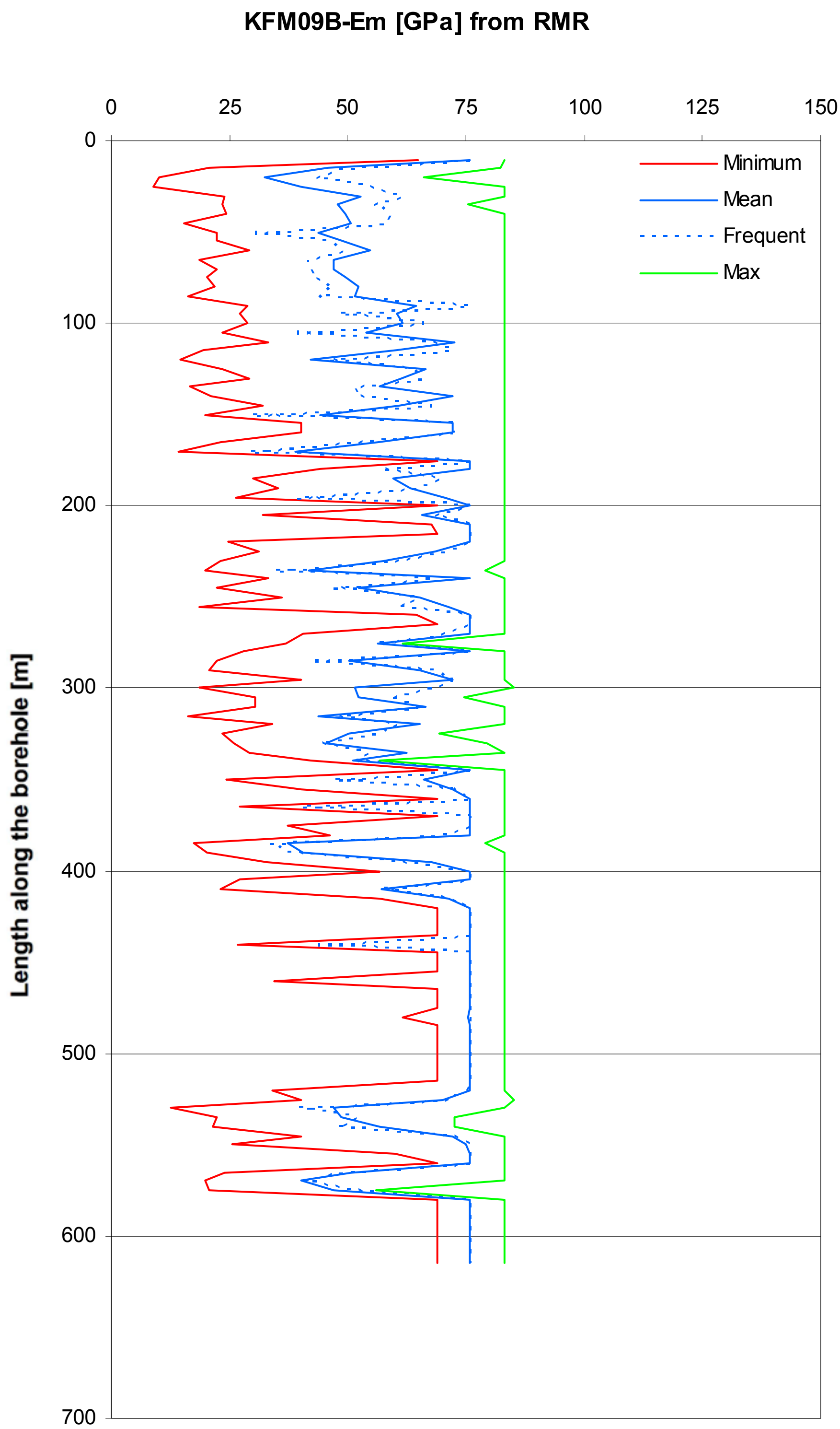
4.4 Deformation modulus

4.4.1 RMR

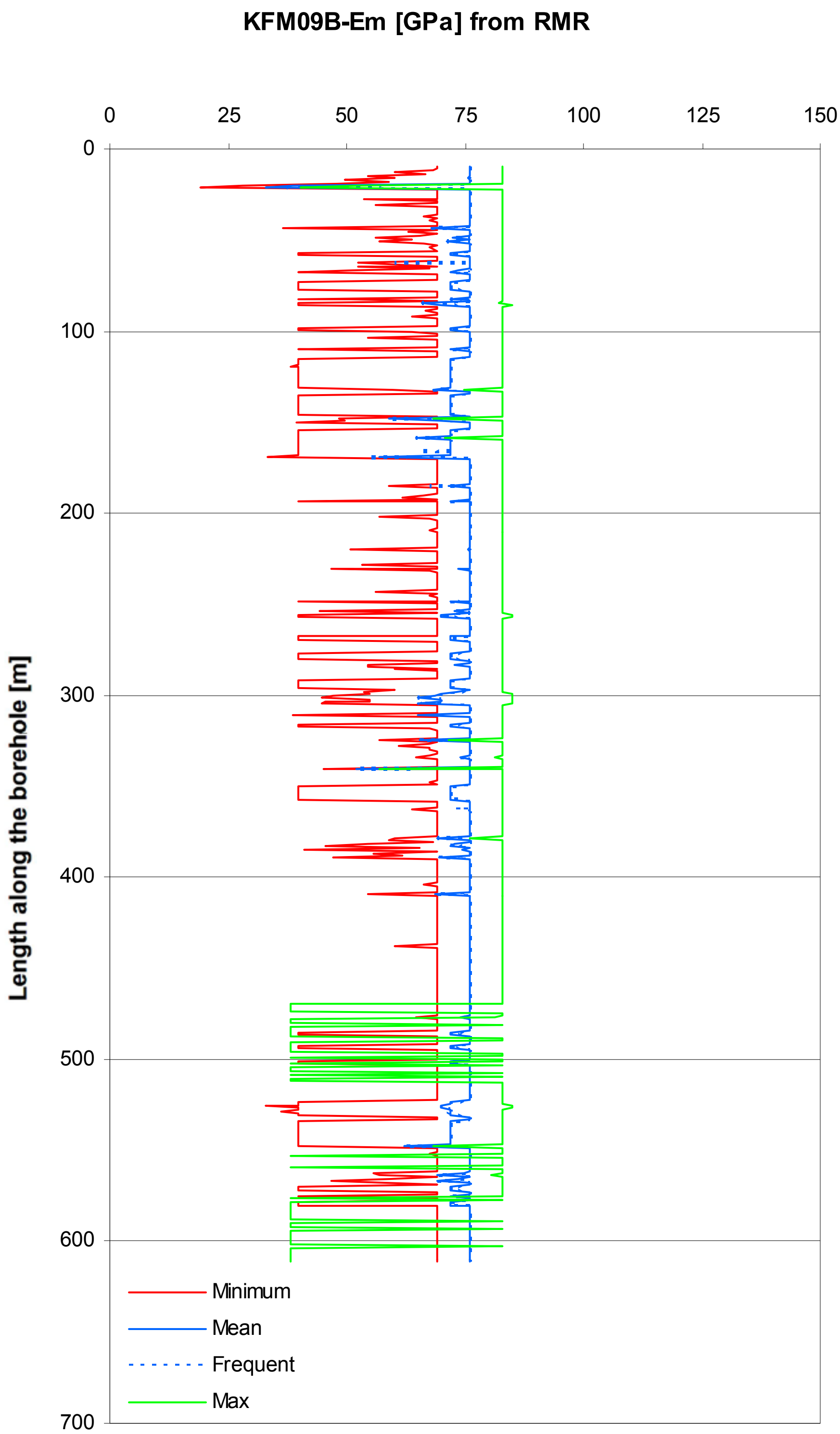
Deformation modulus Em derived from RMR along borehole KFM09B (core sections of 5 m).

Rock unit length along borehole [m]	Minimum Em [GPa]	Average Em [GPa]	Frequent Em [GPa]	Maximum Em [GPa]	Standard deviation [GPa]	Min possible Em [GPa]	Max possible Em [GPa]
5–110	32.6	52.5	50.7	76	10.1	9	83
110–135	42.3	57.4	60.5	66.6	9.2	14.49	83
135–170	39	59.5	60.6	72	13.7	14.13	83
170–260	41.6	68	70.9	76	10	18.78	83
260–305	50.2	63.9	65.1	76	11.4	18.5	85
305–320	44	58.6	65.2	66.6	12.7	16.3	83
320–340	45.5	52.3	50.6	62.3	7.1	23.5	83
340–360	65.9	72.5	74	76	4.8	24.5	83
360–415	37.2	66.3	76	76	14.8	17.2	83
415–445	76	76	76	76	–	26.6	83
445–485	75.5	75.9	76	76	0.2	34.5	83
485–520	76	76	76	76	–	34	83
520–550	47	61.5	63.3	74.8	12.3	12.4	85
550–565	50.8	67.6	76	76	14.5	23.9	83
565–575	40.2	43.6	43.6	46.9	4.7	19.9	83
575–615	76	76	76	76	–	69	83
Rock Mass	39	70.4	76	76	9.6	14.1	85
Deformation zones	32.6	56.8	53.8	76	12.3	9	85
Whole borehole	32.6	64.5	70.9	76	12.7	9	85

Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM09B. The values are given every 5 m.

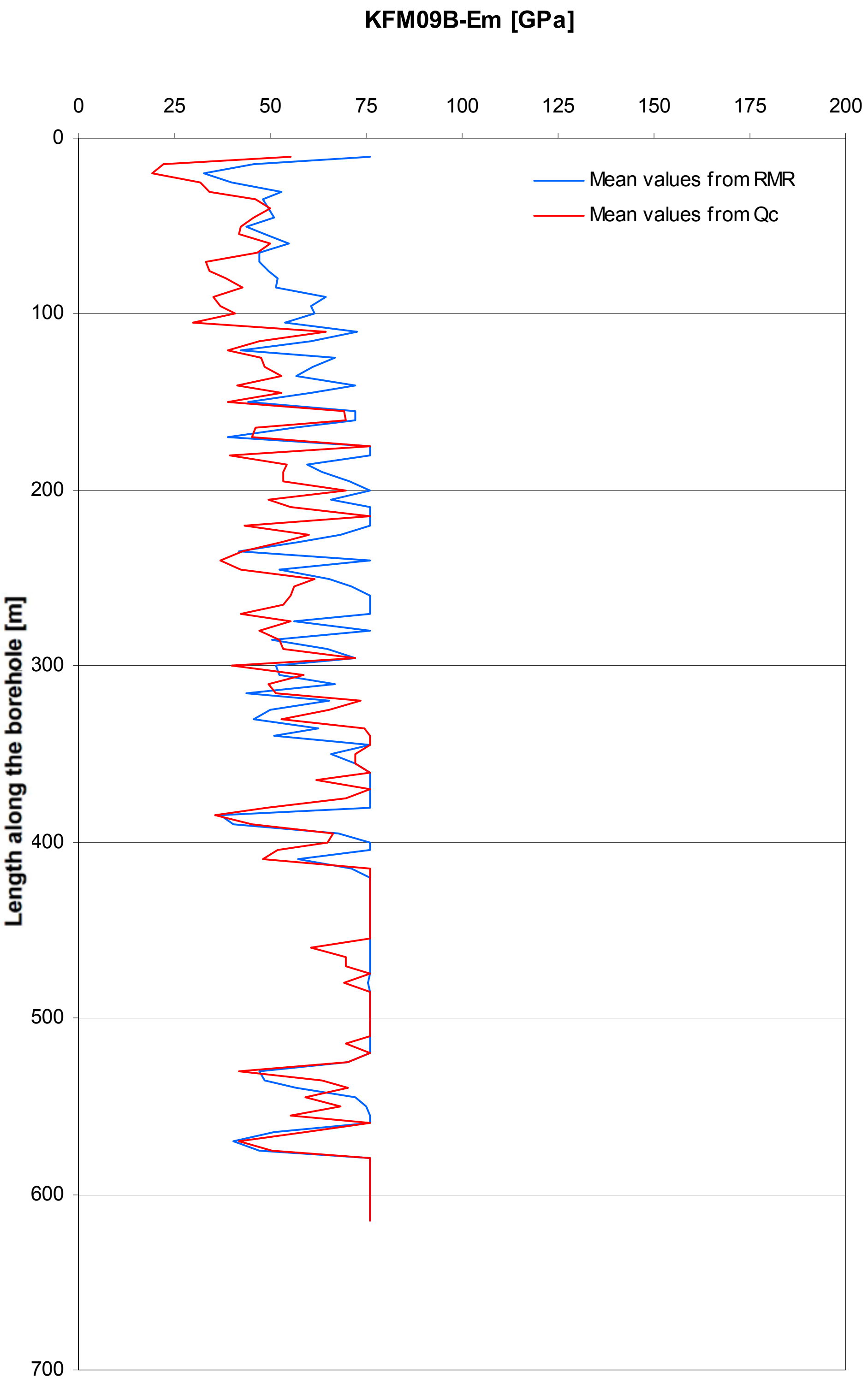


Variation of the deformation modulus of the rock mass obtained from RMR along borehole KFM09B. The values are given every 1 m.

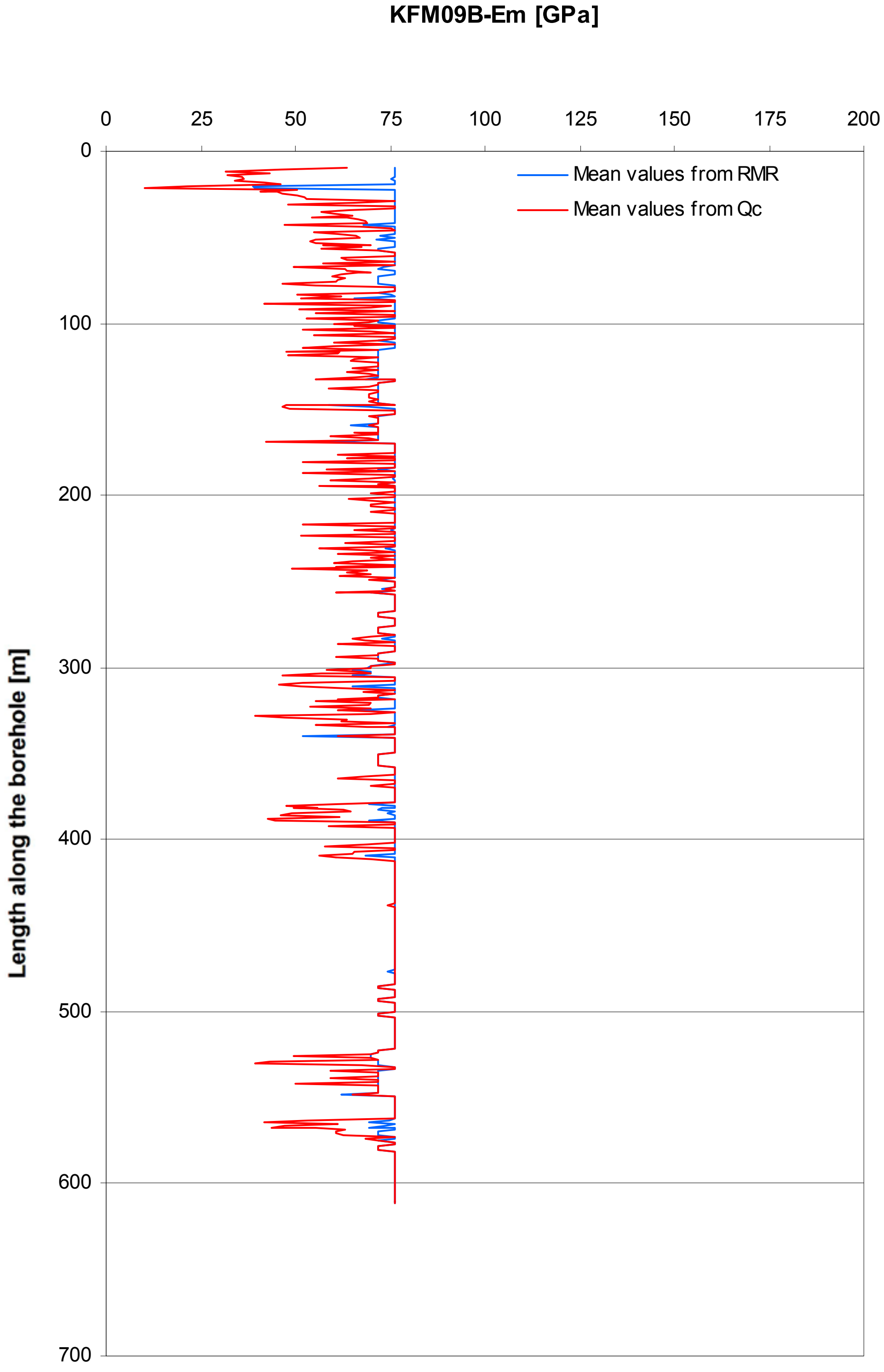


4.4.2 Comparison

Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc along borehole KFM01B. The values are given every 5 m.



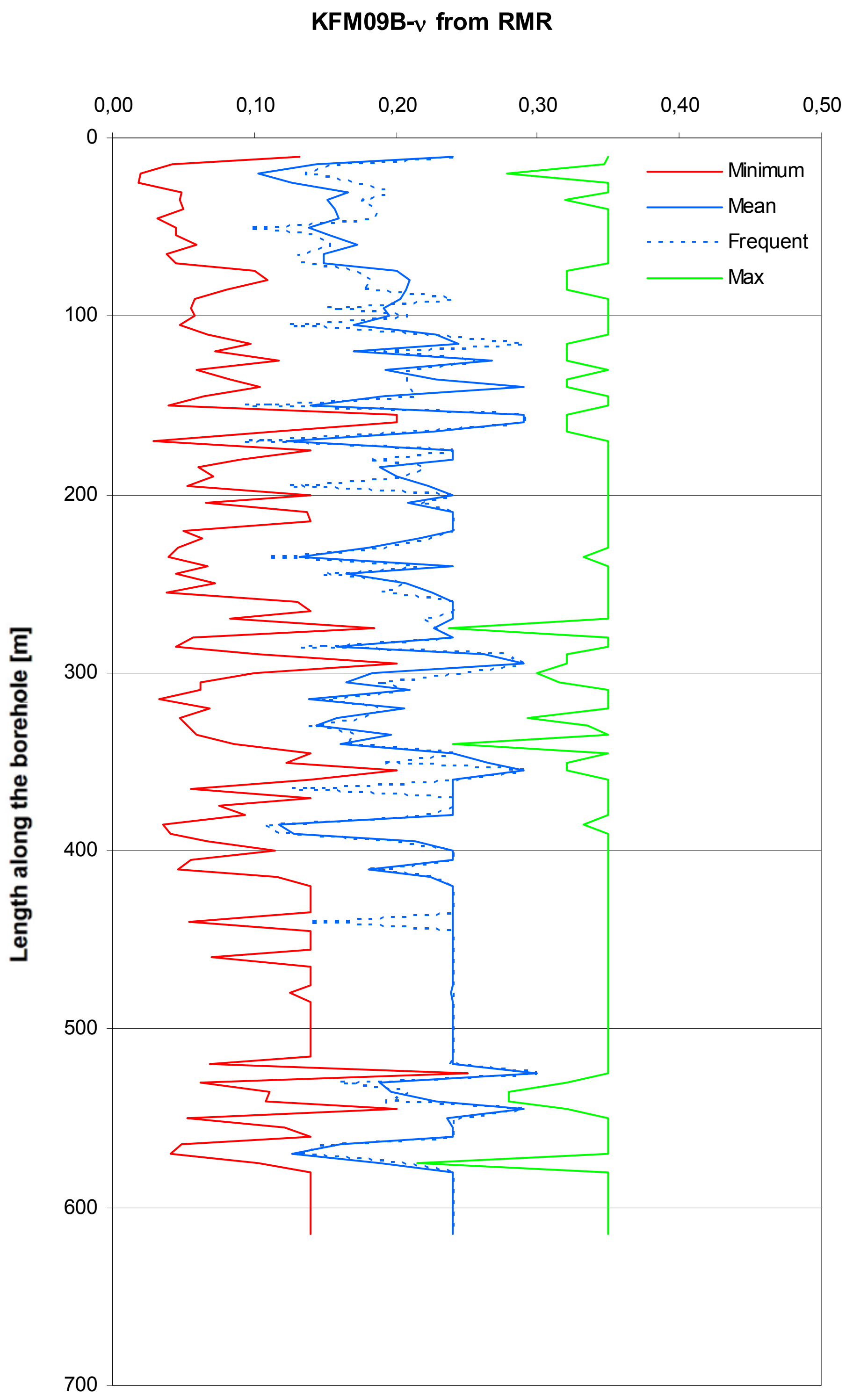
Comparison between the mean values of the deformation modulus E_m obtained from RMR and Qc for different depths for borehole KFM01B. The values are given every 1 m.



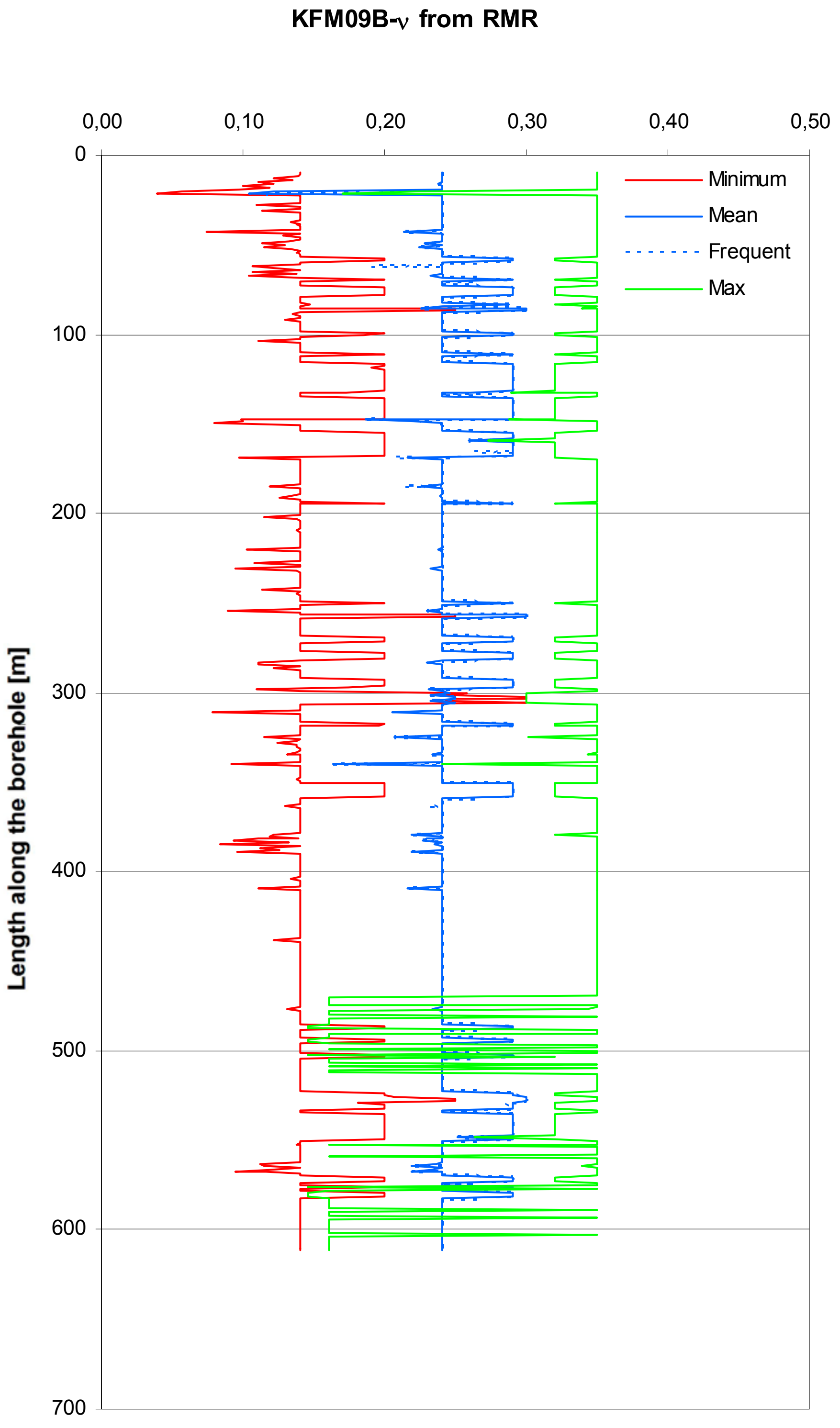
4.5 Poisson's ratio

4.5.1 RMR

Variation of Poisson's ratio (ν) along borehole KFM09B (Hoek & Brown's a=0.5). The values are given every 5 m.



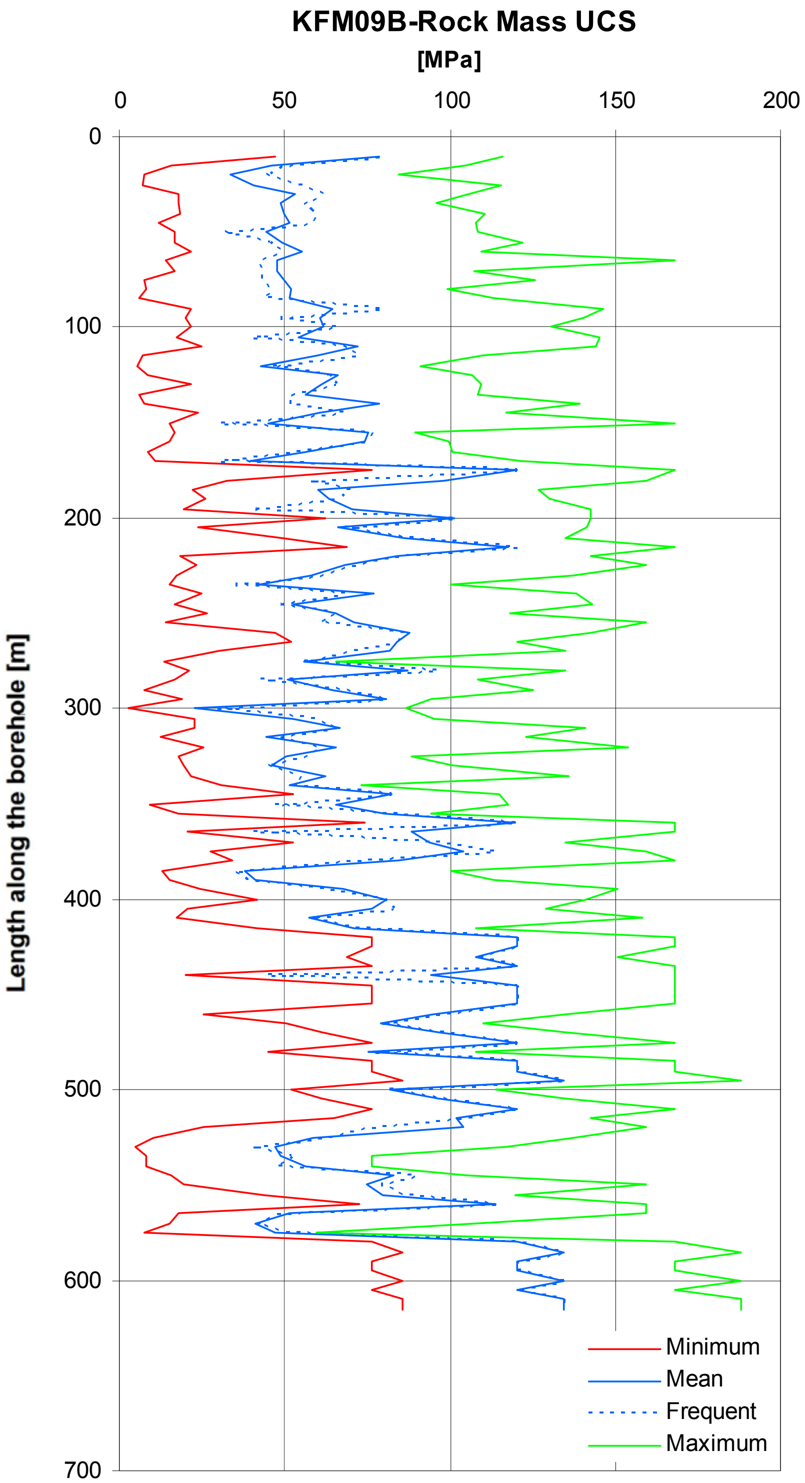
Variation of Poisson's ratio (ν) along borehole KFM09B (Hoek & Brown's a=0.5). The values are given every 1 m.



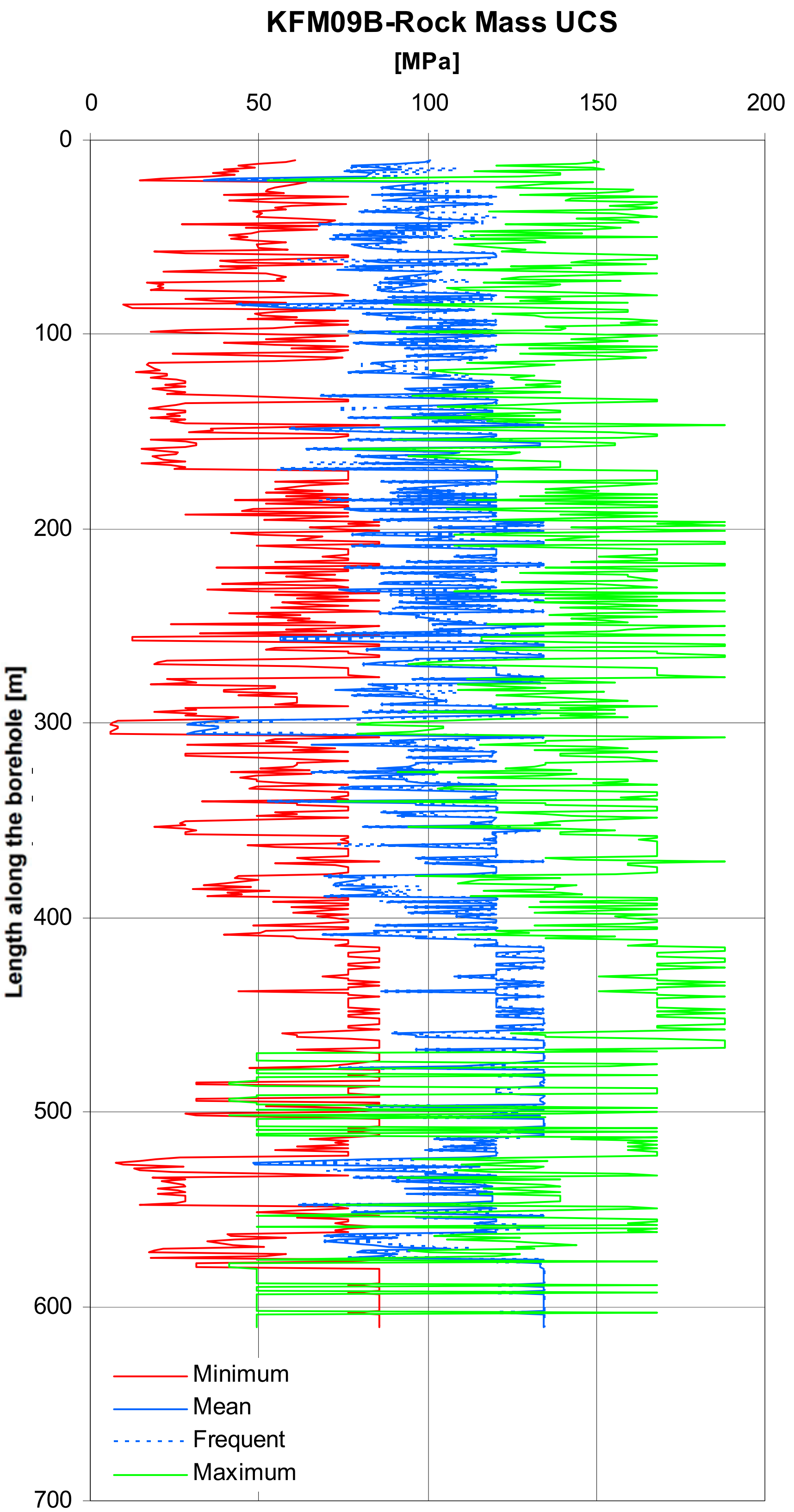
4.6 Uniaxial compressive strength

4.6.1 RMR

Variation of the uniaxial compressive strength of the rock mass along borehole KFM09B (Hoek & Brown's a=0.5). The values are given every 5 m.



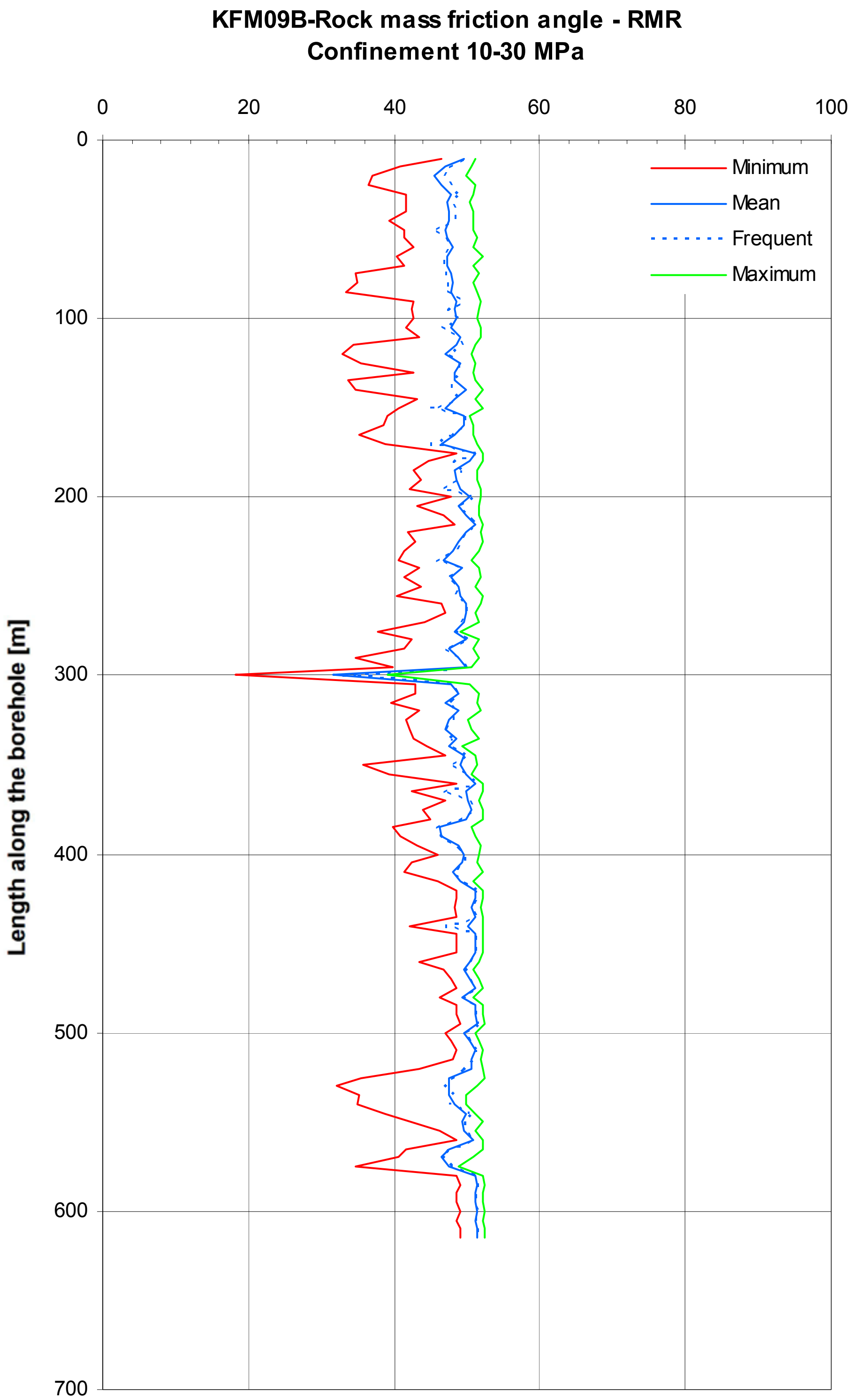
Variation of the uniaxial compressive strength of the rock mass along borehole KFM09B (Hoek & Brown's a=0.5). The values are given every 1 m.



4.7 Friction angle and cohesion and of the rock mass

4.7.1 RMR

Variation of the rock mass friction angle ϕ' from RMR along borehole KFM09B under stress confinement 10-30 MPa (Hoek & Brown's a=0.5). The values are given every 5 m.



Variation of the rock mass cohesion c' from RMR along borehole KFM09B under stress confinement 10-30 MPa (Hoek & Brown's a=0.5). The values are given every 5 m.