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Empirical characterisation of the rock mass along borehole KBH02 and comparison with the results of the EXPECT project

Site descriptive modelling Laxemar stage 2.1

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December 2007

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Abstract

In this report, borehole KBH02, drilled in 1989 between Hålö and Äspö, is characterised from a rock mechanics point of view. The purpose is to investigate the possibility of identifying fracture/deformation zones that can be relevant for the safety evaluation of a nuclear waste repository. Some fracture/deformation zones are recognised along the borehole and compared to the fracture/deformation zones observed along the Äspö Tunnel that runs parallel to the borehole. As the two results are obtained independently, this comparison offers a unique opportunity of adjusting the filters applied to the borehole data for searching for fracture/deformation zones to get the best agreement with the tunnel observations reported by the EXPECT Project.

The characterisation of KBH02 is performed by means of the two independent empirical classification systems, Q and RMR. These systems are applied to the geomechanical data (contained in digital format in the SICADA database) according to SKB's methodology for the "characterisation" of the rock mass, thus disregarding the effect of water pressure and stresses on the rock mass quality. The values of Q and RMR are calculated for borehole sections of 5 m and 1 m length. Average values are also provided for the quality of the rock mass in the Rock Units (volumes with one rock type or homogeneous mixture of rock types) and Deformation Zones (volumes with high frequency of the open and/or partly open fractures) logged along the borehole.

To identify the fracture/deformation zones, thresholds for Q and RMR were used. Different thresholds are shown to be suitable for different applications. The thresholds $Q < 4$ and/or $RMR < 60$ applied to the characterisation of 1 m sections is very effective in recognising the minor deformation zones, long fractures and sometimes the position of water inflows. On the other hand, these thresholds overestimate the extension of the deformation zones along the borehole compared to the tunnel mapping. The thresholds $Q < 1$ and/or $RMR < 40$ applied to the characterisation of 5 m sections provide a rather correct estimation of the total extension of potential fracture/deformation zones along the borehole, although they fail to highlight long fractures and position of water inflows. It is noteworthy to mention that the characterisation of 5 m sections is less time consuming than the characterisation of 1 m sections.

The uncertainty of the average RMR and most frequent Q values were also determined. The uncertainty is only slightly affected by the length of the borehole interval chosen (values are given here for sections of 5 m). The uncertainty of the average RMR is between 1% and 2% of the mean value for the competent rock mass, and between 1% and 6% for the fractured/deformation zones, respectively. The average RMR for the competent rock mass is 63.9 and for the fractured rock 52.6, respectively. The most frequent Q value for the competent rock mass is 11.7 which might vary between 9 and 14. For the fractured rock/deformation zones, the most frequent value of Q is 0.9 and its confidence interval is between 0.6 and 1.6 for borehole sections of 5 m.

Sammanfattning

Borrhålet KBH02, borrat 1989 mellan Hålö och Äspö, karaktäriseras bergmekaniskt i denna rapport. Syftet är att utforska möjligheten att identifiera sprick-/deformationszoner som kan vara intressanta för säkerhetsanalys av ett kärnavfallsförvar. En jämförelse görs mellan sprick-/deformationszoner som identifierades i borrhålet med de observationerna som gjorts i den del av Äspö tunneln som löper längsmed borrhålet och är inrapporterade av EXPECT-projektet. De två resultaten är oberoende av varandra. Valideringen mot tunnelobservationerna kan dessutom förbättra de filterfunktionerna som används för att identifiera sprick-/deformationszoner i borrhålet.

Karaktäriseringen av bergmassan längs borrhål KBH02 är gjort med hjälp av två oberoende empiriska system, Q och RMR. Systemen tillämpas på geomekanisk information i digitalformat från SICADA-databasen och i enighet med SKBs metodologin för karaktärisering av bergmassan, därför är påverkan av vatten och spänningar försummad. Q- och RMR-värden beräknas för varje 1 m eller 5 m lång borrhålslängintervall. Medelvärden ges för bergmassans i Bergdomänerna (bergartmässigt homogena intervall i borrhålet) och i Deformationszonerna (intervall med förhöjd frekvens av delvis eller helt öppna sprickor) som karterats i borrhålet.

För att identifiera sprick- och deformationszoner har olika trösklar för Q- och RMR-värden används. De ger resultat som passar olika tillämpningar. Trösklarna $Q < 4$ och/eller $RMR < 60$ applicerade på karaktäriseringsresultat för 1 m intervall är mycket lämpliga för att identifiera mindre deformationszoner, långa sprickor och ibland för att uppskatta var man kan förvänta sig inläckage av vatten. Å andra sidan överskattar dessa trösklar utsträckningen av deformationszonerna i borrhålet jämfört med tunnelkarteringen. Trösklarna $Q < 1$ och/eller $RMR < 40$ applicerade på karaktäriseringsresultat för 5 m intervall ger en ganska korrekt uppskattning av den totala utsträckningen av potentiella deformationszonerna i borrhålet, fastän de inte kan identifiera långa sprickor eller områden med vatteninläckage. Dock är karaktäriseringen för varje 5 m lång borrhålsintervall mindre tidskrävande än den för 1 m lång borrhålsintervall.

Osäkerheten i medel RMR- och mest frekventa Q-värdena är också redovisade i rapporten. Osäkerheten verkar inte påverkas markant av längden av borrhålsintervallen (värden ges här för 5 m-intervallen). RMR har medelvärde på 63,9 för kompetent bergmassa resp. 52,6 för sprick-/deformations-zoner. För RMR varierar osäkerheten för medelvärdet mellan 1 % och 2 % av själva medelvärdet för bergmassan utanför deformationszonerna resp. mellan 1 % och 6 % för sprick-/deformationszoner. Osäkerhetsintervallet för det mest frekventa Q-värdet sträcker sig mellan 9 och 14 för bergmassan utanför sprick-/deformationszoner resp. mellan 0,6 och 1,6 för sprick-/deformationszoner. Det mest frekventa Q är 11,7 för kompetent bergmassa resp. 0,9 för sprick-/deformationszoner.

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1 Introduction

1.1 Background

The analysed borehole runs parallel to the Äspö HRL access tunnel. The sub-horizontal borehole KBH02 was drilled prior to the tunnel excavation /Rhén et al. 1997/. The borehole starts on the island of Hålö and is close to and nearly parallel to the straight ramp leading down to the spiral section of the Äspö HRL (Figure 1-1). The borehole is drilled with a main inclination of 45°, whereas in the first 60 m the inclination is steeper. The borehole reaches the depth of about 210 m (Table 1-1). Neither BIPS images nor BOREMAP but PETROCORE loggings are available for the borehole.

Table 1-1. Borehole information for KBH02.

Borehole parameters	KBH02
Top coordinates (system ÄSPÖ96)	X = 6,313.830 m Y = 2,170.590 m Z = 5,500 m a.s.l
Length	about 700 m
Dip angle	45°
Dip direction	348°

Figure 1-1. Overview of the Äspö Site with indication of borehole KBH02 /Rhén et al. 1997/.

1.2 Objectives

The objectives of this study on borehole KBH02 are as follows:

- Evaluate the rock mass quality along the borehole by means of the empirical systems RMR and Q.
- Give summary properties for the pseudo-homogeneous rock units identified by the geological single-hole interpretation of the available data.
- Test the hypothesis that it is possible to identify signatures of deformation zones solely by means of the Q and RMR system and independently of previous studies on the same borehole and adjacent tunnel (i.e. "blind test").
- Compare the deformation zones identified by the empirical methods with those resulting from other studies.
- Discuss the results of the characterisation and list the main conclusion of the work.

This rapport was compiled as support document to the Preliminary Site Descriptive Model for Laxemar-Simpevarp, Stage 2.1 /SKB 2006a/.

1.3 Scope

Borehole KBH02 is characterized for the purpose of comparison with the mapping results along a parallel tunnel. By comparing the two results, obtained independently, it will be possible to validate the results of the borehole characterization against a case were a tunnel was actually excavated in the same rock mass.

This Rock Mechanics Report is structured as follows:

- Summary of the PETROCORE data on rock and fractures. The orientation of the fracture is not available, thus the number of fracture sets is estimated based on the fracture data available from boreholes KAV01 /Lanaro and Bäckström 2005/ and KAV04 /Lanaro and Bäckström 2006/.
- Summary of the mechanical properties of the common rock types at the site.
- Application of the RMR and Q empirical systems for determination of the rock quality along the boreholes (see also the appendix). The determination of the input parameters is illustrated as well as the spatial variation, scale effect and uncertainty.
- Comparison of the characterization results with the outcome of the EXPECT Project /SKB 2006b/, a study about the deformation zones and, in particular, about the identification of the features intercepting the access tunnel and borehole KBH02 at the Äspö HRL.
- Discussion of the results and conclusion.
- Appendix.

2 PETROCORE Data

Borehole KBH02 was mapped by examining the drill-core in 1989. For this reason, some of the standard geomechanical parameters are not available or the definitions might slightly differ from what is usually available for SKB's Site Investigations. The geological parameters obtained are stored in SKB's geological database SICADA and consist of:

- Fracture frequency.
- RQD evaluated on core lengths of 1 m.
- Records of "crush" and "core loss".
- Rock types, rock alteration and structural features.

All the fractures reported were assigned to the class "broken" in SICADA. Several of the fractures were classified as "open" or "sealed", but many of them were not assigned to any group. Since this notation has not been used consistently for all the fractures, 168 fractures were used for the rock mass characterisation in this report, only excluding the "sealed" ones. The geological core mapping included RQD (Rock Quality Designation) which indicates the degree of fracturing of the rock mass and the following geological features of the analysed fractures were observed:

- Depth of occurrence.
- Mineralization or infilling.
- Roughness and surface features.
- Alteration conditions.
- Width (the parameter "aperture" is not available for the fractures identified as open in PETROCORE).

The Q-parameter Joint Alteration Number (J_a), usually determined during core mapping by the geologists, was not provided for this borehole. This parameter was inferred in this report based on fracture width, roughness, surface, shearing and the kind of infillings.

2.1 Borehole KBH02

The orientation of the fractures along this borehole was not measured because the core was not oriented nor BIPS-pictures were available. For this reason, the number of fracture sets cannot be directly determined. Instead, the Q-parameter Joint Set Number (J_n), which is based on the number of sets of fractures occurring in a certain borehole section, was estimated using a specially designed relation between J_n and RQD. Based on the concept of "relative block size" /Barton 2002/, this relation was established using the data available for borehole KAV01 and KAV04 where fracture orientation is available. These boreholes were characterised for Simpevarp and Laxemar Site Descriptive Model, version 1.2 /SKB 2005, 2006c/ and are located within the same fracture domain as KBH02 (see Section 5.2).

The fracture frequency and RQD are stored in SICADA for each metre of borehole length. For the characterisation, average, minimum and maximum values are also determined for borehole sections of 5 m length. The variations of the total fracture frequency, the estimated fracture spacing and RQD along borehole KBH02 are shown in Figure 2-1. The fracture frequency increases steadily to a length of about 210 m where it decreases again down to a depth of about 280 m. This interval contains a deformation zone which is about 80 m wide. The deformation zone is clearer in the plot of RQD where the values drop below 50 on several instances. The total spacing of the fractures varies between 1 and 2 m along the entire core with a few sections with distance between fractures of up to 6 m. These sections concur with low fracture frequency and high RQD values. Another deformation zone is visible towards the bottom of the borehole.

The plot of the total spacing with depth for every 5 m section of borehole is also shown in Figure 2-1. The total spacing calculated over 5 m intervals have a larger statistical significance than the spacing derived for each 1 m intervals.

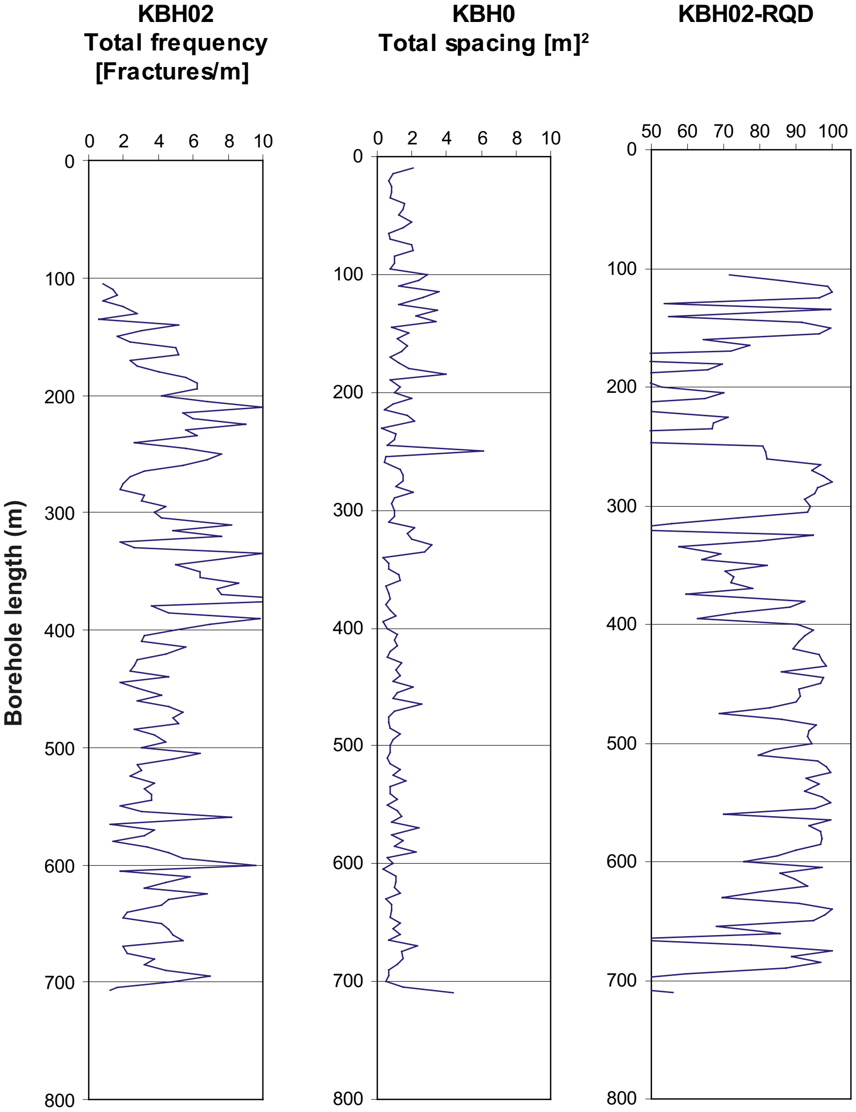

__Figure 2-1.__ Variation of the total fracture frequency, estimated spacing between fractures and RQD with depth for borehole KBH02. Due to lack of fracture orientation information, no Terzaghi's correction has been applied when calculating the spacing. The values of the fracture frequency and spacing are averaged for each 5 m length of borehole.

3 Mechanical properties of the intact rock and fractures

The mechanical properties of the rock have to be assigned according to the different rock types observed along the borehole. However, no testing was performed on samples taken from borehole KBH02. Thus, the mechanical properties of the intact rock for different rock types were taken as the results from other boreholes at the Simpevarp-Laxemar Site summarized in Table 3-1 /Lanaro et al. 2006/. This table shows the statistics of the uniaxial compressive strength of the dominant rock types to be used for the empirical characterisation.

Some of the observed rock types in borehole KBH02 were not tested even in the other boreholes at the Site. For these rock types, like granodiorite, mylonite and aplite, the mechanical properties were estimated based on literature values (e.g. /SKB 2004, SKB 2006d/, Table 3-2).

Table 3-1. Summary of the results of uniaxial compressive tests performed on intact rock samples from borehole KSH01A, KSH02A, KLX02 and KLX04 /Lanaro et al. 2006/.

Rock type	Number of samples	Minimum UCS [MPa]	Mean UCS [MPa]	Frequent UCS [MPa]	Maximum UCS [MPa]	UCS Standard deviation [MPa]
Fine-grained dioritoid	10	109	205	230	264	51
Quartz monzonite to monzodiorite	10	118	161	164	193	24
Granite to quartz monzodiorite	30	151	192	195	239	21
Fine-grained dioritoid with sealed fractures	5	92	126	131	158	31

Table 3-2. Estimated mechanical properties of the granodiorite, mylonite and aplite in borehole KBH02.

Rock type	Minimum UCS [MPa]	Mean UCS [MPa]	Frequent UCS [MPa]	Maximum UCS [MPa]
Granodiorite	150	240	240	325
Mylonite	45	110	110	160
Aplite	150	190	190	325

4 Partitioning of borehole KBH02

The "single-hole interpretation" provides the partitioning of the boreholes into Rock Units (RU, pseudo-homogeneous rock volumes with a predominant rock type or particular mixture of them) and Deformation Zones (DZ, zones of higher fracture frequency and alteration often observed as seismic and radar reflectors). For borehole KBH02, there is not such interpretation. For this reason, a simplified partitioning was based on:

- The occurring rock types for defining the Rock Units.
- RQD (< 60), "crush" and "core loss" for identifying the Deformation Zones.

For Rock Mechanics purposes, this partitioning was used to investigate the variation of the quality of the rock mass between different homogeneous sections of the borehole. The fractured zones were also accurately checked and only the ones that would correspond to considerably reduced rock mass quality were considered as individual objects in the Rock Mechanics analysis.

Based on the dominant rock types, five types of Rock Units were identified (Table 4-1). These Rock Units occur along borehole KBH02 according to the list in Table 4-2. In the same table, also the list of the possible Deformation Zones is provided.

Table 4-1. Description of the different rock units (RU1 to 5) occurring along borehole KBH02 /from SICADA 2005/.

Rock unit	Description
RU 1	Granite
RU 2	Mylonite
RU 3	Granite and aplite
RU 4	Aplite
RU 5	Granodiorite and aplite

Table 4-2. Definition of the rock units and deformation zones in borehole KBH02 /SICADA 2005/.

Depth [m]	Rock unit	Depth [m]	Deformation zones
100–235	RU 1	100–110	DZ 1
		125–130	DZ 2
		135–140	DZ 3
		155–235	DZ 4
235–245	RU 2		
245–305	RU 1		
305–355	RU 3	310–320	DZ 5
		330–345	DZ 6
		350–355	DZ 7
335–360	RU 2		
360–395	RU 4	390–395	DZ 8
395–550	RU 1	470–475	DZ 9
		505–510	DZ 10
550–705	RU 5	625–630	DZ 11
		650–655	DZ 12
		665–670	DZ 13
		690–705	DZ 14

5 Characterisation of the rock mass along the borehole

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

5.1 Equations for RMR and Q

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

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

where the subscripts strength, RQD, spacing, conditions, water, orientation refer to the strength of the intact rock, the Rock Quality Designation, the conditions and spacing of the fracture, the groundwater conditions and the orientation of the fracture sets with respect to the hypothetical tunnel orientation, respectively. In /Bieniawski 1989/, each rating is provided with a description and a table with typical values.

The basic equation for Q is:

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

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 5-1. 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

5.2 Relation between RQD and J_n at Simpevarp

J_n is an essential parameter for the rock mechanics characterisation by means of the Q system /Barton 2002/. For borehole KBH02, J_n must be estimated as we do not have information about the orientation of the fractures. J_n is the rating that takes into account the number of joint sets in a certain rock domain (e.g. 9 for 3 sets of fractures, 4 for 2 sets, etc), in this study, borehole sections of either 5 or 1 m were considered. For KBH02, we have to use other geomechanical parameters for estimating J_n.

Other than J_n, another parameter based on the frequency of fractures along the borehole is RQD (Rock Quality Designation), which is the percentage of complete drill-core intact portions longer than 100 mm that occur per metre of a selected borehole section. In this study, the RQD is also averaged for 5 m long borehole sections.

Some boreholes at the Site happened to be close to KBH02. These are KAV01 and KAV04, where KAV04 is the closest. Assuming that borehole KBH02 is located within the same fracture domain as the other two boreholes, the hypothesis that they exhibit the same correlation between characterisation parameters as KBH02 is made. For these boreholes, fracture orientation data are available, thus, a relation between RQD and fracture frequency and J_n is established. Besides this, the ratio RQD/J_n is also used by /Barton 2002/ as parameter for providing information on the relative block size in the rock mass. The block size depends on the number of joint sets.

Fracture information from the borehole KAV01 and KAV04 is divided into competent rock mass (outside the deformation zones) and rock in the fractured rock/deformation zones to take into account the fact that the fractured rock generally presents sections with more fracture sets than the competent rock.

The data from the two boreholes are evaluated separately and the resulting trends are compared. The most extreme cases are obtained for the “worst case scenario” and “best case scenario” applicable to borehole KBH02, respectively. The average case for the mean trends for the two cases is used as the average relation for KBH02.

When making a statistical analysis of the input parameters for Q, the minimum, mean, frequent and maximum values are calculated over a certain borehole domain. Here, the analysis is done by plotting RQD against J_n each other to obtain the spectrum of variation. The “worst case scenario” is where the minimum value of RQD is plotted against the maximum value of J_n. The maximum value of RQD is plotted against the minimum value of J_n to represent the “best case scenario”. Average values of RQD are plotted against average values of J_n. The results of this estimation are presented in Figure 5-1.

The result from the “worst case scenario” can be seen on the right limit in the plots in Figure 5-1. When looking at these two cases, the most extreme of the two possible “worst case scenario” is found for KAV01. This scenario is obtained from the maximum J_n versus minimum RQD and assumes J_n to be 15 for RQD ≤ 90.5 and 1 for RQD ≥ 98. Within this RQD interval, the linear trend in Equation 3 was used for the “worst case” for the rock mass outside the deformation zones:

$$\max J_n = -3.6 \min RQD + 360.8 \tag{3}$$

The “best case scenario” is described by the red trend lines in the plots in Figure 5-1. The lower boundary for minimum J_n is set to 1, which occurs when the maximum RQD ≥ 62; J_n is set to 15 when maximum RQD ≤ 36. Between these two extremes ($36 < \text{RQD} < 62$), the minimum J_n follows the red trend line described by the Equation 4:

$$\min J_n = -0{,}5 \max RQD + 34.9 \tag{4}$$

The “best case scenario” described here is chosen so that only 10% of the values of the maximum RQD and minimum J_n fall below the red lines in Figure 5-1.

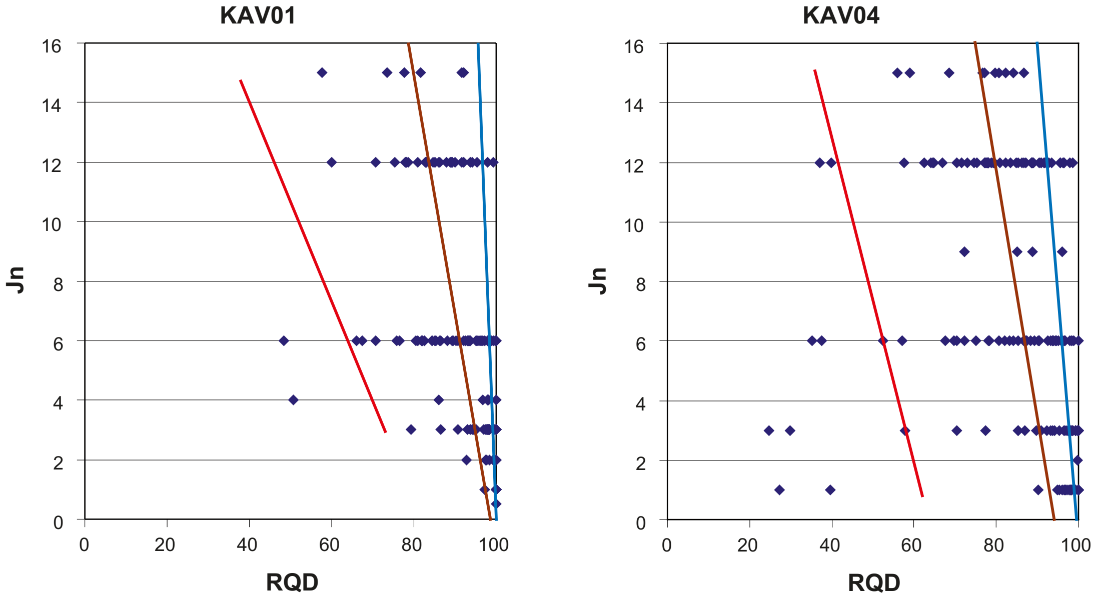

Figure 5-1. *The RQD for borehole sections of 5 m versus J_n values from borehole KAV01 (left) and KAV04 (right) at Simpevarp. The relations between the two parameters are plotted for: the "best case scenario" (red line), "average case" (dark blue line with squares), and "worst case scenario" (light blue line).*

To decide which trend line to use for the average and frequent values, the linear trends for the mean values for borehole KAV01 and KAV04 are compared. In the diagram of RQD versus J_n for drill-core KAV01, the average trend line is:

$$J_n = -0.79RQD + 78,7 \tag{5}$$

In the diagram of RQD versus J_n for borehole KAV04, the average relation between RDQ and mean J_n with equation:

$$J_n = -0.83RQD + 78.3 \tag{6}$$

Considering that Equations 5 and 6 are very similar, the relation used for the mean values in this report is the average of the trends found in the two boreholes:

$$J_n = -0.8RQD + 78.5 \tag{7}$$

5.3 Relation between J_n and fracture frequency at Simpevarp

The correlation between J_n and the fracture frequency was investigated for the same two boreholes KAV01 and KAV04. For these boreholes, it was found that the relation between the two parameters was not as strong as the correlation between J_n and RQD, therefore the latter relation was used for the evaluation of J_n for KBH02.

5.4 Quality of the rock mass along KBH02

5.4.1 Characterisation with RMR

The geomechanical parameters were determined for two different lengths of sections along the borehole KBH02. One investigation was made for sections of 5 m and one for 1 m length (see also the appendix). For each section the statistical parameters (minimum, average, most frequent and maximum) for RMR were determined. The RQD, fracture conditions, spacing rating used to estimate the RMR are shown in Figure 5-2 and Figure 5-3. When comparing the RMR ratings for the different rock types, the mylonite stands out as much less competent and with lower RMR rating that the other rock types. This can be expected for a rock classified as mylonite in contraposition to rock types of more intact kind like granite and aplite. The RMR rating for the mylonite at depth (235–245 m) in KBH02 falls just between the two RMR rating classes "fair" and "poor rock" (RMR for 5 m interval is 41.2 and for 1 m is 38.1), whereas all the sections with granite, granodiorite and aplite fall within the RMR rating classes of "good" and "fair rock" mass.

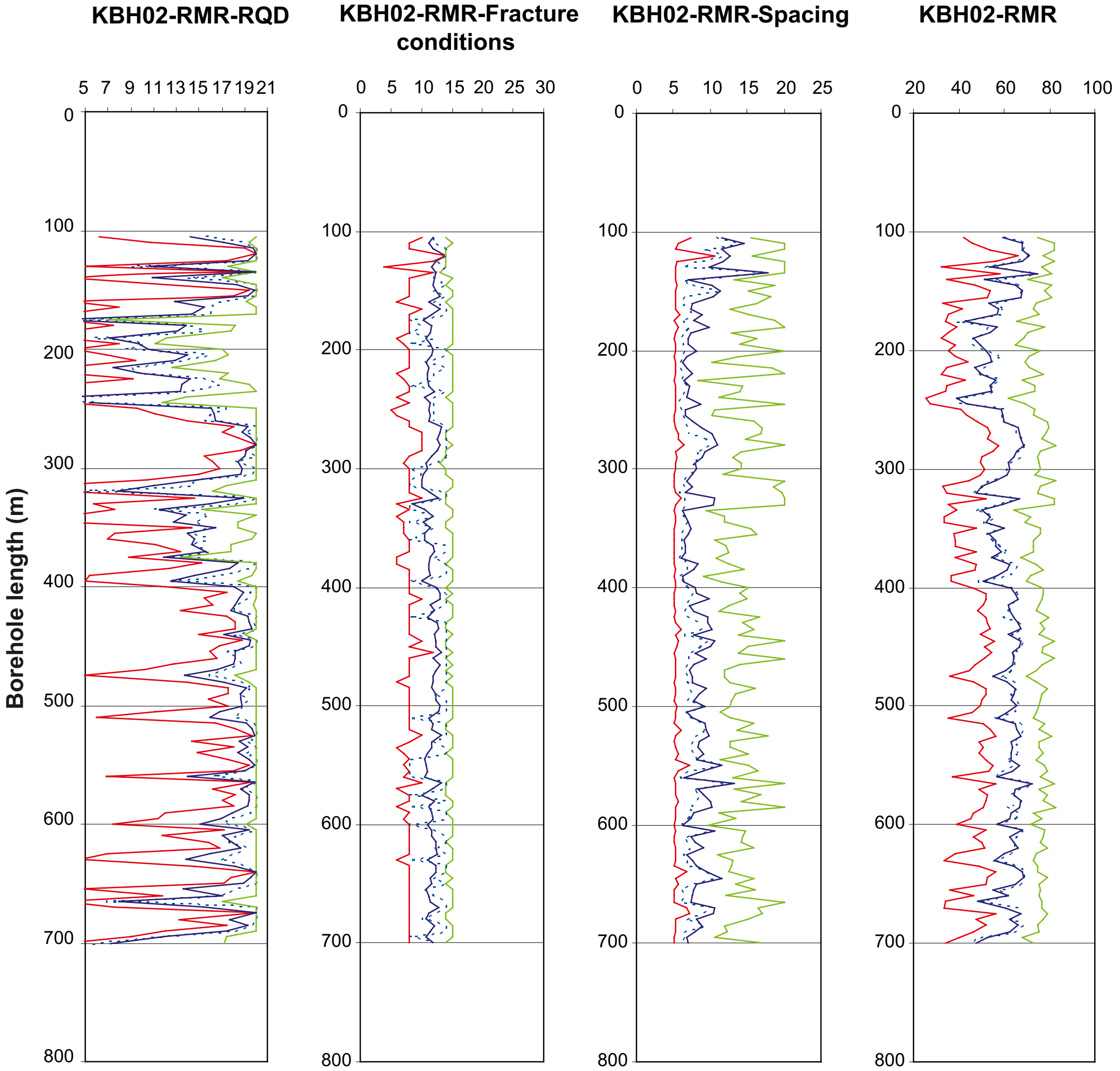

Figure 5-2. Ratings for RMR characterisation and resulting RMR values for borehole KBH02. The ratings for RQD, fracture conditions, fracture spacing are plotted along the borehole together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, and most frequent and maximum values observed every core section of 5 m length, respectively. The possible maximum and minimum values are only used for the evaluation of the uncertainties.

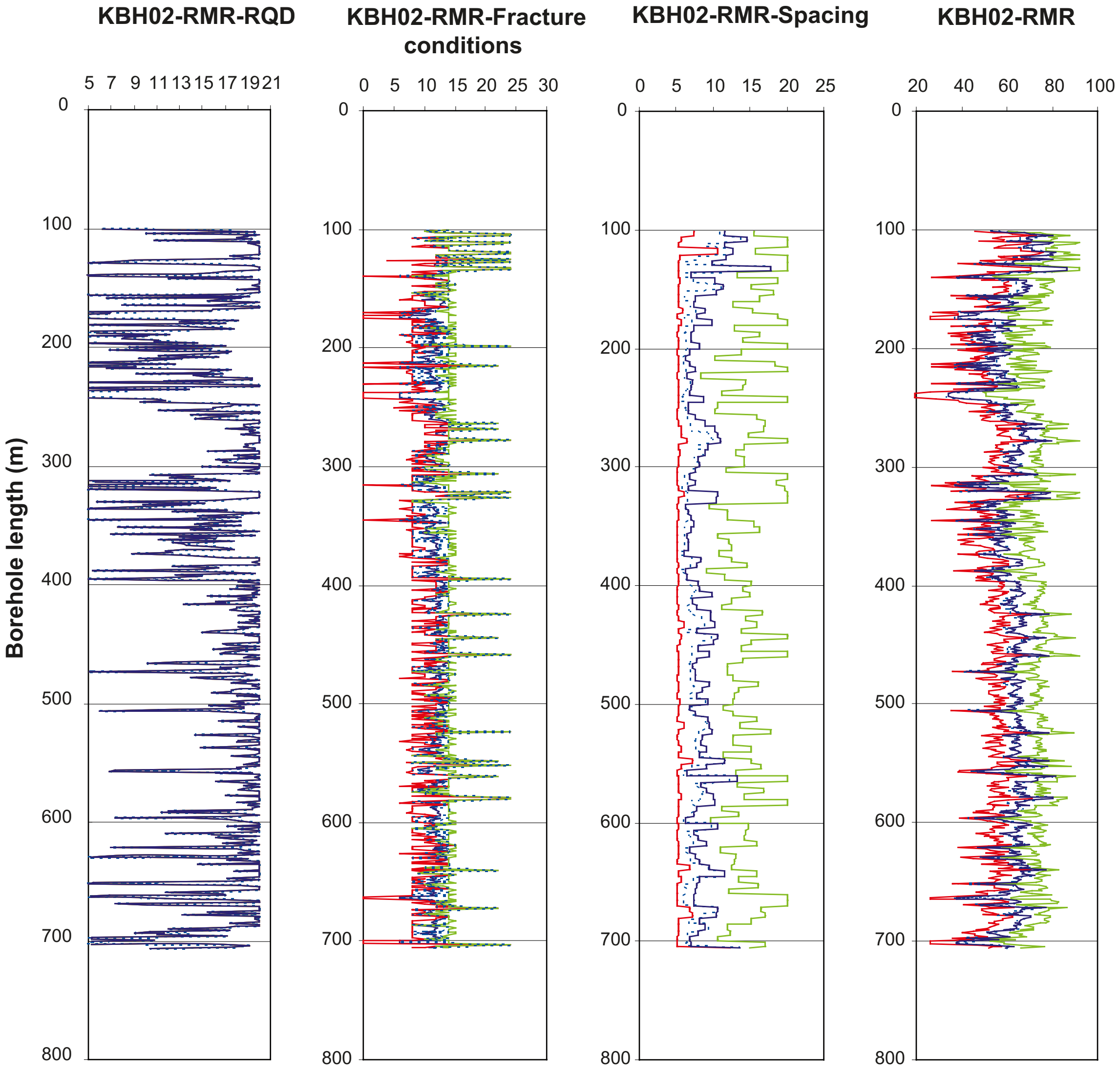

Figure 5-3. *Ratings for RMR characterisation and resulting RMR values for borehole KBH02. The ratings for RQD, fracture conditions, fracture spacing are plotted along the borehole together with RMR. The lines in red, blue, dashed blue and green represent the minimum, average, and most frequent and maximum values observed every core section of 1 m length, respectively. The possible maximum and minimum values are only used for the evaluation of the uncertainties.*

Figure 5-4 and Figure 5-5 show the frequency distribution of RMR for the competent rock mass and fractured rock in KBH02. Both the tables show that the rock in fractured zones has more variable quality than the competent rock. Furthermore, the characterisation performed on borehole sections of 1 m results in the same distribution of RMR values for the competent rock, but a much more widely spread distribution of the properties of the fractured rock mass compared with the results for 5 m borehole sections. This can be explained with the averaging effect that applies to longer borehole sections.

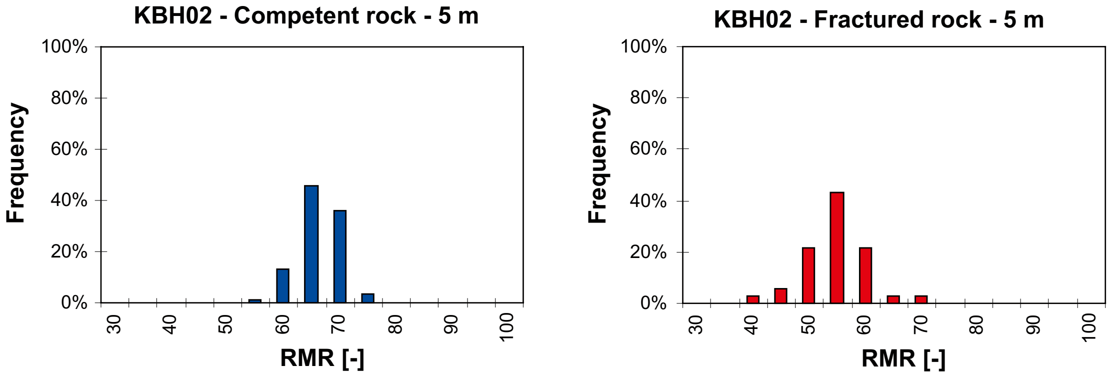

Figure 5-4. *Frequency distributions of the RMR values calculated on borehole sections of 5 m for competent rock mass (left) and fractured rock (right) along KBH02.*

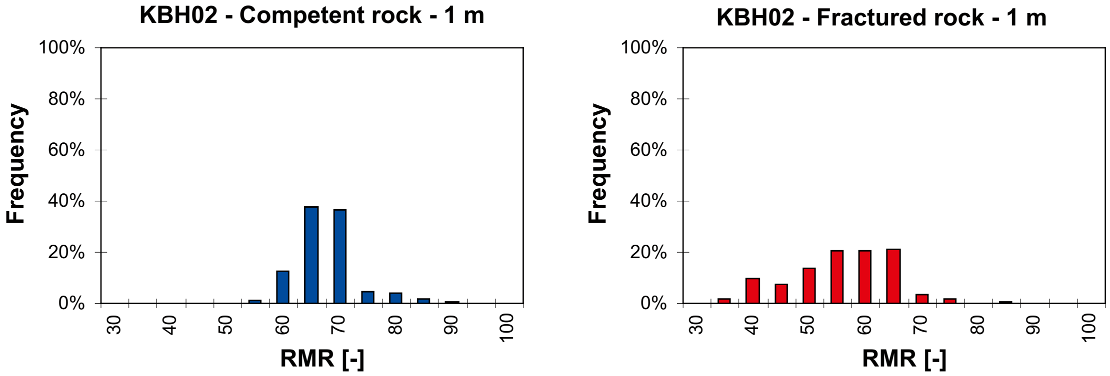

Figure 5-5. *Frequency distributions of the RMR values calculated on borehole sections of 1 m for competent rock mass (left) and fractured rock (right) along KBH02.*

5.4.2 Characterisation with Q

To obtain Q, parameters like the number of fracture sets J_n, the fracture roughness parameter J_r, the fracture alteration parameter J_a and the stress reduction factor SRF must be determined. These are presented in Figure 5-6 and Figure 5-7 as derived from borehole information for sections of 1 and 5 m length. Due to lack of orientation information, the fracture set number J_n has been estimated by using the relations in Section 5.2 based on information from boreholes KAV01 and KAV04. Between 235 and 245 m, the average Q is lower than for the other rock units in the borehole. The poorest Q observed at this depth is about 0.1 which is classified by the Q system as "very poor rock". The rest of the rock mass along the borehole falls under the class of "good rock" mass with Q rates between 10 and 40 with a few exceptions.

The frequency distribution of Q for the competent rock does not seem to follow a normal but rather a uniform distribution (see Figure 5-8 and Figure 5-9, left). Concerning the quality of the rock mass in the more fractured parts, this seems to be more peaked around values of 1 to 4. Differently than for RMR, Q does not show much variation in spread when taking 1 m borehole intervals instead of 5 m. Thus, Q could be less sensitive to the local features than RMR is (cf. Section 5.4.1).

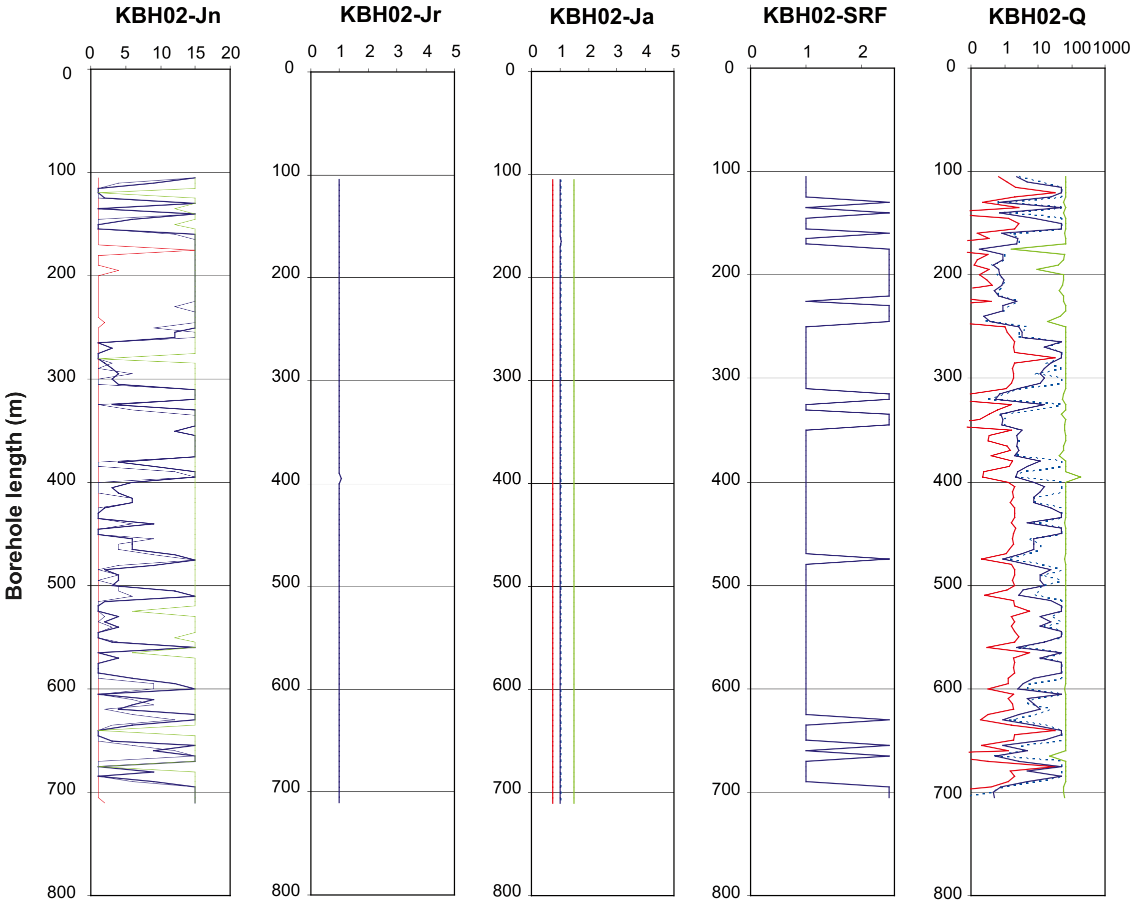

Figure 5-6. *Numbers for Q characterisation and resulting Q values for borehole KBH02. The number for fracture set number, fracture roughness, fracture alteration and SRF are plotted along the borehole together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, and most frequent and maximum values observed every core section of 5 m length, respectively. The possible maximum and minimum values are only used for the evaluation of the uncertainties.*

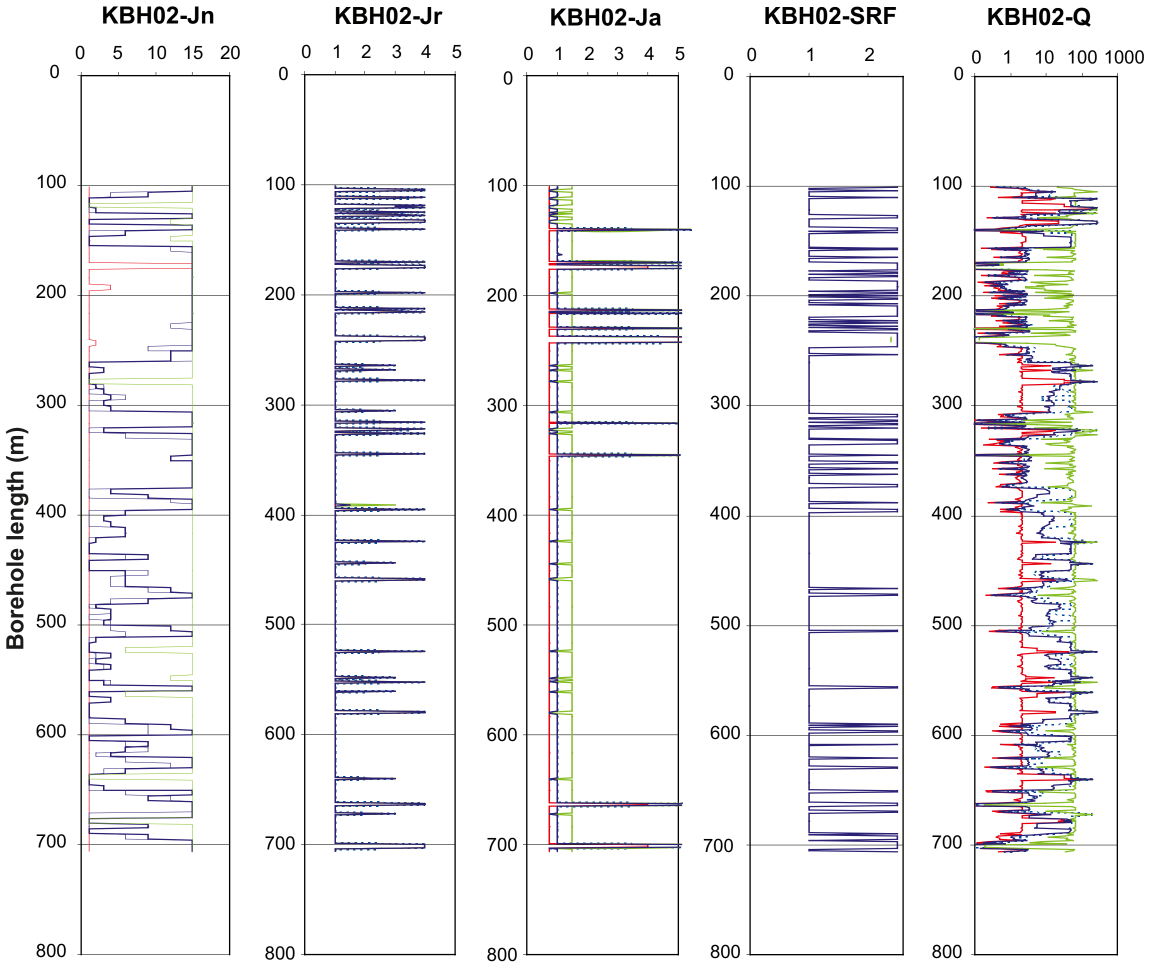

Figure 5-7. *Numbers for Q characterisation and resulting Q values for borehole KBH02. The number for fracture set number, fracture roughness; fracture alteration and SRF are plotted along the borehole together with Q. The lines in red, blue, dashed blue and green represent the minimum, average, and most frequent and maximum values observed every core section of 1 m length, respectively. The possible maximum and minimum values are only used for the evaluation of the uncertainties.*

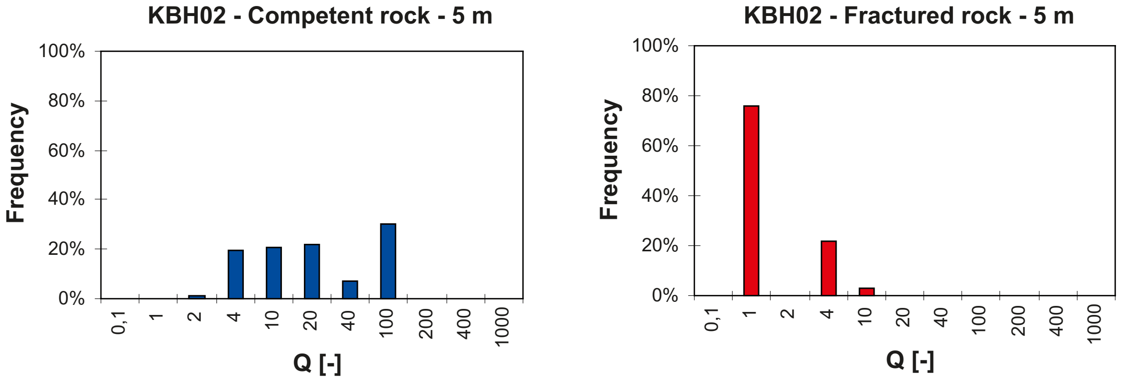

Figure 5-8. *Frequency distributions of the Q values calculated on borehole sections of 5 m for competent rock mass (left) and fractured rock (right) along KBH02.*

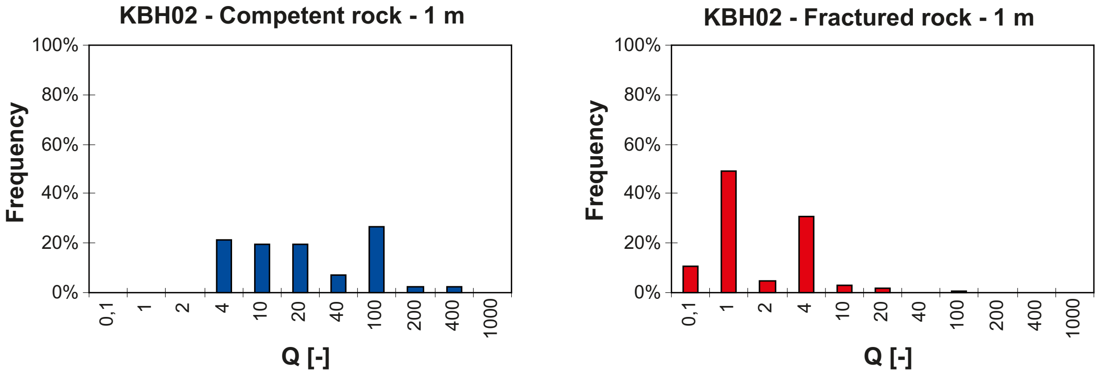

Figure 5-9. *Frequency distributions of the Q values calculated on borehole sections of 1 m for competent rock mass (left) and fractured rock (right) along KBH02.*

5.5 Evaluation of the uncertainties

5.5.1 Background

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

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

The spatial variability of the geological parameters adds more variability to the indices and ratings and this also mirrors onto the uncertainty of the mean value. For removing the spatial variability, the differences between possible maximum and mean value and possible minimum and mean value are evaluated for each section of 1 m or 5 m borehole length 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 Δconf mean is obtained as:

$$\Delta_{conf\ mean} = \pm \frac{1.96\,\sigma}{\sqrt{n}} \tag{8}$$

where σ is the standard deviation of the population and n is the number of values of the each sample. In KBH02, there are on average 6 sections of 5 m within each rock unit in competent rock, and there are around 2 sections of 5 m within each deformation zone.

In practice, two confidence intervals are determined by the proposed technique, one related to the maximum value of RMR and Q, and the other related to the minimum value:

$$\Delta P_{+conf\ mean} = \frac{P_{MAX} - P_{MEAN}}{\sqrt{n}} \tag{9}$$

$$\Delta P_{-conf\ mean} = \frac{P_{MEAN} - P_{MIN}}{\sqrt{n}}$$

where P is the rating, either RMR or Q, with its possible maximum and minimum values and mean value, respectively.

5.5.2 Uncertainty of RMR and Q

The uncertainty of RMR and Q is calculated based on Section 5.5.1 and the interval of variation of the mean are expressed by means of the width of the interval of possible variation of the mean value as:

- For RMR, by the percentage of the mean value itself (Table 5-2).
- For Q, by the range of values of possible variation of the most frequent value of Q (Table 5-3).

Since the Q system is somehow structured according to a logarithmic scale, Equations 8 and 9 are applied to the log10Q, and then reconverted to Q values. Table 5-2 and Table 5-3 also provide a comparison of the uncertainty interval of the mean RMR and Q when these are calculated over sections of borehole of 5 or 1 m length. It can be seen that the uncertainty on the parameters determined on shorter borehole sections is less than that determined for longer borehole sections. This is due to the fact that shorter sections do not apply averaging processes in the same extent as for the longer sections, thus the uncertainty on the mean values is smaller. Furthermore, being the sections of 1 m more numerous than the sections of 5 m, their statistics are calculated over a larger population and are therefore more stable (e.g. have narrower uncertainty intervals).

Table 5-2. Uncertainty of the mean values of RMR (as a percentage of the mean value) for borehole KBH02.

	Competent rock mass		**Fractured rock**	
	Lower confidence on the mean	**Upper confidence on the mean**	**Lower confidence on the mean**	**Upper confidence on the mean**
KBH02 5 m sections	–2%	+2%	–5%	+6%
KBH02 1 m sections	–1%	+1%	–1%	+2%

Table 5-3. Uncertainty of the most frequent values of Q (as range of Q values) for borehole KBH02.

	Competent rock mass		**Fractured rock**	
	Lower confidence on the mean	**Upper confidence on the mean**	**Lower confidence on the mean**	**Upper confidence on the mean**
KBH02 5 m sections	9	14	0.6	1.6
KBH02 1 m sections	12	17	0.8	1.0

6 Determination of minor deformation zones and comparison with the results of the Expect Project

Even though the Fennoscandian shield is one of the most tectonically stable areas in the world, there have been post-glacial movements /Lagerbäck 1991, Mörner 1996, 2004, Mörner et al. 2000/. A sudden movement in one of the many fracture zones crossing this shield can jeopardize the safety of a nuclear waste repository if it has an unfavourable position. Major efforts have been made to investigate the size of fractures that will be able to deform sufficiently to break a canister /La Pointe et al. 1997, La Pointe and Caldouhos 1999, La Pointe et al. 2000, La Pointe et al. 2002, Munier and Hökmark 2004/. These fracture zones are called minor deformation zones (MDZ), defined as "an essentially 2-dimensional structure whose lateral extent is < 1,000 m and width < 5 m. MDZ commonly show evidence of both brittle and ductile deformation. They can be characterised by brittle, low-cohesive products such as fractures, breccias and gouge or by cohesive strongly foliated or mylonitic rock the product of ductile deformation" in /SKB 2006b/. They typically have a radius between 50 and 250 m, and it is crucial to identify these features during the construction phase of a repository. To find ways to identify MDZ, the EXPECT (EXPloitation ratio and resPECT distance) Project was carried out /SKB 2006b/. Several methods for identifying long fractures prior to the excavation and from tunnel and borehole observations have been investigated. These methods (e.g. geophysical methods, rock mass characterization) might provide the geological, hydraulic and mechanical properties of the rock mass necessary to identify MDZ.

In the EXPECT Project, geological and geomechanical information from borehole KBH02 has been used for comparison against the data collected along the Access Tunnel of the Äspö Hard Rock Laboratory. The main aim of the study was to investigate the deformation zones identified at the site. Borehole KBH02, the tunnel mapping data and data obtained from other borehole investigations were used to study the mutual correlation of the results and test the technique for identification of the fracture zones. It is worth to mention that the EXPECT Project did not make use of the rock mass characterisation/classification systems RMR and Q routinely used in rock mechanics.

In this report, an alternative method for the identification of MDZ using the empirical systems Q and RMR is tested. Different signatures of interesting minor deformation zones are identified and analysed. The results are then compared with the outcome of the EXPECT Project.

6.1 Determination of the deformation zones based on the empirical systems Q and RMR

The characterisation in Section 5 can be used to investigate the presence of a particular signature that identifies the deformation zones not only in geological terms, such as "a sub-planar structure with a small thickness relative to its lateral extent in which defirmation has been concentrated" /SKB 2006b/, but also in terms of rock mass quality for rock mechanics applications. In this section, different "filters" are applied at the same time to the values of Q and RMR. The sections of borehole with Q and RMR lower than the threshold values are assumed to be "minor deformation zones" and they can sometimes be grouped together with contiguous sections to form larger and/or "deterministic deformation zones". Two signatures were tested: one applicable to very good rock masses (e.g. Forsmark Site /SKB 2006c/), and the other applicable to fairly good rock masses (e.g. Simpevarp and Laxemar /SKB 2005, 2006c/). Conclusions about the applicability of these "signatures" to the Laxemar-Simpevarp Site are also drawn.

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

The first 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 crossed by deformation zones (e.g. Forsmark /SKB 2006d/). This signature can be expressed by the following thresholds for Q and RMR:

Deformation Zone Signature 1: $Q < 4$ *and/or* $RMR < 60$ (10)

The application of this signature to the data in Section 5 results into the plots in Figure 6-1 and Figure 6-2 for Q and RMR, respectively. The deformation zones identified by Equation 10 are highlighted in grey on the right side of the figures. It can be observed that, although the characterisation performed on 5 m borehole sections cannot recognise the smallest deformation zones, it provides a precise estimation of the width of the larger deformation zones (Table 6-1). This is due to the averaging process of the characterisation for 5 m intervals that tends to put together contiguous sections of poorer or better rock mass resulting into localised and persistent deformation zones along the borehole.

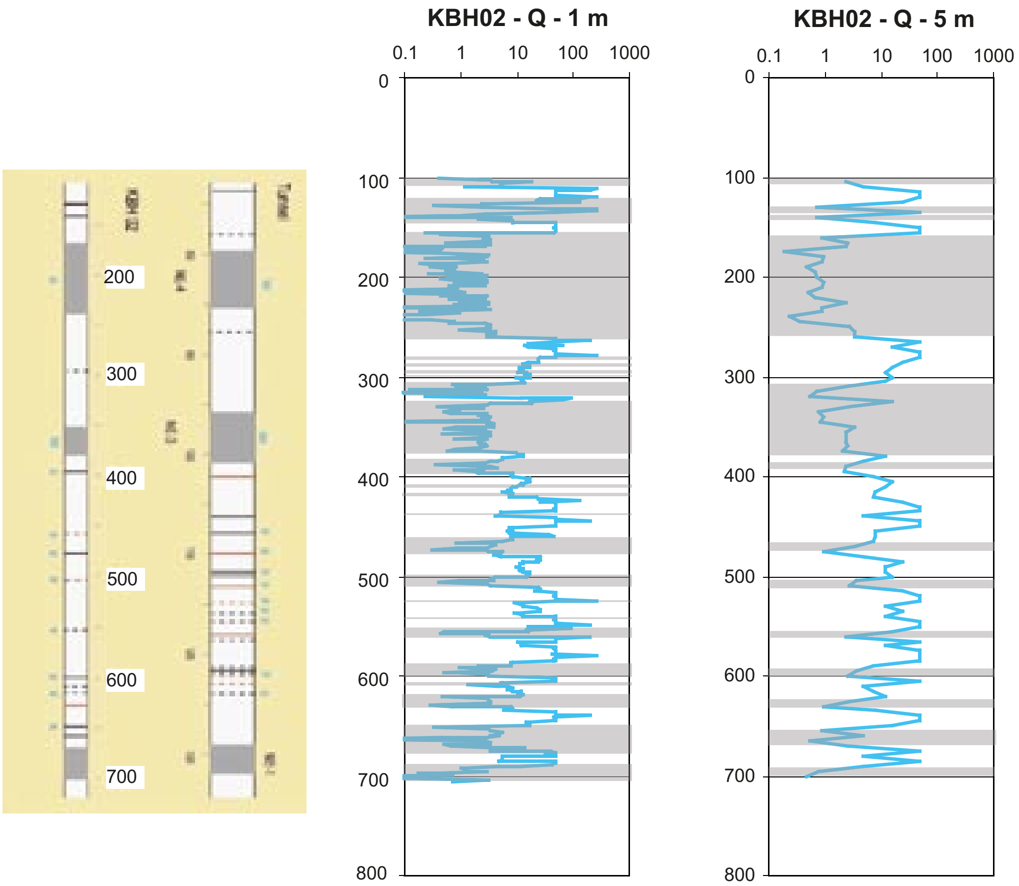

Figure 6-1. *Mean Q for borehole sections of length of 1 m (centre) and 5 m (right). The deformation zones identified according to Signature 1 in Equation 10 are marked in grey. On the left, the zones independently identified in borehole KBH02 and the Äspö HRL Access Tunnel by the EXPECT Project /SKB 2006b/ are presented.*

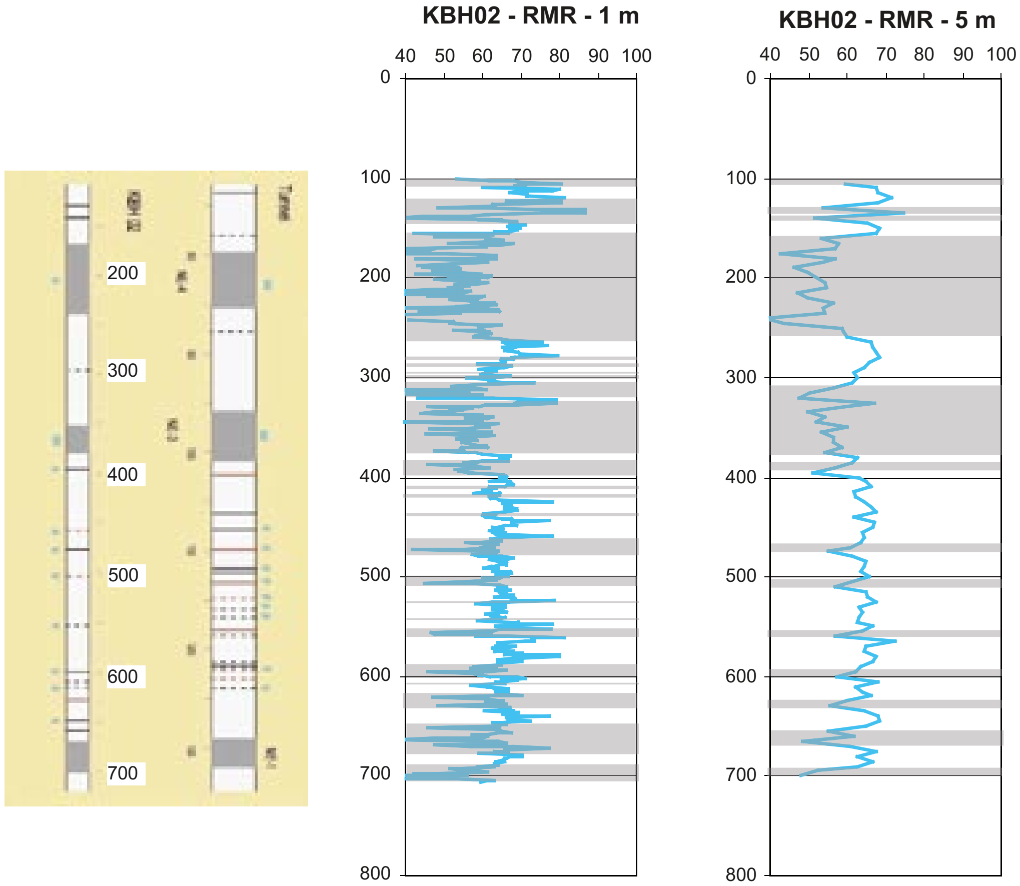

Figure 6-2. *Mean RMR for borehole sections of 1 m (centre) and 5 m (right) along KBH02. The deformation zones identified according to Signature 1 in Equation 10 are marked in grey. On the left, the zones independently identified in borehole KBH02 and the Äspö HRL Access Tunnel by the EXPECT Project /SKB 2006b/ are presented.*

Table 6-1. Deformation zones identified in KBH02 by means of Signature 1 applied to the empirical values of Q and RMR.

Deformation zones 1 m sections	Apparent thickness 1 m sections	Deformation zones 5 m sections	Apparent thickness 5 m sections
100–104 m	≥ 4 m	100–105 m	≥ 5 m
109–110 m	1 m		
125–129 m	4 m	125–130 m	5 m
135–142 m	7 m	135–140 m	5 m
155–260 m	105 m	155–260 m	105 m
286–287 m	1 m		
290–291 m	1 m		
295–296 m	1 m		
300–301 m	1 m		
306–320 m	14 m		
326–377 m	51 m	305–390 m	85 m
383–396 m	13 m		
411–412 m	1 m		
415–416 m	1 m		
438–439 m	1 m		
464–479 m	15 m	465–475 m	10 m
501–510 m	9 m	500–510 m	10 m
526–527 m	1 m		
543–544 m	1 m		
555–560 m	5 m	555–560 m	5 m
589–600 m	11 m	590–600 m	10 m
608–609 m	1 m		
620–630 m	10 m	620–630 m	10 m
650–678 m	28 m	650–670 m	20 m
689–706 m	≥ 17 m	695–705 m	≥ 10 m

6.1.2 Signature 1: Comparison with the results of the EXPECT Project

Figure 6-1 and Figure 6-2 compare the results of the empirical characterisation presented in this report with the results independently obtained by the EXPECT Project /SKB 2006b/ for borehole KBH02 and the adjacent Äspö HRL Access Tunnel. The plots are shown with the same scale, thus it can be immediately concluded that, compared to tunnel mapping, Signature 1 applied to KBH02 can identify the large deformation zones (NE-4, NE-3 and NE-1) although it tends to overestimate their width.

Table 6-2 shows that most of the minor features observed in the tunnel by the EXPECT Project can be also identified by the empirical characterisation with a certain approximation of the position of occurrence due to the fact that borehole KBH02 (between 100 and 700 m) and the Äspö HRL Access Tunnel (between 750 and 1,350) are not exactly parallel to each other and are located about 20–25 m from each other.

Table 6-2. Deformation zones identified in KBH02 by the EXPECT Project and by means of Signature 1 applied to the values of rock mass quality obtained with the empirical systems RMR and Q. The codes indicate: MZ = minor zone; LF = long fractures; deterministic DZ = NE-1, NE-3 and NE-4. In grey, the sections with good agreement between the two methods are indicated. w and ww indicate small (damp-minor seepage, occasional drops) and large (wet-seepage, minor inflow, drops) water inflow, respectively.

EXPECT Deformation Zones in the tunnel	EXPECT Description	EXPECT Water inflow	This study Deformation Zones Q/RMR 1 m	This study Deformation Zones Q/RMR 5 m
			100–104 m 109–110 m	100–105 m
116 m	MZ			
			125–129 m	125–130 m
			135–142 m	135–140 m
161 m	LF		155–260 m	155–260 m
177–239 m	NE-4	ww		
256 m	LF			
			286–287 m	
			290–291 m	
			295–296 m	
			300–301 m	
			306–320 m	
339–390 m	NE-3	ww	326–377 m	305–390 m
401 m	MZ Fg)		383–396 m	
			411–412 m	
			415–416 m	
441 m	MZ		438–439 m	
461 m	MZ	w	464–479 m	465–475 m
480 m	MZ	w		
501 m	MZ	w	501–510 m	500–510 m
506 m	MZ			
516 m	MZ Fg)	w		
529 m	LF Fg)R)	w	526–527 m	
537 m	LF	w		
546 m	LF R)	w	543–544 m	
561 m	MZ Fg)		555–560 m	555–560 m
566 m	LF Fg)			
591–601 m	MZ+LF R)	w	589–600 m	590–600 m
611 m	LF Fg)		608–609 m	
621 m	LF	w	620–630 m	620–630 m
			650–678 m	650–670 m
671–701 m	NE-1	ww	689–706 m	695–705 m

Fg) zone associated with fine-grained granite.
R) zone associated to radar indicator.

Several features highlighted by Signature 1 do not seem to appear in the tunnel according to the EXPECT Project results (see the fields left in white in Table 6-2). On the other hand, only three of the 21 zones identified by EXPECT could not be recognised by this signature.

6.1.3 Signature 2: Q < 1 and/or RMR < 40

The second signature or criterion for identifying minor and deterministic deformation zones might be more suitable for rock masses with overall lower quality (e.g. Laxemar /SKB 2006c/). The signature can be expressed as:

Deformation Zone Signature 2: $Q < 1$ *and/or* $RMR < 40$ (11)

This signature would give almost no returns in Forsmark, where the rock mass quality has on average about Q of 40 and RMR of 85. On the other hand, it provides useful results at least when the borehole section length of 1 m is concerned. Figure 6-3 and Figure 6-4 show the results of the application of Signature 2 to the results of the empirical characterisation of borehole KBH02. It can be clearly seen that this filter is too demanding when applied to the characterisation of 5 m intervals, detecting very few features. The apparent width of the deformation zones identified by Signature 2 is shown in Table 6-3.

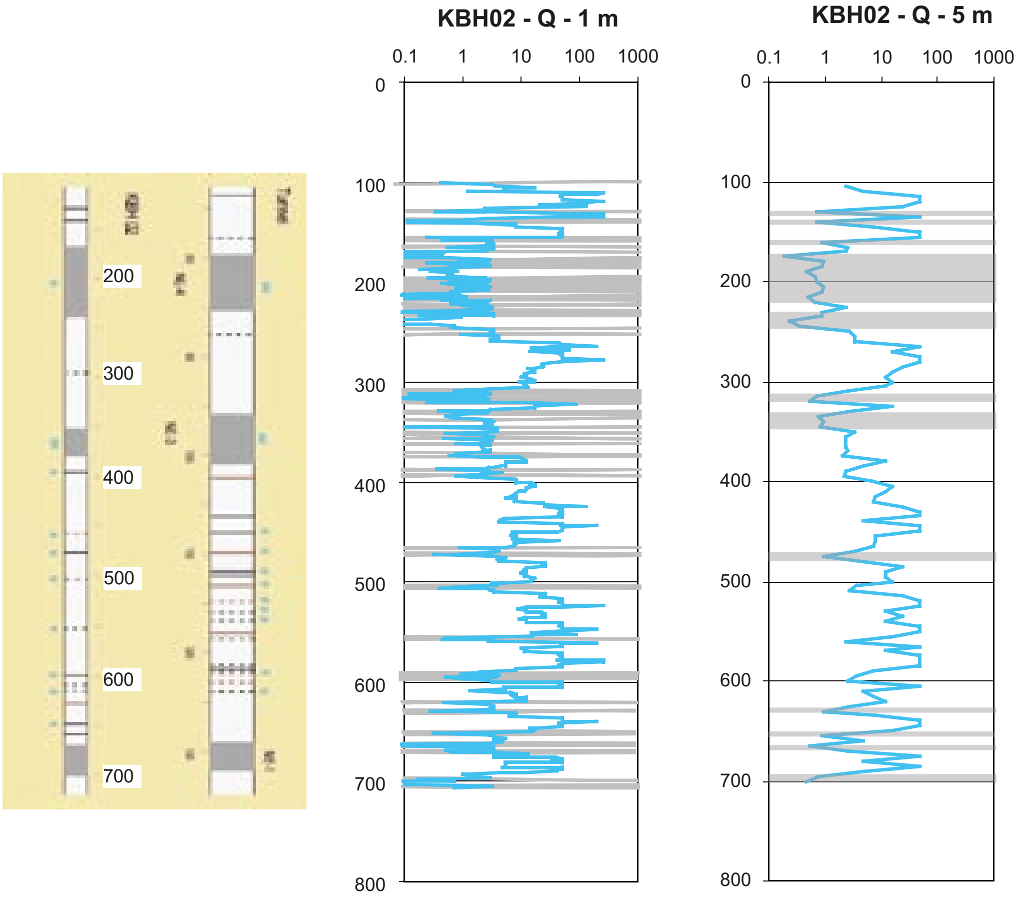

Figure 6-3. *Mean Q for borehole sections of 1 m (centre) and 5 m (right) along KBH02. The deformation zones identified according to Signature 2 in Equation 11 are marked in grey. On the left, the zones independently identified in borehole KBH02 and the Äspö HRL Access Tunnel by the EXPECT Project /SKB 2006b/ are also presented.*

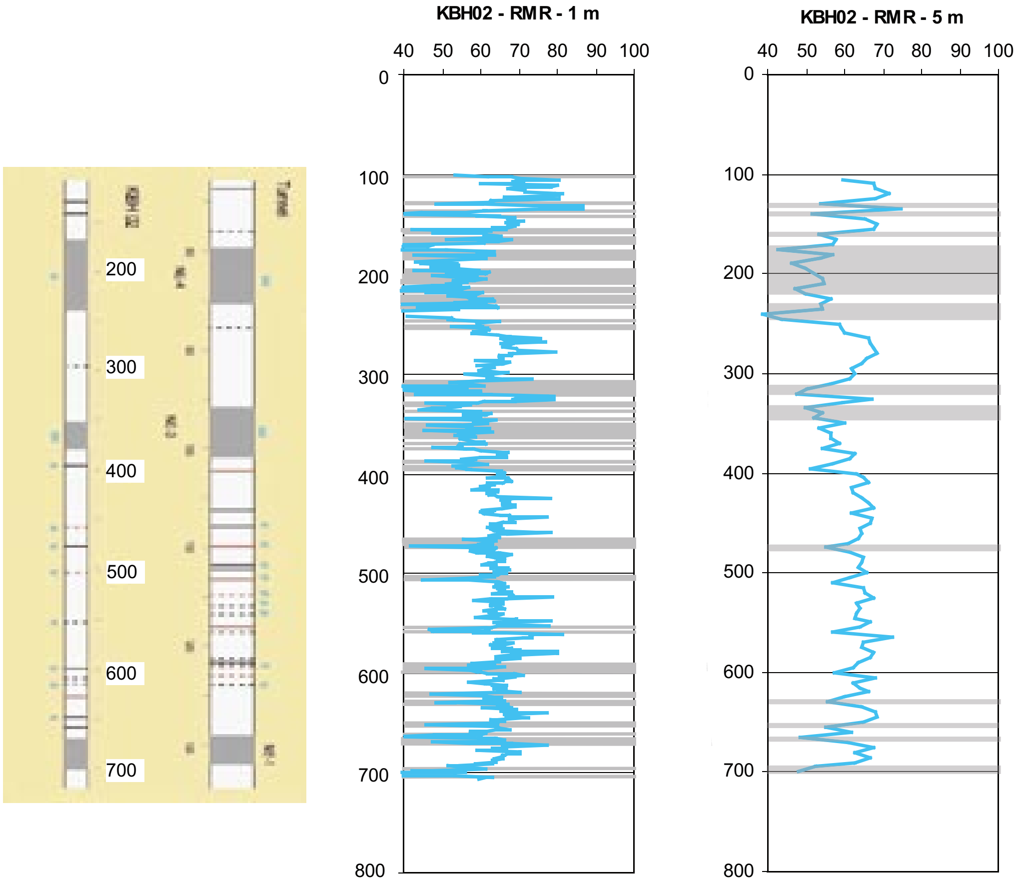

Figure 6-4. *Mean RMR for borehole sections of 1 m (centre) and 5 m (right) along KBH02. The deformation zones identified according to Signature 2 in Equation 11 are marked in grey. On the left, the zones independently identified in borehole KBH02 and the Äspö HRL Access Tunnel by the EXPECT Project /SKB 2006b/ are also presented.*

Table 6-3. Deformation zones identified in KBH02 by means of Signature 2 applied to the empirical values of Q and RMR.

Deformation zones 1 m sections	Apparent thickness 1 m sections	Deformation zones 5 m sections	Apparent thickness 5 m sections
100–101 m	1 m		
128–129 m	1 m	125–140 m	5 m
137–140 m	3 m		
155–158 m	3 m	155–160 m	5 m
164–165 m	1 m		
169–246 m	77 m	170–245 m	75 m
252–253 m	1 m		
307–320 m	13 m	310–320 m	10 m
329–336 m	7 m	330–345 m	15 m
344–345 m	1 m		
350–352 m	2 m		
356–357 m	1 m		
361–362 m	1 m		
371–374 m	3 m		
387–388 m	1 m		
393–394 m	1 m		
465–466 m	1 m		
471–473 m	2 m	470–475 m	5 m
505–506 m	1 m		
555–557 m	1 m		
591–592 m	1 m		
595–597 m	2 m		
620–621 m	1 m		
628–630 m	2 m	625–630 m	5 m
650–652 m	2 m	650–665 m	15 m
661–664 m	3 m		
668–670 m	2 m		
696–706 m	≥10 m	690–700 m	≥ 10 m

6.1.4 Signature 2: Comparison with the result of the EXPECT Project

Signature 2 is able to identify only 13 of the 21 zones mapped by the EXPECT Project along borehole KBH02 /SKB 2006b/. This signature does not seem to be suitable for the characterisation results with 5 m intervals because it does not clearly detect the limits of the major deformation zones (e.g. NE-1). On the other hand, if this signature is applied to Q and RMR values with 1 m characterisation interval, the results become suitable for the recognition of slightly wider zones than for the 5 m characterisation interval, without risk of overestimating their number as for Signature 1.

Table 6-4. Deformation zones identified in KBH02 by the EXPECT Project and by means of Signature 2 applied to the values of rock mass quality obtained with the empirical systems RMR and Q. The codes indicate: MZ = minor zone; LF = long fractures; deterministic DZ = NE-1, NE-3 and NE-4. In grey, the sections with good agreement between the two methods are indicated. w and ww indicate small and large water inflow, respectively.

Deformation Zones in the tunnel	Description	Water inflow	Deformation Zones – Q/RMR 1 m	Deformation Zones – Q/RMR 5 m
			100–101 m	
116 m	MZ		128–129 m	125–140 m
			137–140 m	
161 m	LF		155–158 m	155–160 m
			164–165 m	
177–239 m	NE-4	ww	169–246 m	170–245 m
256 m	LF		252–253 m	
339–390 m	NE-3	ww	307–320 m	310–320 m
			329–336 m	330–345 m
			344–345 m	
			350–352 m	
			356–357 m	
			361–362 m	
			371–374 m	
			387–388 m	
401 m	MZ[Fg]		393–394 m	
441 m	MZ			
461 m	MZ	w	465–466 m	
480 m	MZ	w	471–473 m	470–475 m
501 m	MZ	w		
506 m	MZ		505–506 m	
516 m	MZ[Fg]	w		
529 m	LF[Fg][R]	w		
537 m	LF	w		
546 m	LF[R]	w		
561 m	MZ[Fg]		555–557 m	
566 m	LF[Fg]			
591–601 m	MZ+LF[R]	w	591–592 m	
			595–597 m	
611 m	LF[Fg]			
621 m	LF	w	620–621 m	625–630 m
			628–630 m	
			650–652 m	650–665 m
			661–664 m	
			668–670 m	
671–701 m	NE-1	ww	696–706 m	690–700 m

[Fg] Zones associated with fine-grained granite.
[R] Zones associated to radar indicators.

6.2 Estimation of the actual length of the deformation zones

The geological model for Laxemar version 1.2 /SKB 2006d/ provides a small database of thickness and length of large deterministic deformation zones. Data on thickness can be plotted versus length to study the presence of a relation between the two parameters. Such plot is shown in Figure 6-4. Considering the spread of the data, three envelopes can be determined for the maximum, average and minimum expected values. Such envelops, approximated by exponential functions, can be used to estimate the length of the fracture/deformation zones given their thickness. The apparent thickness of the fracture/deformation zones can be estimated from the borehole information. However, there are often uncertainties in the determination of the real thickness based on the apparent thickness along the borehole since the orientation of the zones might be uncertain or unknown. Based on these premises, rough evaluations of the length of the zones for some recurrent thicknesses are listed in Table 6-5. The average plane of the deformation zone can make different angles α with the borehole axis. Therefore, the predictions can be corrected by applying a factor sin (α).

Table 6-5. Estimation of the length of deformation zones based on their thickness. The zones are assumed to be perpendicular to a borehole oriented parallel to KBH02.

Thickness	Length [km]		
	Min	Mean	Max
1 m	0.01	0.06	0.22
5 m	0.07	0.4	1.5
10 m	0.16	0.9	3.6
20 m	0.4	2.2	8.3
30 m	0.6	3.5	14
50 m	1.2	6.6	25
85 m	2.2	13	48
105 m	2.8	16	62

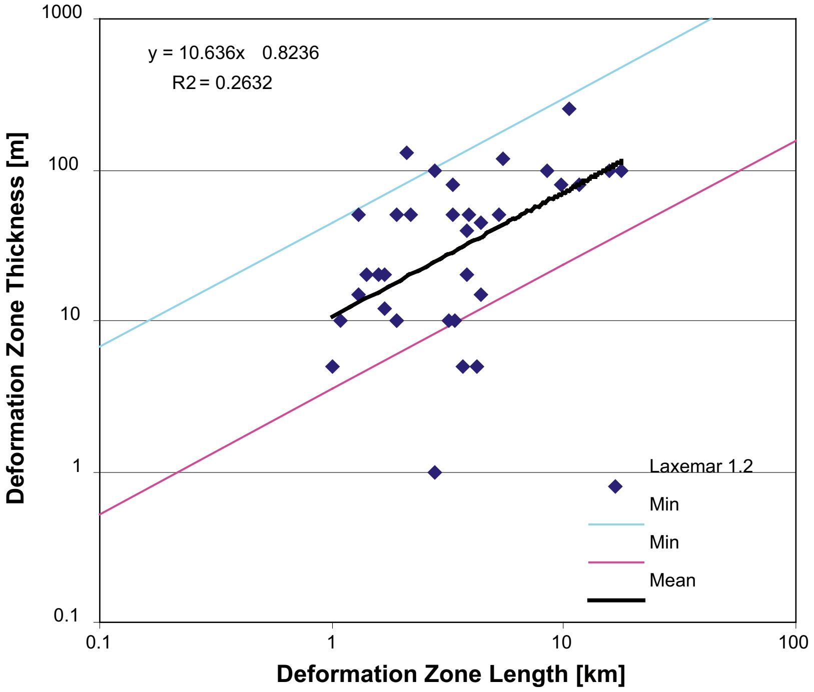

Figure 6-5. Relation thickness-length for the deformation zones in Laxemar 1.2 /SKB 2006c/.

7 Discussion

The tables in Section 6 show that the matching between the zones along KBH02 and along the Äspö Access Tunnel might differ by some metres. A maximum difference of 5 m is allowed between the location of the zones in the borehole and the location of the zones extrapolated from the access tunnel. If the difference is larger than 5 m, the zones in the borehole in the tunnel are not correlated.

Of the two signatures adopted in this report, Signature 1 is better in identifying the minor zones and long fractures than Signature 2 (Table 7-1). Between 75% and 90% of such features are recognised by applying thresholds to the results of the borehole characterisation performed on sections of 1 m. However, minor zones (MZ) are also rather well determined by Signature 2, although its more restrictive thresholds. This does not apply to the long fractures probably because long fractures (LF) do not directly affect the rock mass quality expressed by Q and RMR. Also the number of measurable water inflows (w) is not well predicted by the Signatures since water conditions are not an input parameter of the empirical characterisation of the rock mass along the borehole (contrary to "design" application of RMR and Q).

By introducing less restrictive thresholds as for Signature 1, the position of more numerous features can be determined. This is due to the fact that parameters as fracture aperture, alteration, shearing and infilling might affect the characterisation even if less markedly compared to the minor zones that are often associated with higher fracture frequency. In Table 7-1 the number of MZ, LF and w identified in the different signatures are compared to the Access Tunnel mapping and the match is expressed in percentage within brackets. With Signature 1, however, the total extension of the deformation zones might be overestimated (from 24% to 46% as shown in Table 7-1).

Table 7-1. Summary of the comparison between the Äspö HRL Access Tunnel mapping reported by the EXPECT Project /SKB 2006b/ and the empirical characterisation of borehole KBH02 with 1 m sections by means of Signature 1 and 2.

	Number of minor zones MZ	Number of long fracture LF	Number of water inflows w	Percentage in length of deformation zones
Access Tunnel mapping	10 MZ	8 LF	9 w	23%[1)]
Borehole characterisation 1 m – Signature 1	9 MZ (90%)	6 LF (75%)	7 w (78%)	51%[2)]
Borehole characterisation 1 m – Signature 2	8 MZ (80%)	3 LF (38%)	4 w (44%)	24%[2)]

[1)] Deterministic deformation zones only.
[2)] All deformation zones.

Table 7-2. Summary of the comparison between the Äspö HRL Access Tunnel mapping reported by the EXPECT Project /SKB 2006b/ and the empirical characterisation of borehole KBH02 with 5 m sections by means of Signature 1 and 2.

	Number of minor zones MZ	Number of long fracture LF	Number of water inflows w	Percentage in length of deformation zones
Tunnel mapping	10 MZ	8 LF	9 w	23%[1)]
Borehole characterisation 5 m – Signature 1	5 MZ (50%)	3 LF (38%)	4 w (44%)	46%[2)]
Borehole characterisation 5 m – Signature 2	2 MZ (20%)	2 LF (25%)	3 w (33%)	26%[2)]

[1)] Deterministic deformation zones only.
[2)] All deformation zones.

When applying the signatures to the empirical characterisation results obtained for each 5 m interval, nearly the same total length of deformation zones as for 1 m intervals is obtained (Table 7-2). On the other hand, the 5 m interval characterisation fails to locate the position of most of the long fractures and water bearing features, irrespective of the used signature. Signature 2 applied to the 5 m characterisation intervals provide almost the exact total extension of deformation zones along the borehole. The same result is obtained by Signature 2 applied on 1 m interval characterisation, but this characterisation is more detailed and thus more time consuming.

The correlation between the values of Q and RMR obtained in this report for the characterisation (J_w = 1, SRF = 1 outside the deformation zones) of borehole KBH02 can be studied in Figure 7-1 and Figure 7-2 for borehole intervals of 5 m and 1 m, respectively. The results, even thought the parameter J_n and J_a for Q and the evaluation of the fracture spacing and length to be used in RMR were estimated based on poorer data that usually available for the SKB Site Investigations /Andersson et al. 2002, Röshoff et al. 2002/, are in very good agreement with the correlations published earlier in the literature. When comparion the results from KBH02 with the results from boreholes in the Simpevarp and Laxemar area, seen in Figure 7-3, the 5 m interval results overlap and the range is quite consistent compared to the other boreholes. The range of the results for 1 m interval shows a wider variation than for 5 m due to averaging effects on all parameters applied by longer borehole intervals.

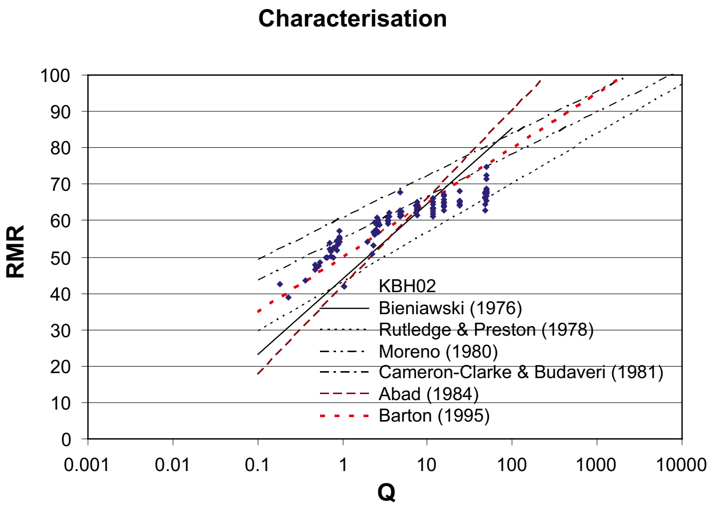

Figure 7-1. Correlation between RMR and Q for the characterisation of the rock mass along borehole KBH02 (core intervals of 5 m). The characterisation results are compared with some design relations from the literature.

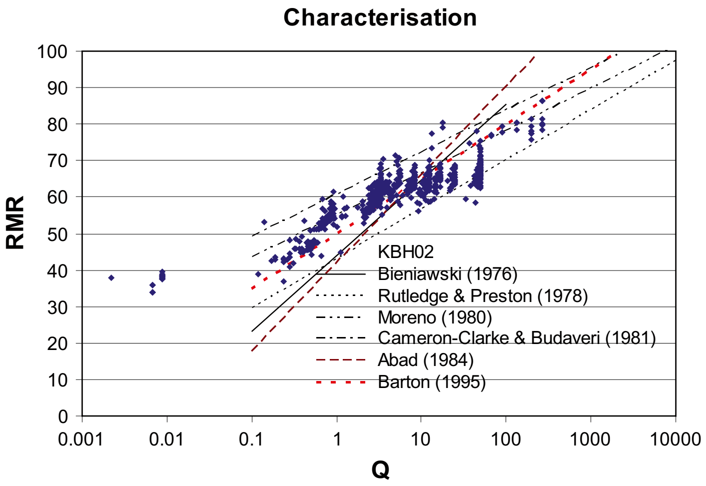

Figure 7-2. *Correlation between RMR and Q for the characterisation of the rock mass along borehole KBH02 (core sections of 1 m). The characterisation results are compared with some design relations from the literature.*

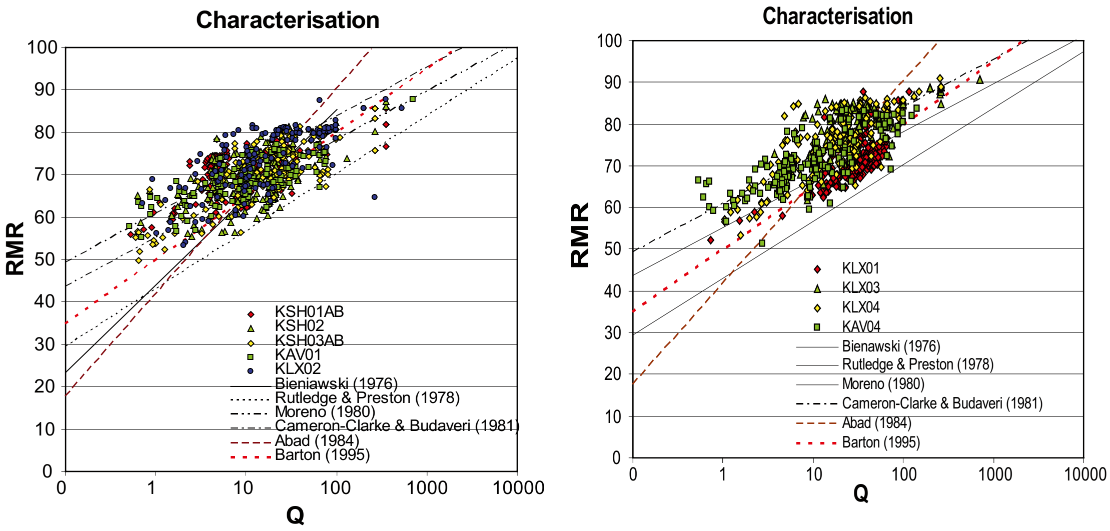

Figure 7-3. *a) Correlation between RMR and Q for the characterisation of the rock mass along boreholes KSH01AB, KSH02, KSH03AB, KAV01 and KLX02 (core sections of 5 m) from /Lanaro and Bäckström 2005a/. b) Correlation between RMR and Q for the characterisation of the rock mass along boreholes KLX01, KLX03, KLX04 and KAV04 (core sections of 5 m) from /Lanaro and Bäckström 2005b/ The characterisation results are compared with some design relations from the literature.*

8 Conclusions

The conclusion of this study is that the Q and RMR empirical systems exclusively applied to PETROCORE data (SICADA) give a fairly good match with the tunnel mapping results concerning number, location and thickness of the major zones. Furthermore, this study indicates that the empirical characterization carried out on 1 m sections by using the thresholds $Q < 4$ and/or $RMR < 60$ (Signature 1) is suitable for the localisation of the minor features outside the major deformation zones. Of the 19 minor zones and long fractures identified by the EXPECT Project, 15 could be also detected by the borehole empirical characterisation in approximately the same position.

The comparison of the characterization of 1 m sections of KBH02 with the adjacent tunnel mapping have also the potential to estimate the frequency of "water bearing" minor zones and long fractures in the tunnel /SKB 2006b/. In fact, by means of the thresholds $Q < 4$ and/or $RMR < 60$ (Signature 1), the position of 7 out of 9 water bearing features in the tunnel could be predicted by the borehole characterisation. The number of minor zones and long fractures may be of importance for hydraulic modelling (i.e. flow and grouting analyses), even thought these zones are not expected to influence much the mechanical stability assessments. It may be interesting to notice that the Q and RMR systems applied for characterisation do not make use any flow information as input of the rock mass quality determination (contrary to "design" applications that consider rock stresses, water pressure and tunnel orientation). However, the total "volume" (i.e. length along a borehole) of minor zones would be overestimated if the thresholds of $Q < 4$ and/or $RMR < 60$ (Signature 1) are used to determine the extension of the deformation zones. Thus, the thresholds of $Q < 1$ and/or $RMR < 40$ (Signature 2) applied to 5 m sections might be more suitable for the identification of the major deformation zones (e.g. NE-1).

The uncertainty of the average RMR and most frequent Q values were also determined. The uncertainty is only slightly affected by the length of the borehole interval chosen (values are given here for sections of 5 m). For RMR, the uncertainty of the mean is between 1% and 2% of the mean RMR value itself for the competent rock mass and between 1% and 6% for the fractured/deformation zones, respectively. The average RMR for the competent rock mass is 63.9 and for the fractured rock 52.6, respectively. For Q, the most frequent value is 11.7 which might vary between 9 and 14 for the competent rock mass. For the fractured rock/deformation zones, the most frequent value of Q is 0.9 and its uncertainty interval is between 0.6 and 1.6.

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Appendix

KBH02: Rock mass quality

A.1 RMR

RMR values along borehole KBH02 (core sections of 5 m)

Rock unit depth [m]		Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
100–235	RU 1	59.6	63.7	63.7	67.7	5.7	32.2	82.3
235–245	RU 2	38.9	41.2	41.2	43.6	3.4	25.2	69.5
245–305	RU 1	47.6	63.5	63.5	68.7	3.4	41.1	82.9
305–355	RU 3	47.6	55	53.6	67.1	5.9	33.2	82.9
355–360	RU 2	56.3	56.3	56.3	56.3		38.4	73.2
360–395	RU 4	50.9	57.3	57	62.5	4	36.5	77.4
395–550	RU 1	55	63.7	64	67.6	2.8	35.6	81.9
550–705	RU 5	47.8	62.3	63.7	72.6	5.9	33.3	83
RU 1		42.6	61.3	63.3	74.7	6.4	32.2	82.9
RU 2		38.9	51.1	53.2	60	7.4	25.2	76.1
Competent rock		54.2	63.9	64.3	74.7	3.8	35.3	83
Deformation zones		38.9	52.6	53.3	67.7	5.3	25.2	82.3
Whole borehole		38.9	60.4	62.3	74.7	6.8	25.2	83

RMR values along borehole KBH02 (core sections of 1 m)

Rock unit depth [m]		Minimum RMR	Average RMR	Frequent RMR	Maximum RMR	Standard deviation	Min possible RMR	Max possible RMR
100–237	RU 1	36.9	59.7	60.8	86.5	11.1	25.9	91.9
237–244	RU 2	33.9	38.1	35.8	52.4	6.8	19.3	71.7
244–307	RU 1	51.8	64.1	64.7	79.7	5.3	39	91.9
307–355	RU 3	37.4	56.8	57.5	79.2	9.5	26.6	91.9
355–359	RU 2	45.4	56.3	58.3	63	7.6	38.4	72.2
359–398	RU 4	45.8	58.3	57.5	67	5	36.8	77
398–553	RU 1	41.9	64.5	64.4	78.5	4.7	35.6	91.9
553–705	RU 5	37.7	62.5	64.2	81.3	8.1	26.4	90
RU 1		36.9	62.6	63.6	86.5	8.2	25.9	91.9
RU 2		33.9	44.7	41	63	11.3	19.3	72.2
Competent rock		43.8	65.2	64.8	86.5	5.4	33.5	91.9
Deformation zones		33.9	53.5	54.8	80.3	9	19.3	87.5
Whole borehole		33.9	61.5	63.1	86.5	8.6	19.3	91.9

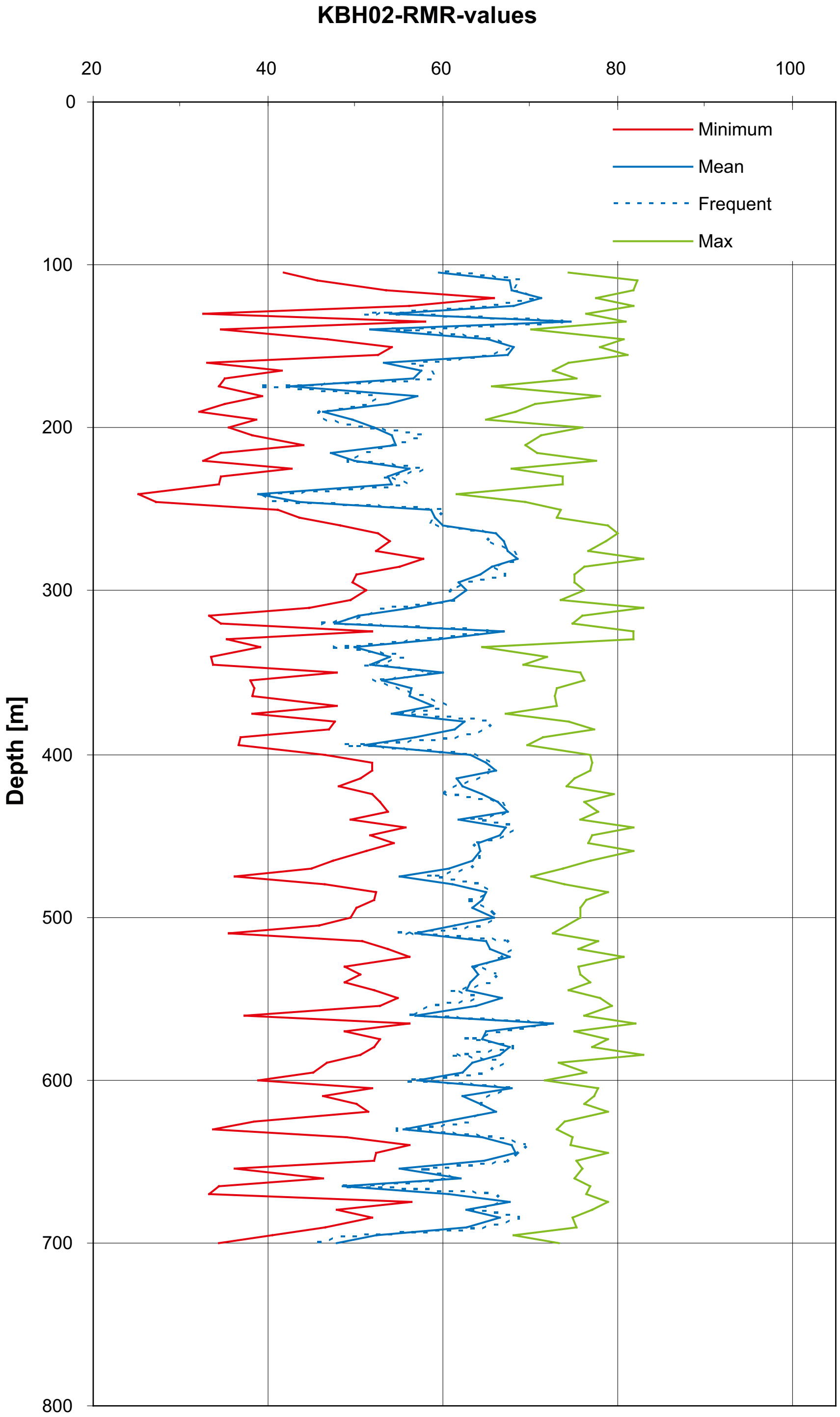

Figure A1-1. *Variation of RMR with depth for borehole KBH02. The values are given every 5 m.*

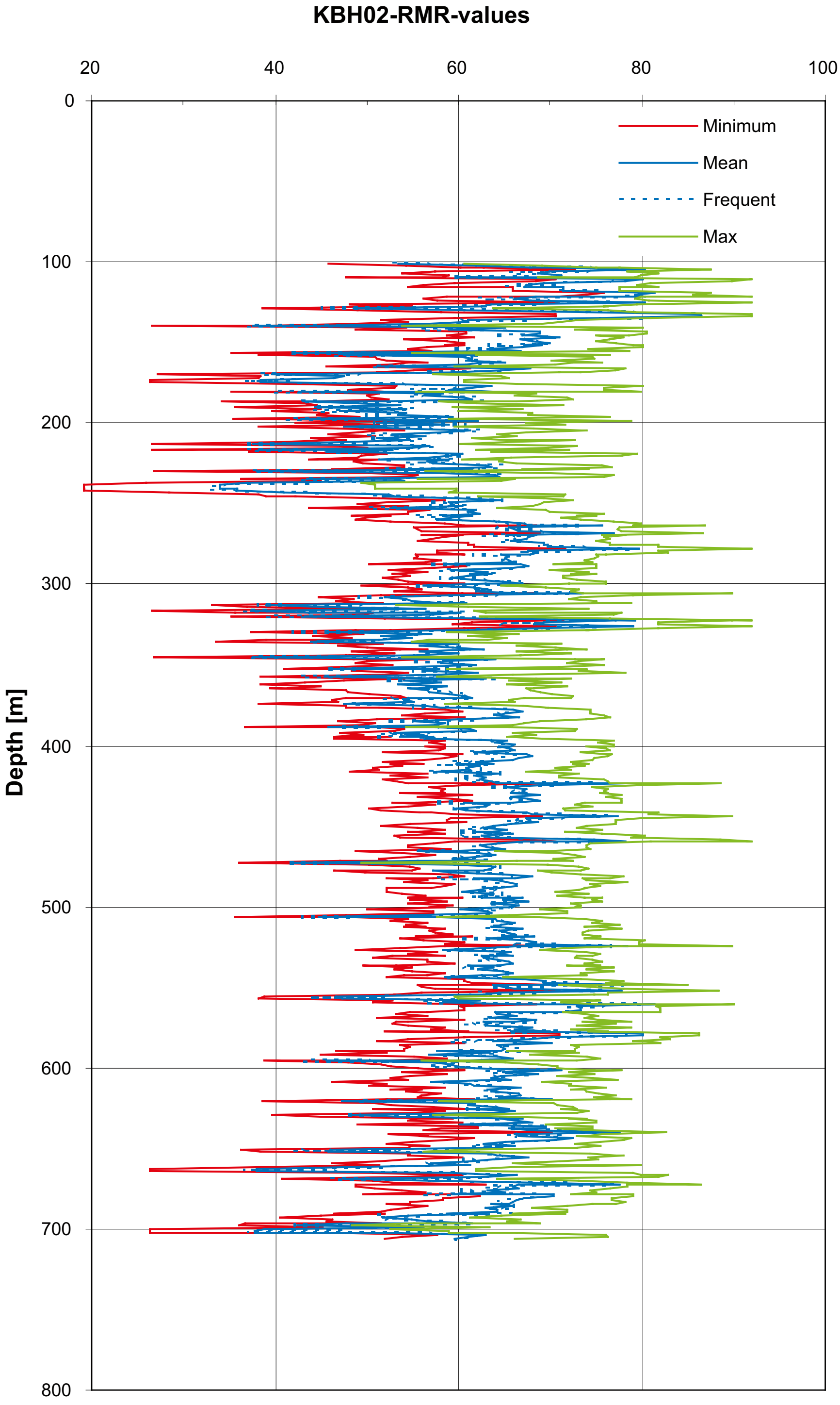

Figure A1-2. *Variation of RMR with depth for borehole KBH02. The values are given every 1 m.*

A.2 Q

Q values along borehole KBH02 (core sections of 5 m)

Rock unit depth [m]		Minimum Q	Average Q	Frequent Q	Maximum Q	Standard deviation	Min possible Q	Max possible Q
100–235	RU 1	2.4	3.6	3.6	4.8	1.7	0.01	66.7
235–245	RU 2	0.2	0.3	0.3	0.4	0.1	0.01	46
245–305	RU 1	0.5	20.9	15.7	50	18	1.1	66.7
305–355	RU 3	0.5	3	1.6	15.8	4.6	0.01	66.7
355–360	RU 2	2.4	2.4	2.4	2.4		0.3	65.3
360–395	RU 4	2	4	2.4	11.5	3.5	0.2	184
395–550	RU 1	0.9	20.7	11.7	49.8	18.1	0.2	66.7
550–705	RU 5	0.5	18.5	7.5	50	20.7	0.01	66.7
RU 1		0.2	17.1	7.6	50	18.8	0.01	66.7
RU 2		0.2	1.5	0.9	3.4	1.2	0.01	66.7
Competent rock		2	21.3	11.7	50	19.2	0.2	66.7
Deformation zones		0.2	1.2	0.9	4.8	1	0.01	184
Whole borehole		0.2	15.1	4.9	50	18.5	0.01	184

Q values along borehole KBH02 (core sections of 1 m)

Rock unit depth [m]		Minimum Q	Average Q	Frequent Q	Maximum Q	Standard deviation	Min possible Q	Max possible Q
100–237	RU 1	0.002	23.2	2.6	266.7	57.1	0.002	266.7
237–244	RU 2	0.007	0.1	0.01	0.7	0.3	0.004	18.3
244–307	RU 1	0.6	26.8	14.3	266.7	42	0.4	266.7
307–355	RU 3	0.009	6.2	2.6	88.9	15.8	0.007	266.7
355–359	RU 2	0.5	2.3	2.8	3.3	1.3	0.3	65.3
359–398	RU 4	0.4	4	2.7	12.5	3.4	0.2	184
398–553	RU 1	0.3	25.8	12.5	266.7	34.6	0.2	266.7
553–705	RU 5	0.009	22.4	6.3	266.7	40.2	0.007	266.7
RU 1		0.002	25	8.3	266.7	45.7	0.002	266.7
RU 2		0.007	0.9	0.3	3.3	1.3	0.004	65.3
Competent rock		0.7	29.9	12.5	266.7	47.2	0.2	266.7
Deformation zones		0.002	1.9	0.8	46	3.9	0.002	266.7
Whole borehole		0.002	21	5.5	266.7	41.2	0.002	266.7

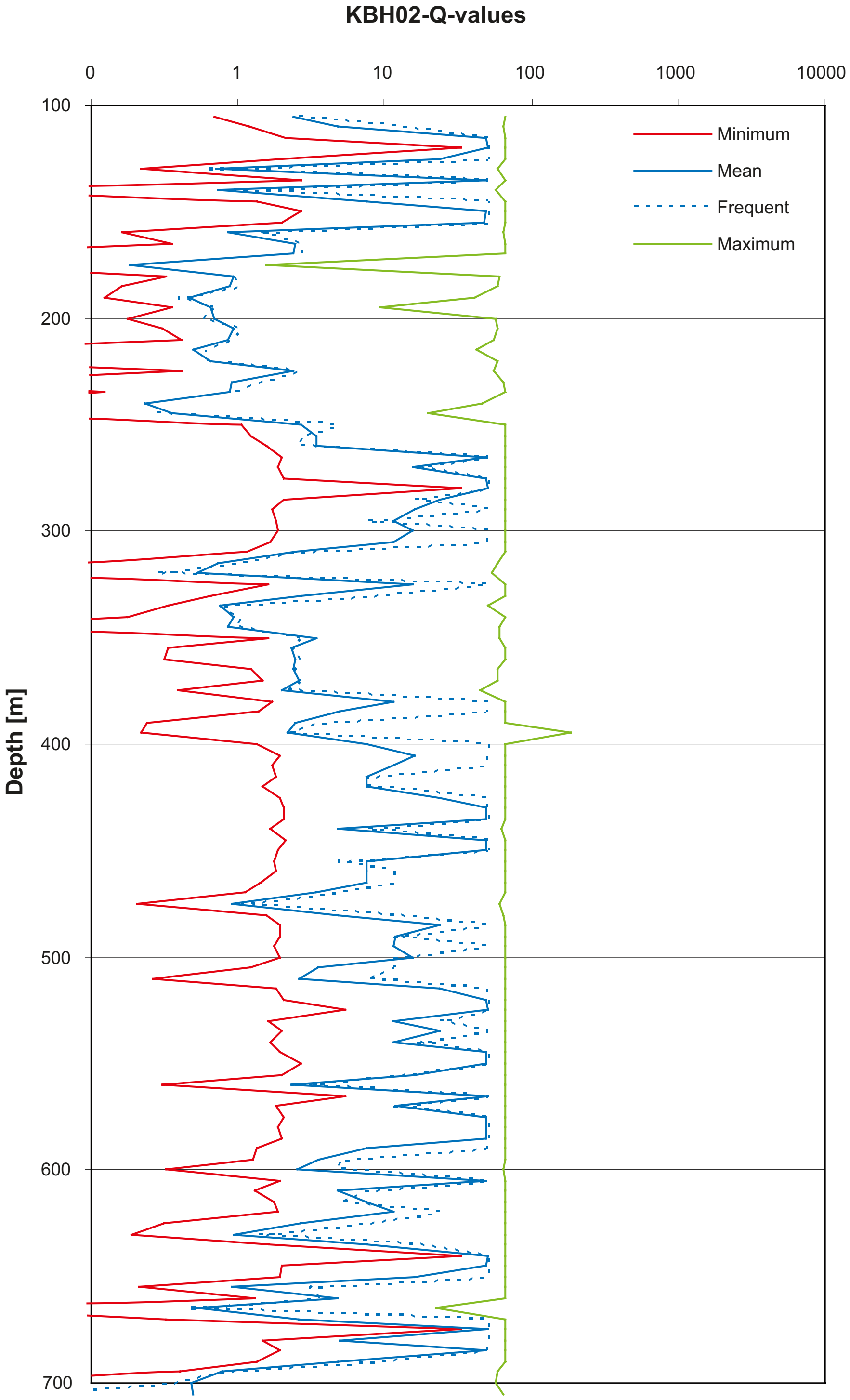

Figure A2-1. *Variation of Q with depth for borehole KBH02. The values are given every 5 m.*

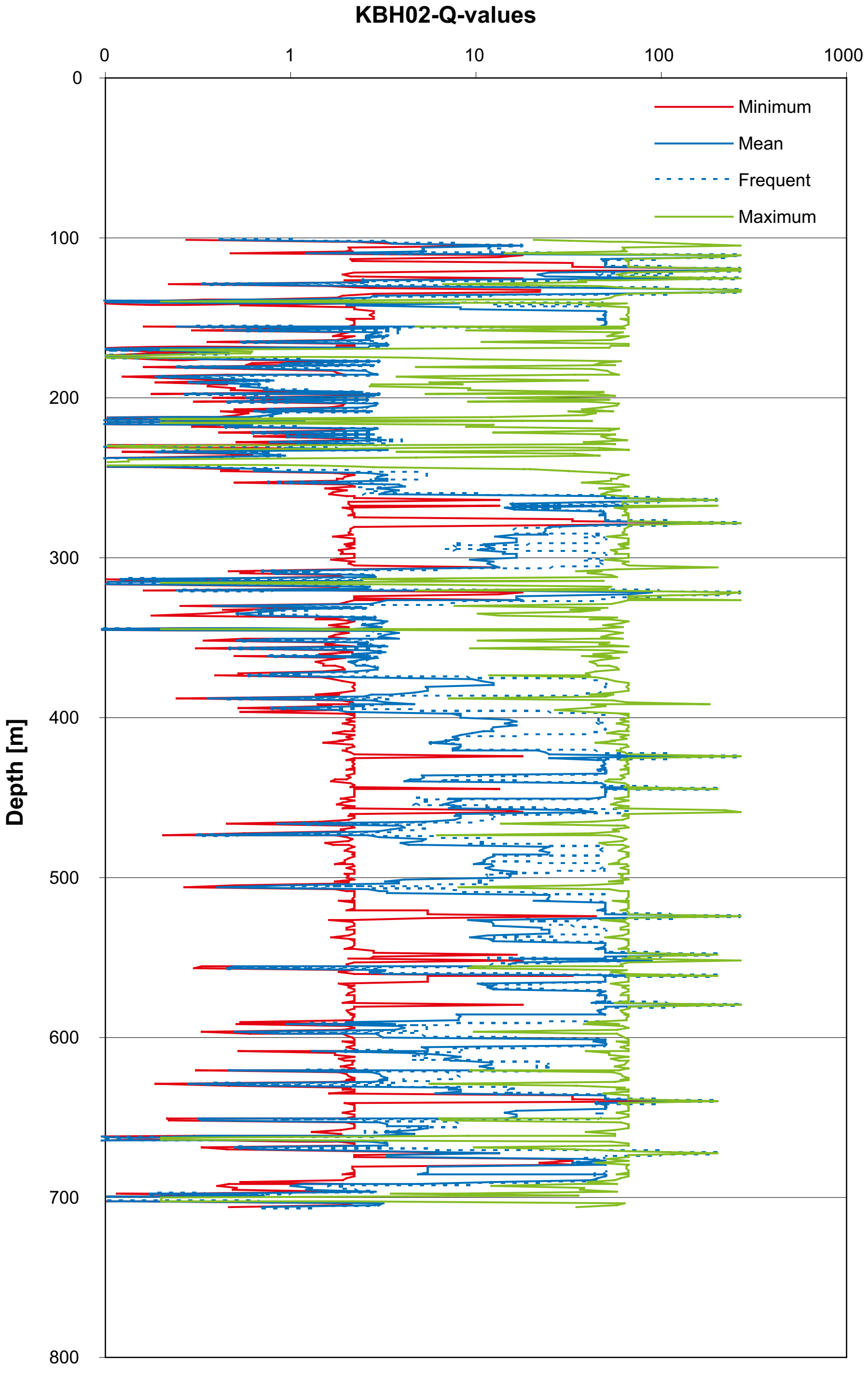

Figure A2-2. *Variation of Q with depth for borehole KBH02. The values are given every 1 m.*