R-05-89

Rock mechanics site descriptive model – empirical approach

Preliminary site description Forsmark area – version 1.2

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Abstract

This report summarises the results of the characterisation of the rock mass at the Forsmark Site obtained with the Empirical Approach. These results will be "harmonised" with the characterisation results obtained with the Theoretical Approach and will lead to the Rock Mechanics Model for the Forsmark Site Descriptive Model version 1.2. The Rock Mechanics Model provides rock mass parameters to the calculations for design and safety analysis purposes.

The Rock Mechanics "single-hole interpretation" provides the rock mass properties along four boreholes drilled at the site. These rock mass property data are analysed in sub-sets based on the geometrical and geological description provided by the Rock Domain and Deformation Zone Model for Forsmark 1.2. Rock mechanics data concern four rock domains and twelve deformation zones.

The variability with depth of the properties of the rock domains was analysed. Contrary to the Forsmark Site Descriptive Model Version 1.1, no clear trends were observed in the boreholes KFM02A, KFM03A and KFM04A. Moreover, the mechanical properties estimated for the rock domains were similar to the properties of the intact rock and they are probably only marginally dependent on the stress field at the site.

The quality of the rock mass in the rock domains, but outside the deformation zones, is "good" to "very good" according to the empirical systems Q and RMR. For the largest of the four rock domains, RFM029, the estimated equivalent uniaxial compressive strength of the rock mass is on average around 80 MPa and the deformation modulus is 69 GPa, respectively. This can be compared with the uniaxial compressive strength and deformation modulus of the intact rock, which are respectively 225 MPa and 76 GPa for granitic rocks. The other minor rock domains (RFM012, RFM017 and RFM018) present differences compared to RFM029, at most, in the order of –42% for the uniaxial compressive strength and –7% for the deformation modulus.

The properties of the competent rock mass in domain RFM029 below the Deformation Zone ZFMNE00A2 are slightly better than those for the rock mass below this zone.

The deformation zones were analysed separately. The average quality of the rock mass in the deformation zones is classified as "good rock" by the empirical systems. However, section of "poor rock" were also observed (minimum Q=1.8). The average deformation modulus deformations zones is around 58 GPa, 15% lower than the deformation modulus of rock domain RFM029. On average, the equivalent uniaxial compressive strength of the rock mass in the deformation zones is 55 MPa, which is 31% lower than for RFM029. The properties listed above are also representative for the Deformation Zone ZFMNE00A2 that dominates in terms of length extension along the boreholes. The lowest deformation modulus and uniaxial compressive strength of the deformation zones are 28 GPa and 14 MPa, respectively.

Sammanfattning

Denna rapport sammanställer resultat från karakteriseringen av bergmassan i Forsmark baserad på empiriska metoder. Resultaten kommer att ”harmoniseras” med karakteriseringen som tas fram med hjälp av teoretiska metoder, dvs numerisk modellering. Slutresultatet blir den Bergmekaniska modellen för Forsmark platsbeskrivande modell version 1.2 som tillhandahåller bergmassansparametrar till projektering och säkerhetsanalys.

Bergmekaniska enhållstolkningar av borrhålsdata tillför bergmassans mekaniska egenskaper längs fyra borrhål. Den empiriska modelleringen baseras på dessa egenskaper och sammanställer data för de bergdomänerna och deformationszonerna identifierade av geologimodellerna for platsen.

Bergegenskaper analyserades med hänsyn till eventuellt djupberoende. Till skillnad från Forsmark platsbeskrivande modell version 1.1, observerades här inget tydligt djupberoende av de bergmekaniska parametrarna i borrhålen KFM02A, KFM03A och KFM04A. Dessutom är de bergmekaniska parametrarna så nära det intakta bergets parametrar att inget spännings- eller djupberoende är troligt.

Bergmassans kvalité i bergdomänerna och utanför deformationszonerna klassas som ”bra” till ”mycket bra” berg av de empiriska systemen Q och RMR. För den största bergdomänen RFM029 uppskattas den ekvivalenta enaxlig tryckhållfasthet kring 80 MPa och deformationsmodulen runt 69 GPa (granitisk intakt berg har enaxlig tryckhållfasthet på 225 MPa och deformationsmodul runt 76 GPa. Bergmassans egenskaper i domän RFM029 under zon ZFMNE00A2 är bättre än för bergmassan ovanför zonen. Skillnader på –42 % för enaxlig tryckhållfasthet respektive –7 % för deformationsmodulen observeras mellan de mindre bergdomänerna (RFM012, RFM017 och RFM018) och RFM029.

Deformationszonerna i borrhålen analyserades separat. Bergmassan medelkvalité i deformationszonerna klassas som ”bra berg” enligt de empiriska systemen. Vissa partier uppvisar sämre kvalitet (minimum Q=1.8). Medelvärdet på deformationsmodulen i deformationszonerna ligger runt 58 GPa, som är 15 % lägre är den för bergdomän RFM029. I genomsnitt ligger den enaxliga tryckhållfastheten kring 55 MPa som är 31 % lägre än den för RFM029. Dessa egenskaper är också representativa för deformationszon ZFMNE00A2 som dominerar längs borrhålen. Den lägsta deformationsmodulen och enaxliga tryckhållfastheten i deformationszonerna är 28 GPa respektive 14 MPa.

Innehåll

1 Introduction

This report summarizes the results of the Rock Mechanics characterization by means of empirical methods of the rock mass along four boreholes at Forsmark (KFM01A, KFM02A, KFM03A and KFM04A). The empirical methods were applied for the purpose of pure "characterization" of the rock mass according to /Andersson et al. 2002, Röshoff et al. 2002/, thus, consideration about excavation geometry, water inflow and safety coefficients are not considered in this study. These aspects will be taken into consideration by the "Design" and "Safety Analysis" studies.

From the quantification of the rock mass quality, several mechanical properties can be estimated. In particular, focus is given to:

- The deformation modulus and Poisson's ratio of the rock mass calculated by means of RMR.
- The equivalent uniaxial compressive strength and tensile strength of the rock mass determined by means of RMR, through GSI, and the Hoek & Brown's Failure Criterion.
- The friction angle, cohesion and apparent uniaxial compressive strength of the rock mass according to the Coulomb's Criterion also determined by means of RMR, through GSI, and the Hoek & Brown's Failure Criterion.

Primarily, the values of the mechanical properties of the rock mass obtained by the Rock Mechanics "single-hole" interpretation of the four boreholes are presented. This provides information about the possible variability of the properties with depth or between drilling sites.

Secondarily, the rock mass along the boreholes is partitioned into rock domains and deformation zones according to the rock domain and Deformation Zone Model identified for the Forsmark Site Descriptive Model version 1.2 (as it was delivered on October 19th, 2004) /SKB 2005/. The rock domains are pseudo-homogeneous volumes of rock that contain rock of similar rock type and have homogeneous fracture distributions. The deformation zones are fractured portions of the rock mass characterized by evidences of ductile and/or brittle deformations, and usually presenting a higher fracture frequency compared with the contiguous rock.

1.1 Background

The four analysed boreholes were drilled into the "tectonic" lens delimited on the North-East by the Singö Fault (regional deformation zone), and on the South-West by the Eckarfjärden Fault (regional deformation zone) (Figure 1-1). The drilling orientations were sub-vertical, except for borehole KFM04A that has an inclination of 60° towards NE (Table 1-1). The tectonic lens presents a steeply-plunging folding in the NW part of the studied volume, and more gently-plunging linear structures in the SE part /SKB 2005/.

Several gently SE- and S-dipping deformation zones were identified from the seismic profiles and the intersection with 24 core and percussion drill-holes. The mechanics of formation of these zones was judged to be mainly brittle deformations, but ductile deformations were also observed (see also Table 4-1). Steeply-dipping deformation zones with NE-ENE and NNW-NNE strike were also observed with prevalent brittle features.

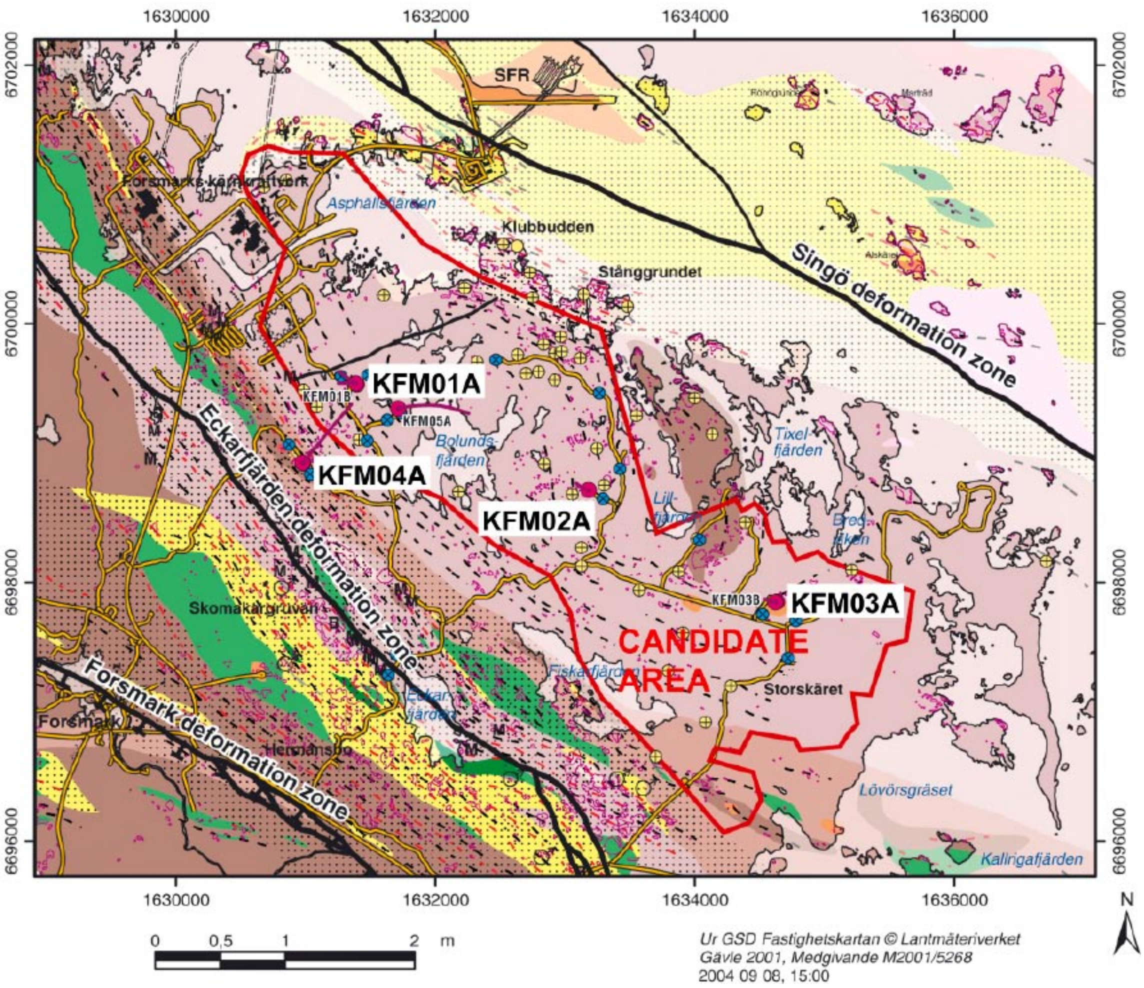

***Figure 1-1.** Overview of the Forsmark Site with indication of the Candidate Area and borehole KFM01A, KFM02A, KFM03A and KFM04A.*

Table 1-1. Length and orientation of the boreholes KFM01A, KFM02A, KFM03A and KFM04A considered for rock mechanics purposes.

Borehole	Core length [m]	Bearing/inclination
KFM01A	102–1,001	318/85
KFM02A	102–1,002	276/85
KFM03A	102–1,001	272/86
KFM04A	108–1,001	045/60

From a lithological point of view, four rock type groups of quartz-rich meta-igneous rocks are identified at the Forsmark Site. They are listed here in an older-to-younger order:

- Rock type group A: Volcanic rocks.
- Rock type group B: Granite to granodiorite, tonalite to granodiorite, diorite to gabbro.
- Rock type group C: Fine- to medium-grained granodiorite, tonalite and subordinate granite. Occurrence: as lenses in group A and B.
- Rock type group D: Fine- to medium-grained granite, aplite, pegmatitic granite and pegmatite. Occurrence: as dykes.

According to this classification, a team of geologists have set up a model composed by 42 pseudo-homogeneous units. Based on these units, four larger rock domains were identified /SKB 2005/ along the four boreholes analysed for the purpose of Rock Mechanics characterisation. These rock domains are: RFM012, RFM017, RFM018 and RFM029, all in Rock Type B. However, each of these rock domains has a predominant rock type within the same rock type group:

- RFM012 and RFN029: Granite to granodiorite, metamorphic (code 101057).
- RFM017 and RFM018: Tonalite to granodiorite, metamorphic (code 101054).

1.2 Objectives

The objectives of this report are as follows:

- Summarise the results from the empirical methods used for the characterisation of the rock mass at the Forsmark Site;
- Provide rock mass quality and mechanical properties (empirically determined) for the four rock domains intercepted by the available core drillholes.
- Provide rock mass quality and mechanical properties (empirically determined) for the deformation zones intercepted by the available core drillholes.
- Extrapolate the values of quality and mechanical properties of the rock mass to some of the rock domains/deformation zones of interest, where Rock Mechanics evaluations are not available.
- Supply the necessary information for the set up of the Rock Mechanics Model of the Forsmark Site.
- Discuss the results of the empirical modelling and list the main conclusions of the work.
- Provide some recommendation for future studies.

1.3 Scope

The continuum equivalent mechanical properties of the rock mass based on empirical relations with the rock mass quality (RMR and Q) are the background database for this study. The deformation modulus, Poisson's ratio, uniaxial compressive and tensile strength, apparent cohesion and friction angle of the rock mass are determined and shown as a function of depth. The uncertainties of the rock mass quality and mechanical properties are also treated and quantified.

The report structures the information as follows:

- A summary section presents the results of the empirical methods applied to borehole KFM01A, KFM02A, KFM03A and KFM04A.
- A section summarizes the mechanical properties of rock domain RFM012, RFM017, RFM018 and RFM029.
- A section summarizes the mechanical properties of 12 deformation zones at the Forsmark Site.
- Discussion of the results.
- Appendices.

2 Empirical characterisation of the rock mass

According to the "single-hole interpretation" of the drill-core geological/rock mechanics information, the borehole KFM01A, KFM02A, KFM03A and KFM04A were originally partitioned into:

- Rock units
- Possible deformation zones.

The rock units were later grouped into larger sub-homogeneous rock domains, while the possible deformation zones were either promoted to become Deterministic Deformation Zones (composing the Deformation Zone Model), or left to the group of Stochastic Deformation Zones, which were considered as stochastic features and incorporated into the Distinct Fracture Network Model /La Pointe et al. 2005/.

A summery of the rock mechanics properties of the intact rock and fractures for Forsmark Model version 1.2 is given by /Lanaro and Fredriksson 2005/. These data are used for the empirical characterisation.

Table 2-1 provides a detailed overview of the extension of the main rock domains and deformation zones along the core drillholes. It can be observed that the fraction of competent rock in the boreholes is rather high (around 87%). Of the observed deformation zones, 99% were promoted to Deterministic Deformation Zones. The denomination of the Deterministic Deformation Zone is given in the legend.

The rock domain RFM029 greatly dominates in the boreholes (85% of the available length of cores). This also roughly mirrors the volumetric extension of the rock units in the Candidate Area, as shown in Figure 2-1.

Table 2-1. Length percentage of competent rock along the boreholes, deformation zones and distribution of the four rock domains RFM012, RFM017, RFM018 and RFM029.

Borehole	Extension in % of the borehole length					
	Competent rock	Deformation zones	RFM012	RFM017	RFM018	RFM029
KFM01A (29–1,001 m)	91.5%	8.5% [1]				100%
KFM02A (12–976 m)	73.0%	27.0% [2]				100%
KFM03A (102–949 m)	90.8%	8.4% [3]		8.6%		91.4%
KFM04A (12–1,001 m)	91.4%	8.6% [4]	32.6%		16.7%	50.7%
All boreholes (3,778.5 m)	86.5%	13.2% [5]	8.6%	1.9%	4.4%	85.1%

[1] KFM01A: This value corresponds to the Deterministic Deformation Zone ZFMNE00A2, ZFMNE1192 and ZFMNE0061.

[2] KFM02A: This value corresponds to the Deterministic Deformation Zone ZFMNE0866, ZFMNE00B6, ZFMNE00A3, ZFMNE1189, ZFMNE00A2, ZFMNE00B4 and ZFMNE1195. The "single-hole interpretation" assigned 0.4% of the borehole length to deformation zones, which was not used by the Deformation Zone Model.

[3] KFM03A: This value corresponds to the Deterministic Deformation Zone ZFMNE00A4, ZFMNE00A7, ZFMNE00B1 and ZFMNE00A3. The "single-hole interpretation" assigned 0.8% of the borehole length to deformation zones, which was not used by the Deformation Zone Model.

[4] KFM04A: This value corresponds to the Deterministic Deformation Zone ZFMNE1187, ZFMNE00A2 and ZFMNE1188.

[5] All boreholes: The "single-hole interpretation" assigned 0.3% of the borehole length to deformation zones, which was not used by the Deformation Zone Model.

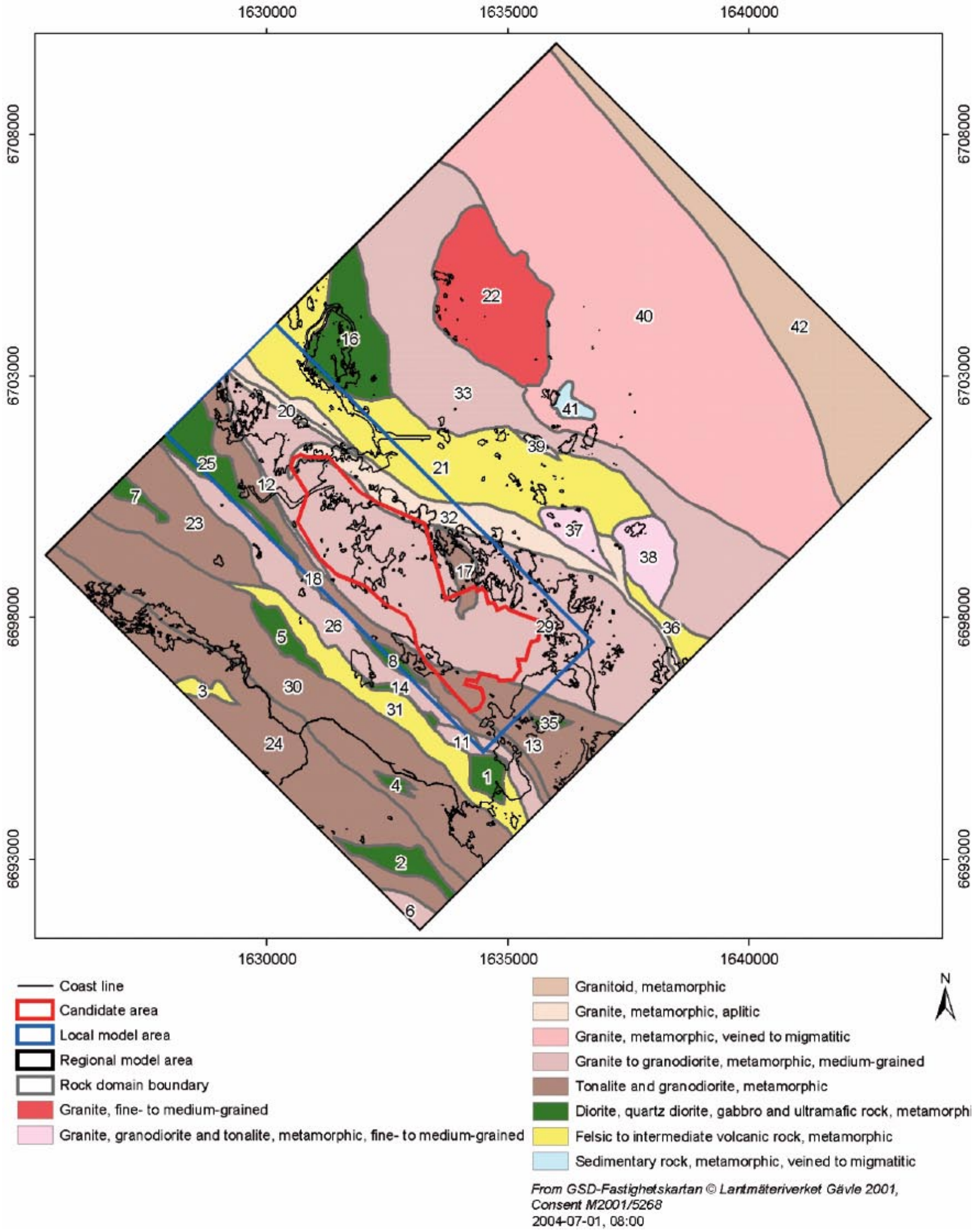

Figure 2-1. *Map of the Rock Domains in the Forsmark Site Descriptive Model v. 1.2 /SKB 2005/. The domains are numbered from 1 to 42. (Some of the domains do not appear on the map due to the resolution.)*

2.1 Comparing the boreholes

The Rock Mechanics estimation of the mechanical properties was carried out in the "single-hole interpretation" of the borehole data /Lanaro 2005a,b,c,d/. The mechanical properties of the rock mass determined by means of empirical relations with the Q, RMR and GSI systems are:

- Equivalent deformation modulus and Poisson's ratio /Serafim and Pereira 1983/.
- Uniaxial compressive strength and tensile strength /Hoek et al. 2002/.
- Apparent friction angle, cohesion and uniaxial compressive strength according to the Coulomb's criterion for confinement stresses (53) between 10 and 30 MPa /Hoek et al. 2002/.

In the following figures, the average mechanical properties estimated for the competent rock mass are compared to the average properties of the deformation zones.

Figure 2-2 shows that the deformation modulus is in general rather high even for the deformation zones. The Young's modulus of the intact rock is on average, independently on the rock type, about 76 GPa /Lanaro and Fredriksson 2005/. The deformation zones present a deformation modulus that is about 15% lower than the competent rock, except for borehole KFM03A, where the presence of poorer rock associated with the rock domains RFM017 raises the difference to about 20%.

Figure 2-3 compares the uniaxial compressive strength of the rock mass estimated by RMR/GSI and the Hoek & Brown's Criterion between the competent and deformation zone. In terms of strength, the deformation zones are very similar in all boreholes. On the other hand, the uniaxial compressive strength of the competent rock is highest for KFM04A were the rock quality is very good under 500 m depth.

Figure 2-4 shows the average apparent friction angle for the competent rock mass and deformation zones. Between 10 and 30 MPa confinement stress, the friction angle varies between 48° and 49° for the competent rock and between 46° and 48° for the deformation zones, respectively. The rock in borehole KFM02A has a lower friction angle on average because of the presence of an extensive deformation zone and of a section of porous ("vuggy") metagranite in the upper part.

The cohesion of the competent rock is on average 20% larger than that of the deformation zone. Moreover, the results from the different boreholes are very consistent (Figure 2-5).

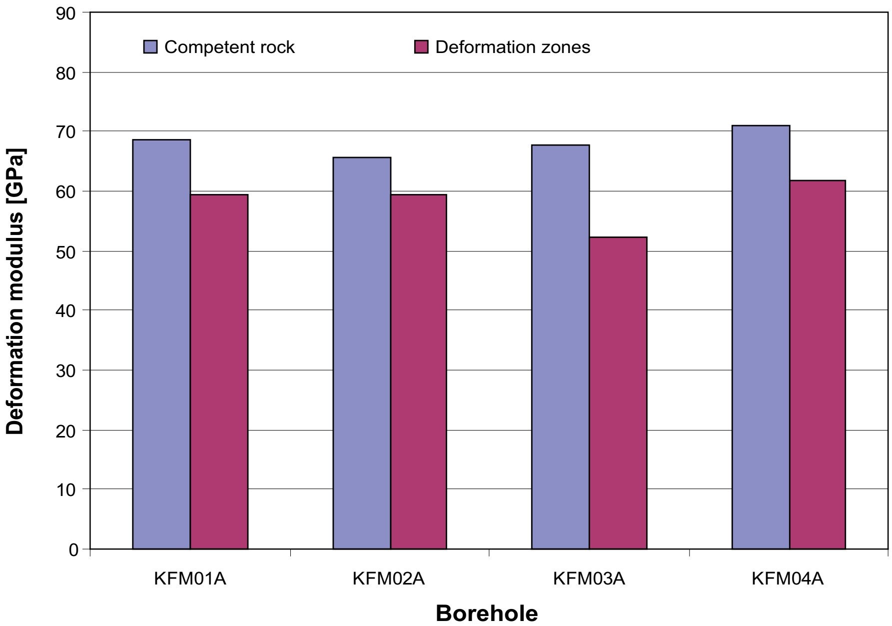

Figure 2-2. *Mean deformation modulus Em of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.*

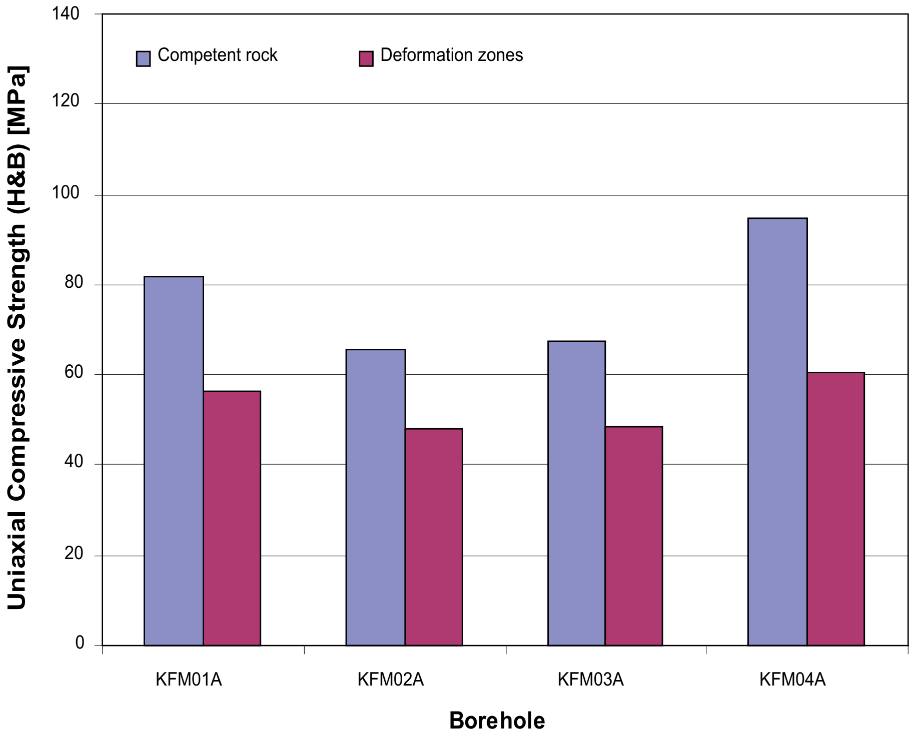

Figure 2-3. *Mean uniaxial compressive strength UCS of the rock mass according to Hoek and Brown's Criterion for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.*

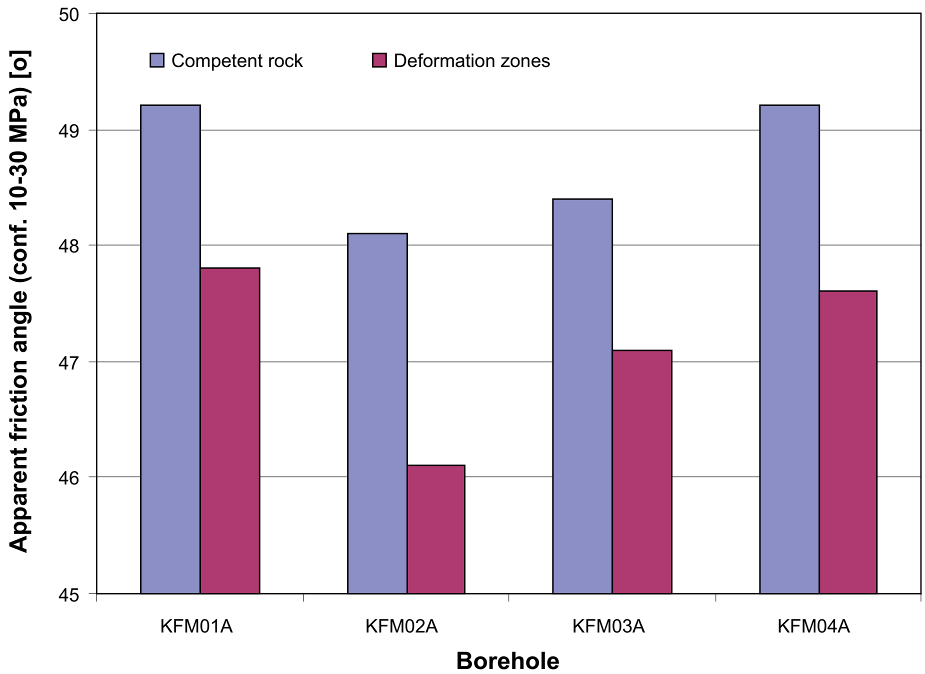

Figure 2-4. *Mean apparent friction angle of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.*

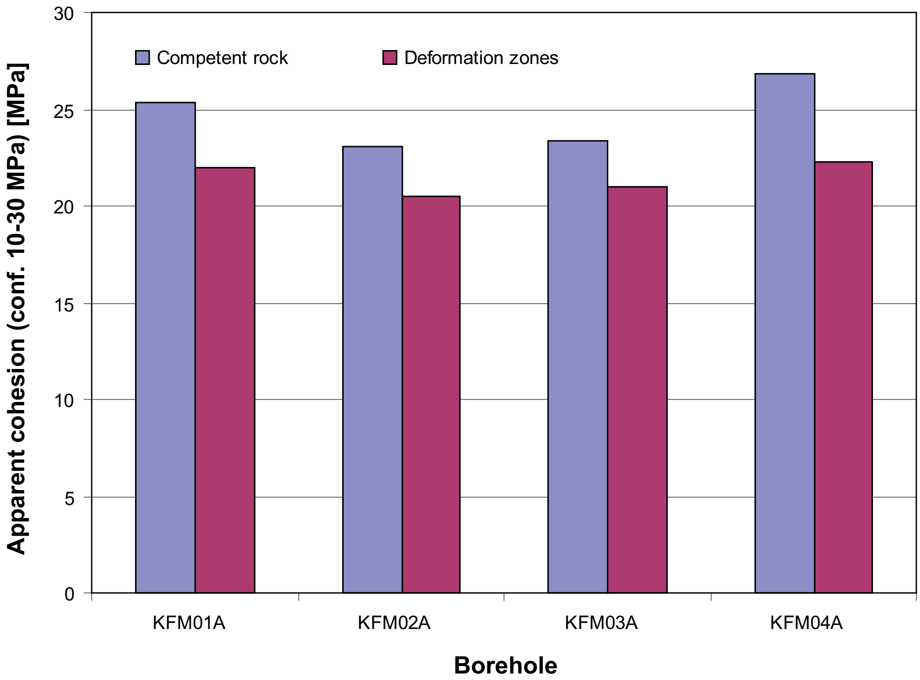

Figure 2-5. *Mean apparent cohesion of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.*

2.2 Variation along the boreholes

In this report, the empirical methods are applied to the core-drilled parts of the boreholes that usually start at a depth of about 100 m. Above this depth, poorer quality of the geological data was provided by percussion boreholes. However, it was decided to neglect these data and to focus on the depth of potential positioning of the repository (around 500 m).

The variation of the mechanical properties of the rock mass with depth shows that, except for borehole KFM01A /SKB 2004/, there is not a clear increasing trend of the properties with depth. The sections of lower mechanical properties are associated with:

- Deformation zones.
- "Vuggy" metagranite (in KFM02A, Figure 2-7).
- Tonalite (in KFM03A).

This is particularly evident for borehole KFM03A (Figure 2-8) and KFM04A (Figure 2-9). In Figure 2-6 and following, the deformation modulus independently obtained by the empirical relation with the Q index /Barton 2002/ is compared with the results obtained from the RMR system. The graphs also show the range of variation of each parameter within each pseudo-homogeneous section of borehole ("rock unit" according to the geological single-hole interpretation) identified by the "single-hole interpretation". These ranges give a quantification of the spatial variability of the parameters on the local scale. On the other hand, the variations from rock unit to rock unit provide the borehole-scale variation of the properties that can sometimes depend on depth and/or on the presence of the deformation zones.

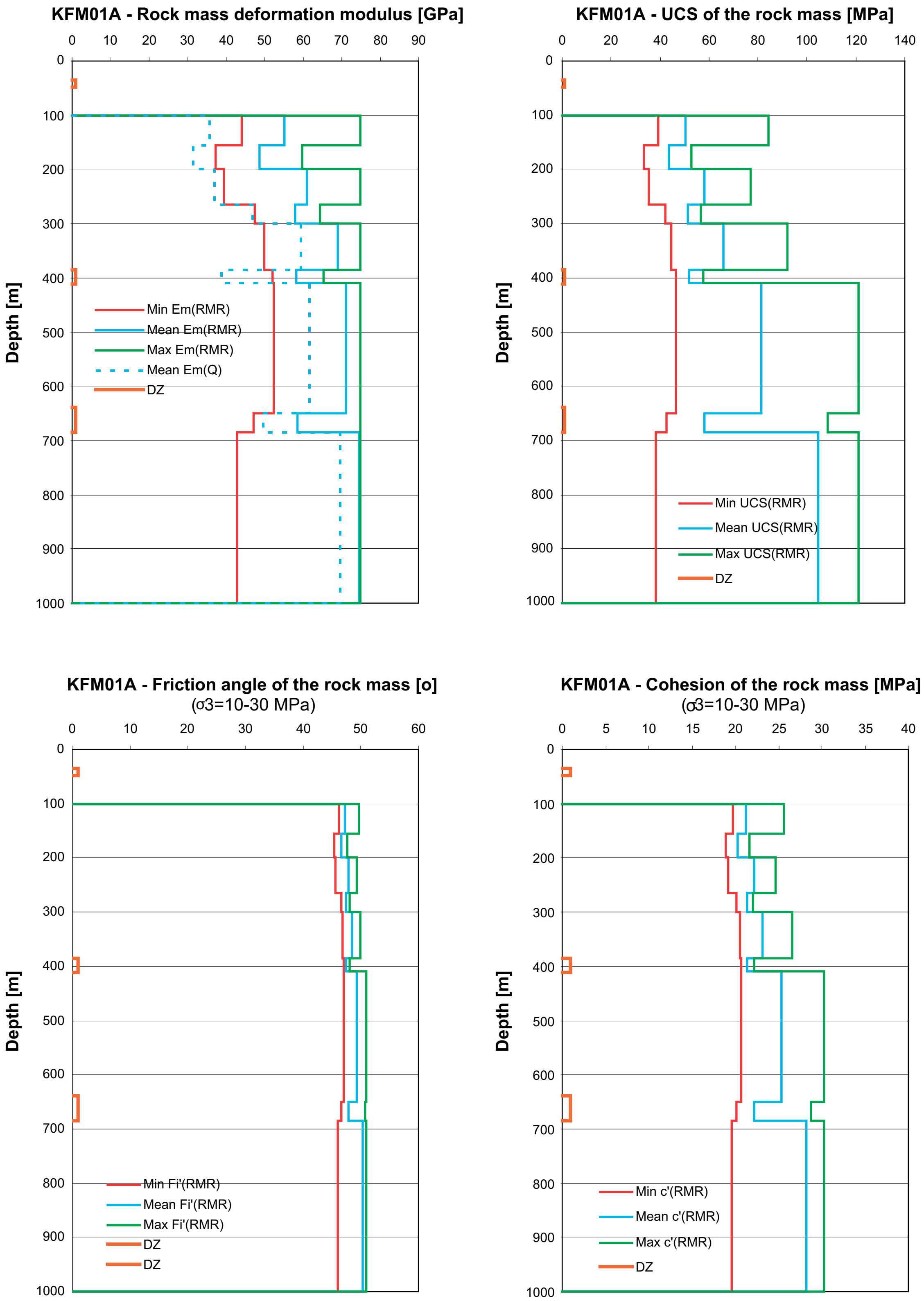

Figure 2-6. *KFM01A. Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown.*

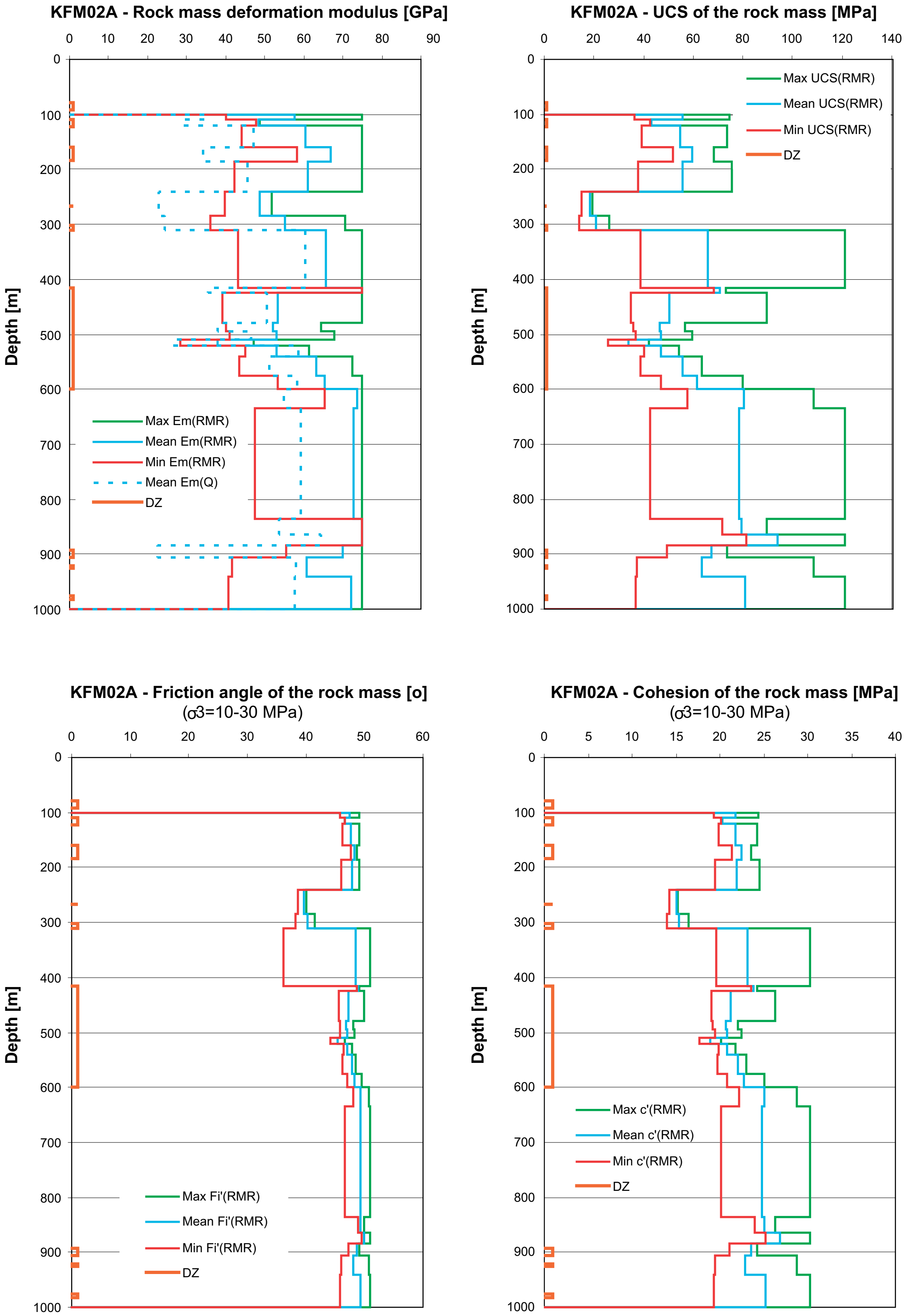

Figure 2-7. *KFM02A. Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown.*

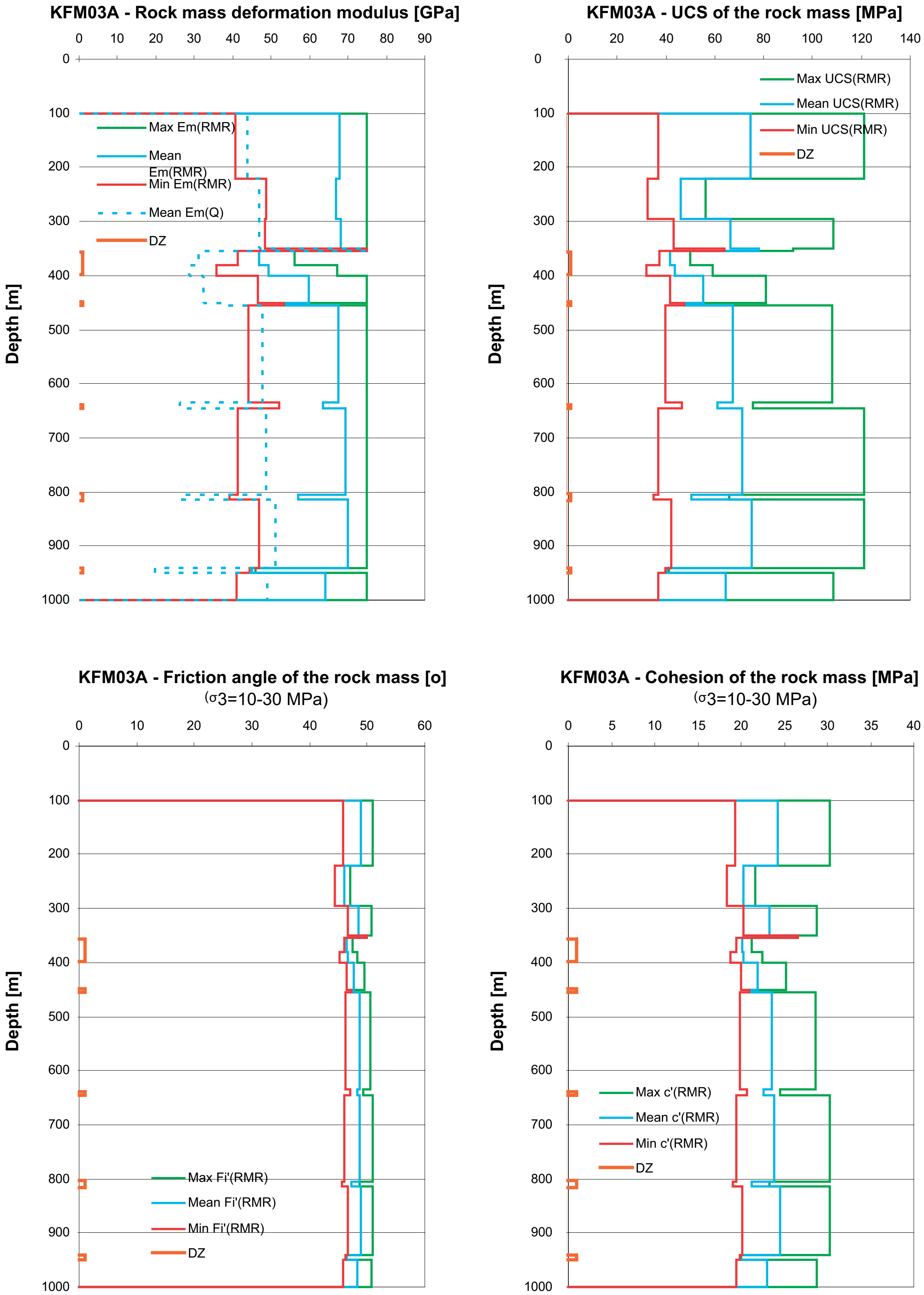

Figure 2-8. *KFM03A. Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown.*

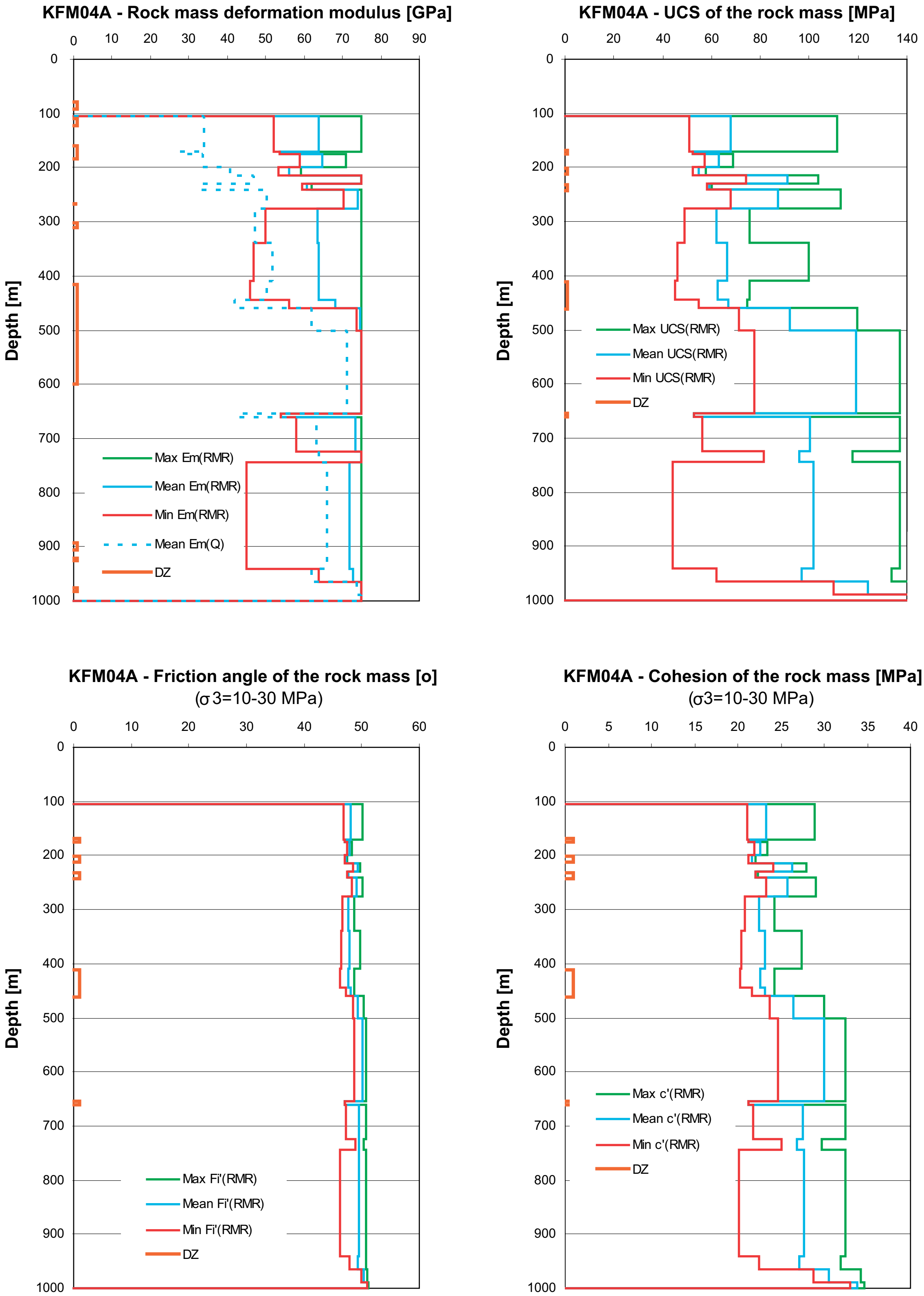

Figure 2-9. *KFM04A. Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown.*

3 Rock domains

The Rock Domain Model provides the partition of the borehole into rock domains according to Figure 3-1. It can be observed that the main part of the boreholes is drilled through rock domain RFM029 (Table 3-1). Moreover, it must be point out that approximately only 15 m of core length can be ascribed to the group of Stochastic Deformation Zones. All the rest of the deformation zone along the boreholes is described in next section about Deterministic Deformation Zones.

In the following sections, summary tables with Q, RMR and the properties of the rock mass seen as an equivalent continuum are provided. In particular, for each rock domain, the deformation modulus, Poisson's ratio, uniaxial compressive strength (from Hoek & Brown's Criterion and Coulomb's Criterion), the tensile strength, apparent friction angle and cohesion are listed.

Table 3-1. Approximated length of rock belonging to the rock domains RFM012, RFM017, RFM018 and RFM029 along the boreholes KFM01A, KFM02A, KFM03A and KFM04A considered for rock mechanics purposes.

Rock domain	Extension in length [m]	
	Competent rock	Deformation zone
RFM012	210	0
RFM017	75	0
RFM018	60	0
RFM029	2,775	15

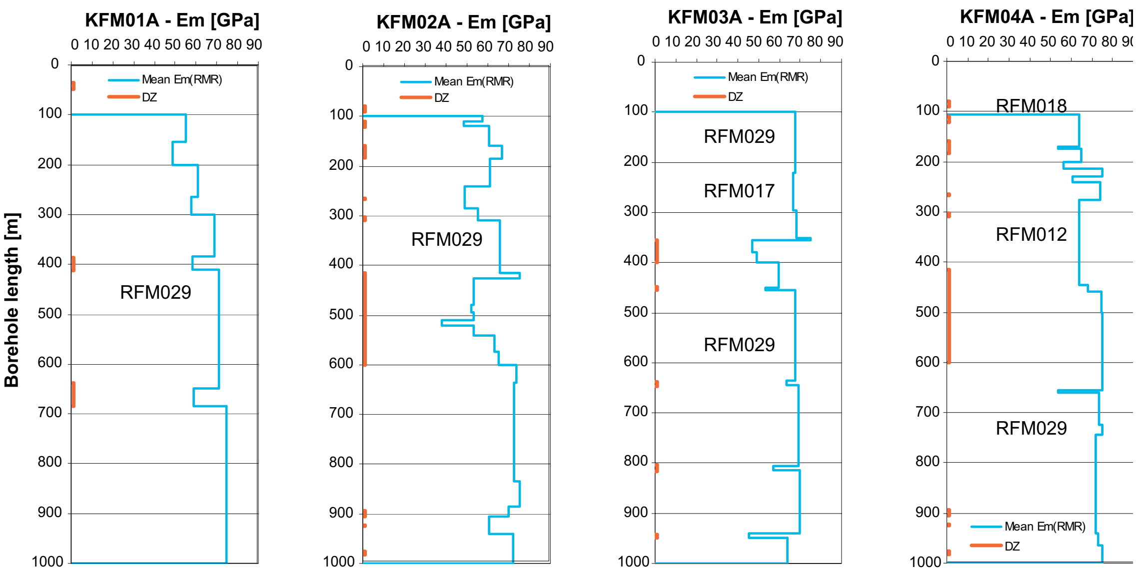

Figure 3-1. Partitioning of the boreholes into Rock Domains and Deformation zones. The mean deformation modulus obtained of the rock mass from RMR along the boreholes is also plotted.

Besides the rock domain given by the Geometrical Model, rock mass properties are given for two portion of RFM029: above and below the deformation zone ZFMNE00A2. In fact, this deformation zones probably cut through the Candidate Area, isolating an upper and lower block. By checking the difference between the material properties of these two blocks, there is the possibility of describing the rock mass more in details.

These properties will be the base of the Rock Mechanics Modelling for the Forsmark Descriptive Model Version 1.2. In Appendix 1, charts that compare the mechanical properties of the rock domains are also provided.

3.1 Rock Quality Index (Q)

The rock quality of the rock mass is evaluated by means of the Q system. A summary is given in Table 3-2. The comparison of the mean values of Q with the most frequent values of Q does not provide a clear classification of the rock domains based on rock mass quality. In other words, the rock mass quality inferred by Q is almost the same for all rock domains. An exception is the rock mass in RFM029 below ZFMNE00A2, which seems to be exceptionally good.

3.2 Rock Mass Rating (RMR)

Even RMR values show that there is not large difference in rock quality between the rock domains in the Candidate Area (see Table 3-3). However, RFM029 below ZFMNE00A2 seems to have the highest quality (RMR around 89), while RFM017 and RFM018 have the lowest (RMR around 83), respectively.

Table 3-2. Q values of the rock domains of the Forsmark Area Model – version 1.2.

Q [–]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean [most freq.]	Max	Min	Mean [most freq.]	Max
RFM012	21.2	78.8 [52.1]	300.0	–	–	–
RFM017	21.3	89.2 [62.5]	350.0	–	–	–
RFM018	4.7	18.2 [16.6]	44.4	–	–	–
RFM029	7.4	370.3 [86.0]	2,133.3	3.0	4.0 [4.3]	4.8
RFM029 above ZFMNE00A2	7.4	162.3 [42.1]	2,133.3			
RFM029 below ZFMNE00A2	7.6	486.5 [136.0]	2,133.3			

Table 3-3. RMR values of the rock domains of the Forsmark Area Model – version 1.2..

RMR [–]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	76.8	84.7/4.5	94.0	–	–	–
RFM017	77.5	83.5/3.5	87.3	–	–	–
RFM018	78.7	83.2/4.3	92.7	–	–	–
RFM029	72.9	87.1/6.1	98.5	74.0	75.4/1.3	76.5
RFM029 above ZFMNE00A2	74.2	84.5/5.2	96.0			
RFM029 below ZFMNE00A2	72.9	88.5/6.2	98.5			

3.3 Uniaxial compressive strength of the rock mass

The comparison between the values of the equivalent uniaxial compressive strength (according to the Hoek & Brown's Criterion) is slightly different. RFM029 has the highest value, with some differences when the volume above ZFMNE00A2 (–18%) and below ZFMNE00A2 (+10%) are considered. RFM012 presents a strength that is about 7% less than RFM029. RFM018 has the same uniaxial compressive strength as RFM029 above ZFMNE00A2. RFM017 shows the lowest strength of all rock domains.

3.4 Deformation modulus of the rock mass

The deformation modulus of the rock mass in RFM029 is rather high and on average about 69 GPa. Some differences can be observed for the rock volume above and below Zone ZFMNE00A2 that are, however, rather small. The deformation modulus is 3% less than the average for the whole rock domain under this zone, and 2% more above the zone, respectively. Quantitatively, the same differences are observed for RFM012 and RFM017 compared to RFM029. Rock domain RFM018 has the lowest deformation modulus, about 7% less than for RFM029. This is due to the fact that RFM018 has the lowest rock mass quality according to Q and RMR among all rock domains.

Table 3-4. Predicted uniaxial compressive strength UCSm (equivalent strength for zero confinement pressure) according to the Hoek and Brown's Criterion for the Rock domains of the Forsmark Area Model – version 1.2.

UCSm [MPa]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	45.8	73.7/19.3	119.5	–	–	–
RFM017	32.6	46.2/8.5	56.1	–	–	–
RFM018	51.0	67.6/18.0	111.2	–	–	–
RFM029	17.8	79.5/28.7	153.3	15.2	31.9/14.5	41.0
RFM029 above ZFMNE00A2	17.8	65.5/22.2	121.3			
RFM029 below ZFMNE00A2	33.6	87.4/29.0	153.3			

Table 3-5. Predicted deformation modulus Em from RMR for the Rock domains of the Forsmark Area Model – version 1.2. (low confinement).

Em [GPa]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	46.7	67.8/9.0	75.0			
RFM017	48.8	66.8/10.3	75.0			
RFM018	52.2	63.9/8.5	75.0			
RFM029	37.4	68.9/9.9	75.0	39.7	43.3/3.2	46.0
RFM029 above ZFMNE00A2	40.2	66.3/10.8	75.0			
RFM029 below ZFMNE00A2	37.4	70.3/9.1	75.0			

3.5 Poisson's ratio of the rock mass

When the Poisson's ratio is concerned, the differences within RFM029 (± 5%) are smaller than compared to the differences within the other rock domains (± 9%). The tonalitic rock domain RFM017 has the highest average Poisson's ratio of 0.24 (due to its predominant rock type), while RFM018 has the lowest Poisson's ratio of 0.20 among all rock domains (due to its low rock mass quality).

3.6 Coulomb's strength criterion of the rock mass

The Coulomb's Criterion is fitted to the Hoek & Brown's Criterion to determine the apparent cohesion c', friction angle φ' and the extrapolated uniaxial compressive strength. This fitting is performed for confinement stresses between 10 and 30 MPa.

The apparent cohesion of RFM029 is around 25 MPa, and within RFM029, it is 7% lower above ZFMNE00A2 and 4% higher below ZFMNE00A2 (Table 3-7). The apparent cohesion of RFM012 is 4% lower than that of RFM029. On the other hand, RFM017 and RFM18 exhibit larger differences compared with RFM029, of –18% and –6%, respectively.

The values of the apparent friction angle are usually not very sensitive to the rock mass quality (Table 3-8). The differences are within 2% in RFM029 and compared to RFM012 and RFM018. The rock domain RFM017 does not follow the same pattern as all the other rock domains because of its high tonalitic content.

By extrapolating the Coulomb's Criterion to a zero confining stress, the apparent uniaxial compressive strength is obtained (Table 3-9). This parameter will be used for comparing the empirical results with the rock mass characterisation by means of numerical results of the Theoretical Model /Andersson et al. 2002/.

Table 3-6. Predicted Poisson's ratio from RMR for the rock domains of the Forsmark Area Model – version 1.2.

v [–]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	0.15	0.22/0.03	0.24			
RFM017	0.18	0.24/0.04	0.27			
RFM018	0.17	0.20/0.03	0.24			
RFM029	0.12	0.22/0.03	0.27	0.13	0.14/0.01	0.15
RFM029 above ZFMNE00A2	0.13	0.21/0.03	0.24			
RFM029 below ZFMNE00A2	0.12	0.23/0.03	0.27			

Table 3-7. Predicted cohesion c' of the rock mass according to the Mohr-Coulomb Criterion for the rock domains of the Forsmark Area Model – version 1.2.

c' [MPa]*	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	20.4	24.0/2.5	30.0			
RFM017	18.3	20.3/1.2	21.6			
RFM018	21.1	23.2/2.3	28.9			
RFM029	14.9	24.9/3.8	34.6	14.3	18.0/3.2	20.0
RFM029 above ZFMNE00A2	14.9	23.1/3.1	30.3			
RFM029 below ZFMNE00A2	18.9	26.0/3.7	34.6			

* Linear envelope between 10 and 30 MPa.

Table 3-8. Predicted friction angle φ' of the rock mass according to the Mohr-Coulomb Criterion for the rock domains of the Forsmark Area Model – version 1.2.

φ' [°]*	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	46.4	48.3/1.0	50.3			
RFM017	44.4	46.0/0.9	47.0			
RFM018	46.9	48.0/1.0	50.1			
RFM029	39.5	48.9/1.9	51.1	38.7	43.8/4.4	46.5
RFM029 above ZFMNE00A2	39.5	48.1/2.3	51.0			
RFM029 below ZFMNE00A2	45.5	49.3/1.4	51.1			

* Linear envelope between 10 and 30 MPa.

Table 3-9. Predicted apparent uniaxial compressive strength UCSm according to the Mohr-Coulomb Criterion for the rock domains of the Forsmark Area Model – version 1.2.

Apparent UCS_m* (Mohr-Coulomb)	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	101.7	126.7/16.8	166.4			
RFM017	87.2	100.5/8.2	109.9			
RFM018	106.7	121.4/15.8	159.2			
RFM029	63.2	134.0/25.5	195.6	59.7	86.2/22.9	100.1
RFM029 above ZFMNE00A2	63.2	121.8/21.9	171.4			
RFM029 below ZFMNE00A2	92.4	140.9/24.8	195.6			

* Linear envelope between 10 and 30 MPa.

3.7 Tensile strength of the rock mass

By using the Hoek & Brown's Criterion, the tensile strength of the rock mass, assumed as a continuous medium, can be determined (Table 3-10). These values should, however, be used with caution when applied to relatively fracture-free rock as the rock at the Forsmark Site.

Table 3-10. Predicted tensile strength TSm according to the Hoek and Brown's Criterion for the rock domains of the Forsmark Area Model – version 1.2.

TS_m [MPa]	Competent rock			Deformation zone		
Rock domain/Deformation zone	Min	Mean/St dev	Max	Min	Mean/St dev	Max
RFM012	0.97	1.87/0.67	3.56			
RFM017	0.63	1.02/0.25	1.32			
RFM018	1.12	1.67/0.63	3.23			
RFM029	0.34	2.01/1.00	4.99	0.27	0.60/0.28	0.78
RFM029 above ZFMNE00A2	0.34	1.51/0.67	3.38			
RFM029 below ZFMNE00A2	0.59	2.29/1.04	4.99			

3.8 Uncertainties

3.8.1 Background

It was decided to correlate the uncertainty of each mechanical parameter P to the range of its possible values obtainable for a certain depth (e.g. location of each core section of 5 m). This range of variation might depend on: i) uncertainty on the input data; ii) opinion of different operators characterising the rock mass; iii) estimation of missing parameters; iv) biases due to sampling direction; v) intrinsic uncertainties of the methods used for the characterisation.

The range of variation of the parameter P at each depth is inferred from the width of the interval between the possible minimum and maximum occurring value of the parameter. For Q and RMR, the range of the possible minimum and maximum values of RMR and Q is obtained by combining the indices and ratings in the most unfavourable and favourable way, respectively. For the other parameters, the range of variation might depend on the variation of Q and RMR, or on that of other mechanical properties (e.g. uniaxial compressive strength from the laboratory tests).

The spatial variability of the geological parameters has to be filtered out because it should not affect the uncertainty on the mean value of P at a certain depth. To take away the spatial variability, the differences between the maximum and mean P, and the minimum and mean P are evaluated for the same depth. These differences are then normalised by the mean value of P itself. Each obtained normalised difference 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:

$$\Delta_{conf\ mean\ of\ P} = \pm \frac{1.96\,\sigma}{\sqrt{n}} \tag{1}$$

where σ is the standard deviation of the parameter population and n is the number of values composing the sample. The number of values n is used to calculate the parameter for each rock domain/deformation zone.

For the rock domain RFM029, the number of values n provided by each borehole is around 150. For RFM012, RFM017 and RFM018, n is around 42, 15 and 12, respectively.

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

$$\begin{aligned} \Delta P_{+conf\ mean} &= \frac{P_{MAX} - P_{MEAN}}{\sqrt{n}} \\ \Delta P_{-conf\ mean} &= \frac{P_{MEAN} - P_{MIN}}{\sqrt{n}} \end{aligned} \tag{2}$$

where P is the parameter with its possible maximum and minimum values and mean value, respectively.

3.8.2 Uncertainty on the rock mass quality and properties

When the method illustrated in Section 3.8.1 is applied to the available data, Table 3-11 is obtained. It can be observed that the size of the available dataset affects the uncertainty of the determination. In fact, RFM017 and RFM018 show almost the same uncertainty of the mean of the rock quality and rock properties, while RFM029 has the lowest values thanks to the great amount of data available. Roughly, we can say that the uncertainty on the parameters from RFM029 is half that on the parameters obtained from the other rock domains.

Table 3-11. Uncertainties of the predicted mechanical properties of the rock domains of the Forsmark Area Model – version 1.2. The uncertainties are given as range of variation of the possible mean value.

Rock domain	RFM012	RFM017	RFM018	RFM029	RFM029 above ZFMNE00A2	RFM029 below ZFMNE00A2
Properties of the rock mass	**Uncertainty of the mean**	**Uncertainty of the mean**	**Uncertainty of the mean**	**Uncertainty of the mean**	**Uncertainty of the mean**	**Uncertainty of the mean**
RMR	–3% +2%	–5% +2%	–6% +3%	–1% +1%	–2% +1%	–2% +1%
Deformation Modulus[1)]	–9% +5%	–14% +20%	–17% +12%	–4% +3%	–6% +4%	–5% +3%
Poisson's ratio[1)]	–7% +7%	–9% +11%	–14% +15%	–3% +3%	–4% +5%	–3% +4%
Uniaxial compressive strength (Hoek & Brown)[2)]	–13% +20%	–18% +26%	–24% +40%	–6% +9%	–8% +12%	–7% +9%
Friction angle[3)]	–4% +2%	–5% +3%	–7% +4%	–2% +1%	–2% +1%	–2% +1%
Cohesion[3)]	–7% +8%	–9% +8%	–13% +15%	–3% +3%	–4% +4%	–4% +3%
Uniaxial compressive strength (Mohr-Coulomb)[3)]	–9% +12%	–12% +13%	–17% +23%	–5% +5%	–6% +7%	–5% +5%
Tensile strength[2)]	–13% +18%	–19% +26%	–25% +36%	–7% +8%	–8% +13%	–7% +8%

[1)] The deformation modulus and the Poisson's ratio of the rock mass are assumed independent on the state of stress due to their high values.

[2)] The uniaxial compressive and tensile strength are obtained from the Hoek and Brown's envelope of the rock mass.

[3)] The apparent uniaxial compressive strength, cohesion and friction angle are obtained from the Coulomb's strength criterion for a confinement stress between 10 and 30 MPa.

If Eq. (2) is applied to Q, the uncertainty becomes very large (between 3% and 70%). This is because the Q system is structured in a logarithmic fashion, and this is not well captured by the technique for estimating the uncertainties that imply a normal distribution of the analysed parameter.

RMR seems to be calculated with high accuracy. The uncertainty on the mean varies between ± 1% to about ± 4% depending on the rock domain considered.

The deformation modulus and the Poisson's ratio are interrelated, thus it happens they have almost the same level of uncertainty of the mean value. The same applies to the uniaxial compressive strength according to Hoek & Brown's and Coulomb's Criterion, and to the tensile strength. For RFM029, the uncertainty of the mean of these strength parameters is about ± 7%.

The uncertainty of the apparent friction angle is rather low, and it is quantified to be less than ± 2% for RFM029. For the same rock domain, the mean value of the apparent cohesion might fluctuate within ± 6%.

4 Deformation zones

Twelve Deterministic Deformation Zones were found to intercept borehole KFM01A, KFM02A, KFM03A and KFM04A /SKB 2005/. The geological description of such deformation zones is shortly presented in Table 4-1, where the estimated length, thickness, orientation and type of deformation are summarised. It can be observed that the length of these zones varies between 700 m and 5 km (with the exception of the alternative interpretation of ZFMNE00A2).

Depending on their thickness and orientation, the zones cross the boreholes in different points and extensions that are shown in Table 4-2. It can be observed that only four zones appear along the same borehole for a consecutive length of more than 40 m. Zone ZFMNE00A2 predominates covering about 40% of the total length of deformation zone along all the boreholes.

Table 4-1. Properties of the deformation zones intercepted by the boreholes KFM01A, KFM02A, KFM03A and KFM04A and considered for rock mechanics purposes. All zones are classified as "ductile/brittle" in /SKB 2005/.

Deformation zones	Length	Thickness	Strike/dip	Comments
ZFMNE1192	1,326 ± 50 m	5 m	073/82	Fractures in KFM01A
ZFMNE0061	1,727 ± 100 m	15 m	068/81	Intersect with KFM01A and linked lineaments
ZFMNE00A2	4,874 ± 200 m (alt. 7,894 ± 500 m)	65 ± 35 m	080/24	Seismic reflector/several boreholes
ZFMNE1189	–	4 m	040/65	Fractures in KFM02A
ZFMNE00B4	–	5 m	050/29	Seismic reflector B4
ZFMNE00A3	3,889 ± 200 m	13 ± 9 m	055/23	Seismic reflector A3
ZFMNE00B6	2,950 ± 200 m	7 ± 4 m	030/32	Seismic reflector B6
ZFMNE1195	1,233 ± 25 m	9 m	080/39	Fractures
ZFMNE00B1	2,208 ± 100 m	7 m	032/27	Seismic reflector B1
ZFMNE00A7	4,090 ± 200 m	17 ± 10 m	055/23	Seismic reflector A7
ZFMNE00A4	4,298 ± 200 m	25 ± 13 m	061/25	Seismic reflector A4
ZFMNE1188	741 ± 50 m	1.5 ± 0.5 m	220/88	Surface geology/KFM04A

Table 4-2. Approximated length of rock belonging to the deformation zones along the boreholes KFM01A, KFM02A, KFM03A and KFM04A considered for rock mechanics purposes.

Deformation Zones	Extension in length	Deformation Zones	Extension in length
ZFMNE1192	25 m in KFM01A	ZFMNE00B6	10 m in KFM02A
ZFMNE0061	45 m in KFM01A	ZFMNE1195	15 m in KFM02A
ZFMNE00A2	105 m in KFM02A + 75 in KFM04A=180 m*	ZFMNE00B1	10 m in KFM03A
ZFMNE1189	15 m in KFM02A	ZFMNE00A7	10 m in KFM03A
ZFMNE00B4	10 m in KFM02A	ZFMNE00A4	45 m in KFM03A
ZFMNE00A3	25 in KFM02A + 15 in KFM03A=40 m	ZFMNE1188	50+5=55 m in KFM04A

* Not accounted for: DZ1 in the percussion-drilled part of KFM01A and, the possible intersection in DZ5 in KFM03A.

For the purpose of grouping the deformation zones according to orientation and/or inclination, the pole plot in Figure 4-1 was produced. This shows that all the zones intercepted by the four boreholes have approximately the same strike. Two groups can be recognised based on the inclination and will be addressed in the following sections as "sub-horizontal" and "sub-vertical".

In the following sections, the rock mass quality according to Q and RMR system is tabulated for each Deterministic Deformation Zone, for the group of "sub-horizontal" zones included and excluded ZFMNE00A2, for the "sub-vertical" zones and for all zones. For the same groups the following mechanical properties of the rock mass in the deformation zones are also reported:

- The deformation modulus and the Poisson's ratio.
- The uniaxial compressive and tensile strength according to the Hoek & Brown's Criterion.
- The apparent friction angle, cohesion and uniaxial compressive strength according to the Coulomb's Criterion.

These properties will be the base of the Rock Mechanics Modelling for the Forsmark Descriptive Model Version 1.2. In the following sections, it can be observed that the rock mass quality of the deformation zones is often, at least on average, "good" or "very good". This can be explained by the fact that the geological definition of a deformation zone does not necessarily imply that the rock mass quality from a Rock Mechanics point of view is low. This is because the geological definition considers ductile and brittle deformations, while, usually, only brittle deformations are associated with low rock mass quality and thus excavation problems.

In Appendix, charts that compare the mechanical properties of the deformation zones are also provided.

4.1 Rock Quality Index (Q)

On average, the value of Q is rather high (> 40) and would classify the rock in the deformation zones as "very good" (Table 4-3). However, the deformation zone with lowest average Q is ZFMNE1195, while the worse Q value occurs in ZFMNE00A7 (Q=1.8). The sub-horizontal deformation zones present an average Q below the average for all deformation zones (minimum Q=15.8).

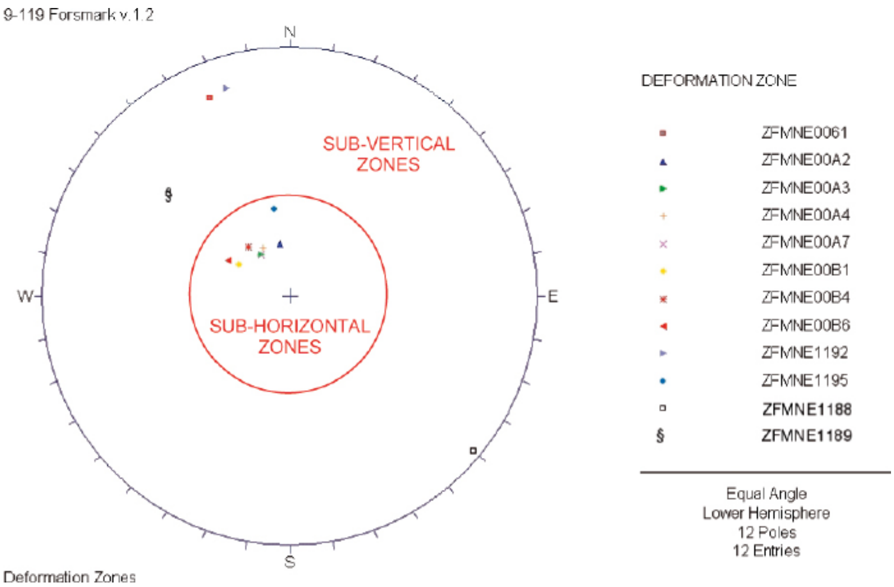

Figure 4-1. *Orientation of the deformation zones intersected by borehole KFM01A, KFM02A, KFM03A and KFM04A.*

Table 4-3. Q values of the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

Deformation Zones	Q [–] Min	Mean [most freq.]	Max	Deformation Zones	Q [–] Min	Mean [most freq.]	Max
ZFMNE1192	15.0	32.3 [25.8]	66.7	ZFMNE00B6	9.1	12.7	16.2
ZFMNE0061	15.2	169.6 [64.9]	1,066.7	ZFMNE1195	2.8	5.0 [3.8]	8.5
ZFMNE00A2	6.8	42.5 [29.9]	154.3	ZFMNE00B1	7.7	9.2	10.8
ZFMNE1189	6.1	17.0 [10.5]	34.4	ZFMNE00A7	1.8	15.2	28.7
ZFMNE00B4	34.2	38.8	43.4	ZFMNE00A4	6.1	14.9 [9.1]	32.7
ZFMNE00A3	5.5	17.6 [15.8]	33.0	ZFMNE1188	24.5	57.8 [38.4]	167.3
ZFMNESubH+A2	1.8	30.7 [19.8]	154.3	ZFMNESubV	6.1	84.8 [37.7]	1,066.7
ZFMNESubH –A2	1.8	15.8 [13.4]	43.4	All ZFMNE	1.8	47.2 [25.5]	1,066.7

4.2 Rock Mass Rating (RMR)

Also RMR classify the deformation zones on average as between "good" and "very good" rock (RMR around 80) (Table 4-4). The deformation zone with lowest RMR is ZFMNE1189 (RMR=76.7). The worse local value occurring when all deformation zones are considered is in ZFMNE00A2 (minimum RMR=68.1).

4.3 Uniaxial compressive strength of the rock mass

The uniaxial compressive strength of the rock mass, interpreted as a continuous medium, can be evaluated by means of GSI and the Hoek & Brown's Criterion. The average strength is quite similar for the sub-horizontal, sub-vertical and all the zones (about 55 MPa, see Table 4-5). However, ZFMNE1189 exhibits the lowest average (mean UCSm=25.5 MPa) and minimum (minimum UCSm=13.9 MPa) value among all deformation zones.

Table 4-4. RMR values of the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

Deformation zones	RMR [–] Min	Mean/St dev	Max	Deformation zones	RMR [–] Min	Mean/St dev	Max
ZFMNE1192	78.6	80.6/1.7	82.6	ZFMNE00B6	77.2	77.3*	77.5
ZFMNE0061	77.1	82.1/5.3	94.0	ZFMNE1195	79.7	84.5/4.2	87.0
ZFMNE00A2	68.1	80.7/5.2	91.5	ZFMNE00B1	78.7	83.1*	87.5
ZFMNE1189	72.4	76.7/5.1	82.3	ZFMNE00A7	77.2	78.1*	79.1
ZFMNE00B4	87.3	87.3*	87.4	ZFMNE00A4	72.1	77.0/3.1	83.1
ZFMNE00A3	73.6	81.1/4.7	85.6	ZFMNE1188	76.5	81.9/2.8	85.6
ZFMNESubH+A2	68.1	80.5/4.9	91.5	ZFMNESubV	72.4	81.2/4.1	94.0
ZFMNESubH –A2	72.1	80.2/4.7	87.5	All ZFMNE	68.1	80.7/4.7	94.0

* There are not enough data for determining the standard deviation.

Table 4-5. Predicted uniaxial compressive strength UCS_m (equivalent strength for zero confinement pressure) according to the Hoek and Brown's Criterion for the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

	UCS_m [MPa]				UCS_m [MPa]		
Deformation zones	Min	Mean/St dev	Max	Deformation zones	Min	Mean/St dev	Max
ZFMNE1192	46.3	51.7/4.7	57.6	ZFMNE00B6	42.7	43.0*	43.3
ZFMNE0061	42.5	58.6/20.9	108.5	ZFMNE1195	49.2	65.3/14.0	73.5
ZFMNE00A2	25.8	56.6/17.5	103.9	ZFMNE00B1	46.4	61.1*	75.8
ZFMNE1189	13.9	25.5/12.5	38.6	ZFMNE00A7	42.7	45.0*	47.4
ZFMNE00B4	74.6	74.9*	75.1	ZFMNE00A4	32.1	42.8/7.7	59.3
ZFMNE00A3	35.0	54.4/12.9	68.2	ZFMNE1188	45.1	61.5/9.3	74.7
ZFMNESubH+A2	25.8	54.7/16.1	103.9	ZFMNESubV	13.9	55.0/17.2	108.5
ZFMNESubH –A2	32.1	52.3/14.0	75.8	All ZFMNE	13.9	54.8/16.3	108.5

* There are not enough data for determining the standard deviation.

4.4 Deformation modulus of the rock mass

Also the deformation modulus is rather similar for each deformation zone. On average the deformation modulus is 58 GPa (Table 4-6). Some zones show the same material property as for the intact rock (Em=75 GPa for ZFMNE00B4), but some has a much lower average deformation modulus (Em=47.9 GPa for ZFMNE1189). The lowest calculated value was about 28 GPa within ZFMNE00A2.

4.5 Poisson's ratio of the rock mass

The Poisson's ratio of the deformation zones vary between 0.15 and 0.24, and most of them exhibit a value around 0.19 (Table 4-7).

Table 4-6. Predicted deformation modulus Em from RMR for the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2. (low confinement).

	E_m [GPa]				E_m [GPa]		
Deformation zones	Min	Mean/St dev	Max	Deformation Zones	Min	Mean/St dev	Max
ZFMNE1192	52.0	58.4/5.5	65.2	ZFMNE00B6	47.9	48.3*	48.6
ZFMNE0061	47.6	59.9/10.1	75.0	ZFMNE1195	55.4	68.5/11.3	75.0
ZFMNE00A2	28.4	58.2/13.1	75.0	ZFMNE00B1	52.2	63.6*	75.0
ZFMNE1189	36.2	47.9/14.6	64.2	ZFMNE00A7	47.9	50.6*	53.3
ZFMNE00B4	75.0	75.0*	75.0	ZFMNE00A4	35.7	48.0/9.0	67.3
ZFMNE00A3	39.0	61.1/14.5	75.0	ZFMNE1188	45.9	63.1/9.5	75.0
ZFMNESubH+A2	28.4	57.8/13.2	75.0	ZFMNESubV	36.2	59.6/10.2	75.0
ZFMNESubH –A2	35.7	52.7/13.5	75.0	All ZFMNE	28.4	58.3/12.3	75.0

* There are not enough data for determining the standard deviation.

Table 4-7. Predicted Poisson's ratio from RMR for the Deterministic deformation zones of the Forsmark Area Model – version 1.2.

	ν [–]				ν [–]		
Deformation zones	**Min**	**Mean/St dev**	**Max**	**Deformation zones**	**Min**	**Mean/St dev**	**Max**
ZFMNE1192	0.17	0.19/0.02	0.21	ZFMNE00B6	0.15	0.15*	0.16
ZFMNE0061	0.15	0.19/0.03	0.24	ZFMNE1195	0.18	0.22 /0.04	0.24
ZFMNE00A2	0.09	0.19/0.04	0.24	ZFMNE00B1	0.17	0.20*	0.24
ZFMNE1189	0.12	0.15/0.05	0.21	ZFMNE00A7	0.15	0.16*	0.17
ZFMNE00B4	0.24	0.24*	0.24	ZFMNE00A4	0.11	0.15/0.03	0.22
ZFMNE00A3	0.12	0.20/0.05	0.24	ZFMNE1188	0.15	0.20/0.03	0.24
ZFMNESubH+A2	0.09	0.18/0.04	0.24	ZFMNESubV	0.12	0.19/0.03	0.24
ZFMNESubH –A2	0.11	0.18/0.04	0.24	All ZFMNE	0.09	0.19/0.04	0.24

* There are not enough data for determining the standard deviation.

4.6 Coulomb's strength criterion of the rock mass

The Coulomb's Criterion is fitted to the Hoek & Brown's Criterion to determine the apparent cohesion c' and friction angle φ'. The fit is performed for confinement stresses between 10 and 30 MPa.

The average cohesion for all deformation zones is around 22 MPa (Table 4-8). As for some other parameters, ZFMNE1189 presents the lowest average value (c'=16.6 MPa) and the lowest single value (c'=14 MPa). Some of the zones have the same properties as the rock domains (e.g. ZFMNE0061).

The friction angle is not as sensitive to bad rock conditions as the cohesion, and the average values vary around 47° (Table 4-9). As for the cohesion, ZFMNE1189 has the lowest average friction angle (φ'=41.8°) and the lowest single value among all deformation zones (φ'=38.2°).

The apparent uniaxial compressive strength is obtained by extrapolation of the Coulomb's Criterion to a zero confinement stress (Table 4-10). This value is given to allow comparison with the results of the Theoretical Model, if available for the deformation zones.

Table 4-8. Predicted cohesion c' of the rock mass according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

	c' [MPa]*				c' [MPa]*		
Deformation zones	**Min**	**Mean/St dev**	**Max**	**Deformation zones**	**Min**	**Mean/St dev**	**Max**
ZFMNE1192	20.7	21.4/0.6	22.2	ZFMNE00B6	20.2	20.3**	20.3
ZFMNE0061	20.2	22.3/2.7	28.7	ZFMNE1195	21.1	23.2/1.8	24.3
ZFMNE00A2	17.7	21.9/2.3	28.0	ZFMNE00B1	20.7	22.6**	24.5
ZFMNE1189	14.0	16.6/2.8	19.6	ZFMNE00A7	20.2	20.5**	20.9
ZFMNE00B4	24.4	24.4**	24.4	ZFMNE00A4	18.7	20.2/1.1	22.4
ZFMNE00A3	19.1	21.8/1.7	23.6	ZFMNE1188	20.3	22.5/1.2	24.2
ZFMNESubH+A2	17.7	21.7/2.1	28.0	ZFMNESubV	14.0	21.6/2.6	28.7
ZFMNESubH –A2	18.7	21.5/1.9	24.5	All ZFMNE	14.0	21.7/2.2	28.7

* Linear envelope between 10 and 30 MPa.

** There are not enough data for determining the standard deviation.

Table 4-9. Predicted friction angle φ' of the rock mass according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

	φ' [°]*				φ' [°]*		
Deformation zones	**Min**	**Mean/St dev**	**Max**	**Deformation zones**	**Min**	**Mean/St dev**	**Max**
ZFMNE1192	47.0	47.5/0.4	48.1	ZFMNE00B6	46.7	46.7**	46.7
ZFMNE0061	46.6	47.9/1.3	50.7	ZFMNE1195	47.3	48.5/1.0	49.1
ZFMNE00A2	44.1	47.5/1.3	49.9	ZFMNE00B1	47.1	48.2**	49.3
ZFMNE1189	38.2	41.8/4.0	46.2	ZFMNE00A7	46.7	46.9**	47.2
ZFMNE00B4	49.2	49.2**	49.2	ZFMNE00A4	45.3	46.6/0.8	48.2
ZFMNE00A3	45.7	47.6/1.2	48.8	ZFMNE1188	46.3	47.7/0.7	48.6
ZFMNESubH+A2	44.1	47.7/1.2	49.9	ZFMNESubV	38.2	47.1/2.3	50.7
ZFMNESubH –A2	45.3	47.4/1.2	49.3	All ZFMNE	38.2	47.3/1.6	50.7

* Linear envelope between 10 and 30 MPa.

** There are not enough data for determining the standard deviation.

Table 4-10. Predicted apparent uniaxial compressive strength UCSm according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

	Apparent UCS_m [1] (Mohr-Coulomb)				Apparent UCS_m [1] (Mohr-Coulomb)		
Deformation zones	**Min**	**Mean/St dev**	**Max**	**Deformation zones**	**Min**	**Mean/St dev**	**Max**
ZFMNE1192	105.2	110.4/4.5	115.9	ZFMNE00B6	101.8	102.1 [2]	102.4
ZFMNE0061	101.6	116.4/18.6	160.5	ZFMNE1195	108.0	122.7/12.7	130.2
ZFMNE00A2	83.5	113.1/15.4	153.0	ZFMNE00B1	105.4	118.8 [2]	132.2
ZFMNE1189	57.8	75.4/20.3	97.7	ZFMNE00A7	101.8	104.0 [2]	106.3
ZFMNE00B4	131.2	131.3 [2]	131.5	ZFMNE00A4	90.8	101.7/7.6	117.5
ZFMNE00A3	93.9	112.6/12.2	125.5	ZFMNE1188	101.0	116.1/8.3	127.8
ZFMNESubH+A2	83.5	112.0/14.4	153.0	ZFMNESubV	57.8	110.8/18.0	160.5
ZFMNESubH –A2	90.8	110.6/13.1	132.2	All ZFMNE	57.8	111.6/15.5	160.5

[1] Linear envelope between 10 and 30 MPa.

[2] There are not enough data for determining the standard deviation.

Table 4-11. Predicted tensile strength TSm according to the Hoek and Brown's Criterion for the Rock Deterministic Deformation Zones of the Forsmark Area Model – version 1.2.

	TS_m [MPa]				TS_m [MPa]		
Deformation zones	**Min**	**Mean/St dev**	**Max**	**Deformation zones**	**Min**	**Mean/St dev**	**Max**
ZFMNE1192	0.91	1.06/0.13	1.23	ZFMNE00B6	0.82	0.83 [1]	0.84
ZFMNE0061	0.81	1.29/0.66	2.91	ZFMNE1195	0.99	1.47/0.41	1.71
ZFMNE00A2	0.41	1.27/0.56	2.94	ZFMNE00B1	0.92	1.35 [1]	1.79
ZFMNE1189	0.24	0.49/0.24	0.72	ZFMNE00A7	0.82	0.88 [1]	0.94
ZFMNE00B4	1.75	1.76 [1]	1.76	ZFMNE00A4	0.56	0.83/0.21	1.28
ZFMNE00A3	0.63	1.15/0.36	1.55	ZFMNE1188	0.95	1.45/0.29	1.88
ZFMNESubH+A2	0.41	1.20/0.50	2.94	ZFMNESubV	0.24	1.23/0.51	2.91
ZFMNESubH –A2	0.56	1.10/0.40	1.79	All ZFMNE	0.24	1.21/0.50	2.94

[1] There are not enough data for determining the standard deviation.

4.7 Tensile strength of the rock mass

The average tensile strength of the rock mass is estimated to be about 1.2 MPa (Table 4-11). The proportion between the tensile strength and the uniaxial compressive strength is found to vary between 1.9% and 2.2% for the analyzed deformation zones.

4.8 Uncertainties

The uncertainties on the Rock Mechanics parameters of the deformation zones are determined according to the procedure specified in Section 3.8.1. The uncertainties for the different groups of deformation zones are listed in Table 4-12. It is worth to mention that most of the uncertainty intervals on the mean are asymmetric. In Table 4-12, the stochastic deformation zones identified by the geological "single-hole interpretation" and not included in the Deformation Zone Model are considered for comparison. This group show the highest uncertainty due to scarcity of the available data (totally only about 15 m of borehole length).

For the sub-horizontal deformation zones, the uncertainty diminishes when ZFMNE00A2 is considered, thanks to the large amount of data available for this zone. The sub-vertical zones exhibit the lowest uncertainty on the mean value of the properties. This is probably due to the fact that sub-vertical zones intersecting the boreholes have to have a clearer signature than sub-horizontal zones, otherwise they would be overlooked and interpreted as borehole section of higher fracture frequency. The fact that sub-vertical zones are intercepted with a small angle with respect to the borehole axis produces a denser sampling of the geological features.

The uncertainty on the determination of the mean mechanical properties of the zones diminishes when all zones together are considered.

Table 4-12. Uncertainties on the predicted mechanical properties of the rock domains of the Forsmark Area Model – version 1.2. The uncertainties are given as range of variation of the possible mean value.

Deformation zones	RFM029 Stochastic def. zones	ZFMNESubH + A2	ZFMNESubH – A2	ZFMNESubV	All ZFMNE
Properties of the rock mass	**Uncertainty on the mean**	**Uncertainty on the mean**	**Uncertainty on the mean**	**Uncertainty on the mean**	**Uncertainty on the mean**
RMR	–21% +13%	–8% +5%	–11% +8%	–7% +4%	–7% +5%
Deformation Modulus [1)]	–50% +75%	–22% +22%	–31% +33%	–21% +19%	–21% +21%
Poisson's ratio [1)]	–44% +91%	–17% +26%	–25% +39%	–16% +23%	–17% +26%
Uniaxial compressive strength (Hoek & Brown) [2)]	–59% +151%	–29% +67%	–40% +99%	–28% +54%	–28% +63%
Friction angle [3)]	–22% +13%	–9% +5%	–13% +17%	–9% +5%	–9% +5%
Cohesion [3)]	–30% +37%	–15% +20%	–21% +29%	–14% +17%	–15% +19%
Uniaxial compressive strength (Mohr-Coulomb) [3)]	–40% +61%	–20% +32%	–28% +46%	–19% +28%	–20% +31%
Tensile strength [2)]	–62% +180%	–30% +76%	–42% +115%	–29% +55%	–29% +70%

[1)] The deformation modulus and the Poisson's ratio of the rock mass are assumed independent on the state of stress due to their high values.

[2)] The uniaxial compressive and tensile strength is obtained from the Hoek and Brown's envelope of the rock mass.

[3)] The apparent uniaxial compressive strength, cohesion and friction angle are obtained from the Coulomb's strength criterion between 10 and 30 MPa confinement stress.

5 Conclusions

This report contains the delivery of the Empirical Approach to the Forsmark Site Descriptive Model – version 1.2. The data presented here will be "harmonized" (integrated and coordinated) with the results of the Theoretical Approach and will lead to the compilation of the Rock Mechanics Model for the Forsmark Site.

Contrary to the Forsmark SDM Version 1.1 /SKB 2004/, the properties of the rock mass are not provided here as a function of depth. This decision was taken for two reasons:

- Only borehole KFM01A showed a clear variation of the rock mass properties with depth.
- The presence of repeated sub-horizontal deformation zones dipping around 25° would indicate that, if a variation with depth would occur, that would be varying depending on the exact location where the boreholes intercept the sub-horizontal zones.

These conclusions are also supported by the moderate differences observed in the rock mass properties. For the empirical modelling, the rock domain RFM029 was considered as a single rock volume or, in alternative, as two volumes cut by the Deformation Zone ZFMNE00A2. In this second hypothesis, the deep part of RFM029 would exhibit mechanical properties slightly higher than the shallow part of RFM029. The analysis shows that the deep part presents a deformation modulus 2% higher than the average for this rock domain, while the shallow part 4% lower than the average. Totally, the difference of the deformation modulus between the shallow and deep part of RFM029 would be at most 6%. When the cohesion of the rock mass is considered, the difference between the shallow and deep part of RFM029 would be at most 11%. These differences do not justify the introduction of a higher degree of detail in the Rock Mechanics Model compared to the rock domain Model at this stage of the study. This also implies that the rock domain RFM029 would not be split into two domains. Furthermore, it is worth to remind that the Empirical Approach was based on the analysis of sections of core drillhole sections deeper than 100 m from the surface, so that surface data are not considered for Rock Mechanics purposes.

Another difference with respect to the Forsmark SDM Version 1.1 is that data is now available for three more rock domains within the Candidate Area at Forsmark. This can improve the knowledge on the rock quality at the boundary of the so-called "tectonic lens" (basically the rock domain RFM029).

The mechanical properties estimated for the rock mass in the rock domains seems to be of "good" to "very good" quality according to the empirical systems Q and RMR applied for characterisation. For RFM029, the equivalent uniaxial compressive strength of the rock mass, interpreted as a continuum medium, is on average around 80 MPa, while the deformation modulus is on average 69 GPa. The intact rock usually exhibits a deformation modulus of 76 GPa, in both granitic and tonalitic rock.

Compared to rock domain RFM029, the differences of the uniaxial compressive strength and the deformation modulus of the other rock domains can respectively be, at most, of the order of –42% and –7% (Figure 5-1).

Due to the fact that the deformation modulus of the rock mass is so close to that of the intact rock, it seems reasonable to assume that the deformation modulus does not vary with stress, and thus with depth.

Twelve deformation zones identified by the Geological Model and intersecting the four boreholes were analysed from a Rock Mechanics point of view. The thickness of these deformation zones varies between 10 and 100 m, thus some zones are predominating in the property database

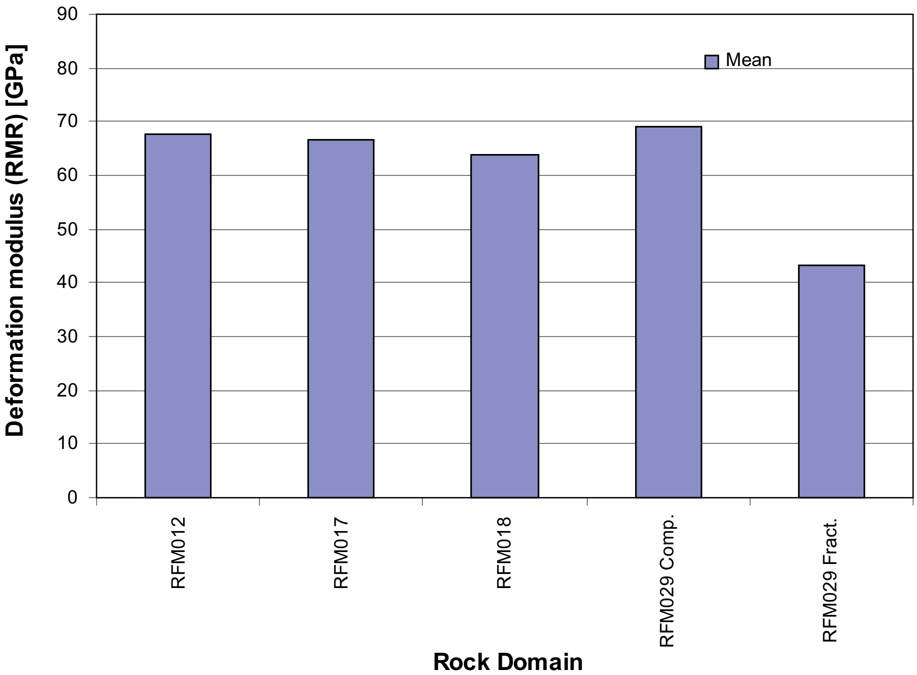

Figure 5-1. *Mean deformation modulus of the rock mass for the Rock Domains RFM012, RFM17, RFM018 and RFM029 ("competent" and "fractured" rock) intercepted by borehole KFM01A, KFM02A, KFM03A and KFM04A.*

(e.g. ZFMNE00A2). The strike of all the deformation zones is very consistent around N60°E, while two prevalent dips of about 25° and 80° were observed. The sampling bias introduced by the fact that the boreholes are sub-vertical causes that:

- Only four of the twelve zones crossed by the four boreholes are sub-vertical.
- The average thickness of the sub-vertical deformation zones is larger than for the sub-horizontal ones. This was adjusted for in the Deformation Zone Model.

The spread of the mechanical properties of the deformation zones could not be correlated either with the orientation, type of deformation nor with the thickness of the zones. It was then decided to group all deformation zones under the same group and provide average, maximum and minimum properties for all twelve zones. The average rock mass quality of the deformation zones is classified as "good rock" by the empirical systems Q and RMR (average Q=47.2; average RMR=80). However, section of "poor rock" were also observed (Q=1.8). The average deformation modulus is around 58 GPa, 15% lower than the deformation modulus of rock domain RFM029 (Figure 5-2). On average, the equivalent uniaxial compressive strength of the rock mass in the deformation zones is 55 MPa, which is 31% lower than for RFM029. It is also interesting to check the minimum mechanical properties occurring in the zones. The lowest deformation modulus and uniaxial compressive strength are 28 GPa and 14 MPa, respectively. The parameters of the Coulomb's shear strength criterion are, on average, 47° for the friction angle and 22 MPa for the cohesion, respectively. The minimum occurring parameters are 38° for the friction angle and 14 MPa for the cohesion. The properties listed here are also representative for the deformation zone ZFMNE00A2 that dominates in terms of length extension along the boreholes.

A special mention should be devoted to the sections of borehole classified as "deformation zone" by the geological "single-hole interpretation" of the borehole data that were excluded from the Deformation Zone Model. For the four boreholes in Forsmark, 99% of the "possible deformation zones" were taken by the Deformation Zone Model as "Deterministic Deformation Zones". In this report, the mechanical properties of the remnant 1% are also summarised under

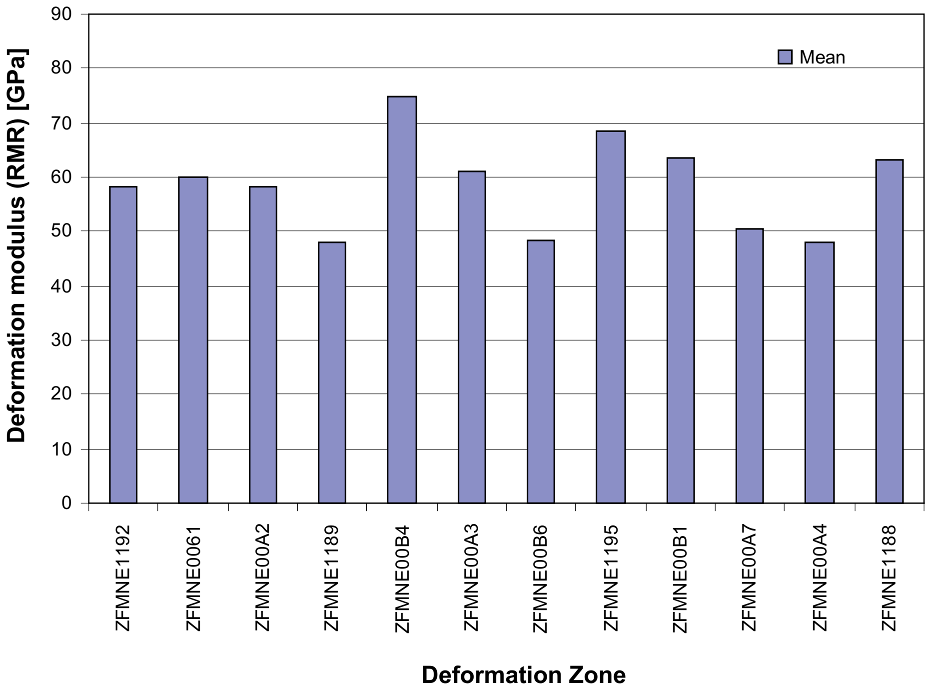

Figure 5-2. *Mean deformation modulus of the rock mass for the Deterministic Deformation Zones intercepted by borehole KFM01A, KFM02A, KFM03A and KFM04A.*

the name "deformation zone" within the rock domains. This fractured rock in RFM029 shows properties very close to the average propertied estimated for the "Deterministic Deformation Zones".

The uncertainties on the parameter estimation were also evaluated by the Empirical Approach. The range of possible values of the input parameters of the empirical systems Q and RMR was studied together with the most favourable and unfavourable combinations of them. Besides this, also the ranges of variation of the laboratory results on rock properties were considered explicitly. For the predominant rock domain RFM029, the uncertainty of the mean of the mechanical properties can be summarised as follows:

- Deformation modulus and the Poisson's ratio: about ± 7%.
- Uniaxial compressive and tensile strength: about ± 8%.
- Apparent friction angle (confinement 10–30 MPa): about ± 2%.
- Apparent cohesion (confinement 10–30 MPa): about ± 6%.

Small rock domains (RFM012, RFM017 and RFM018) have larger uncertainties because there is a much smaller number of determinations of the rock mass properties.

When all deformation zones are considered, the following uncertainty of the mean value of the mechanical properties can be summarised (symmetric intervals are adopted):

- Deformation modulus and Poisson's ratio: about ± 20%.
- Uniaxial compressive and tensile strength: about ± 30%.
- Apparent friction angle (confinement 10–30 MPa): about ± 8%.
- Apparent cohesion (confinement 10–30 MPa): about ± 17%.

After the "harmonization" results obtained by means of the Theoretical Approach, the mechanical properties of the rock mass will be applied in the calculations for design and safety analysis of the deep repository at the Forsmark Candidate Site.

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Appendix

Summary of the results of the empirical model

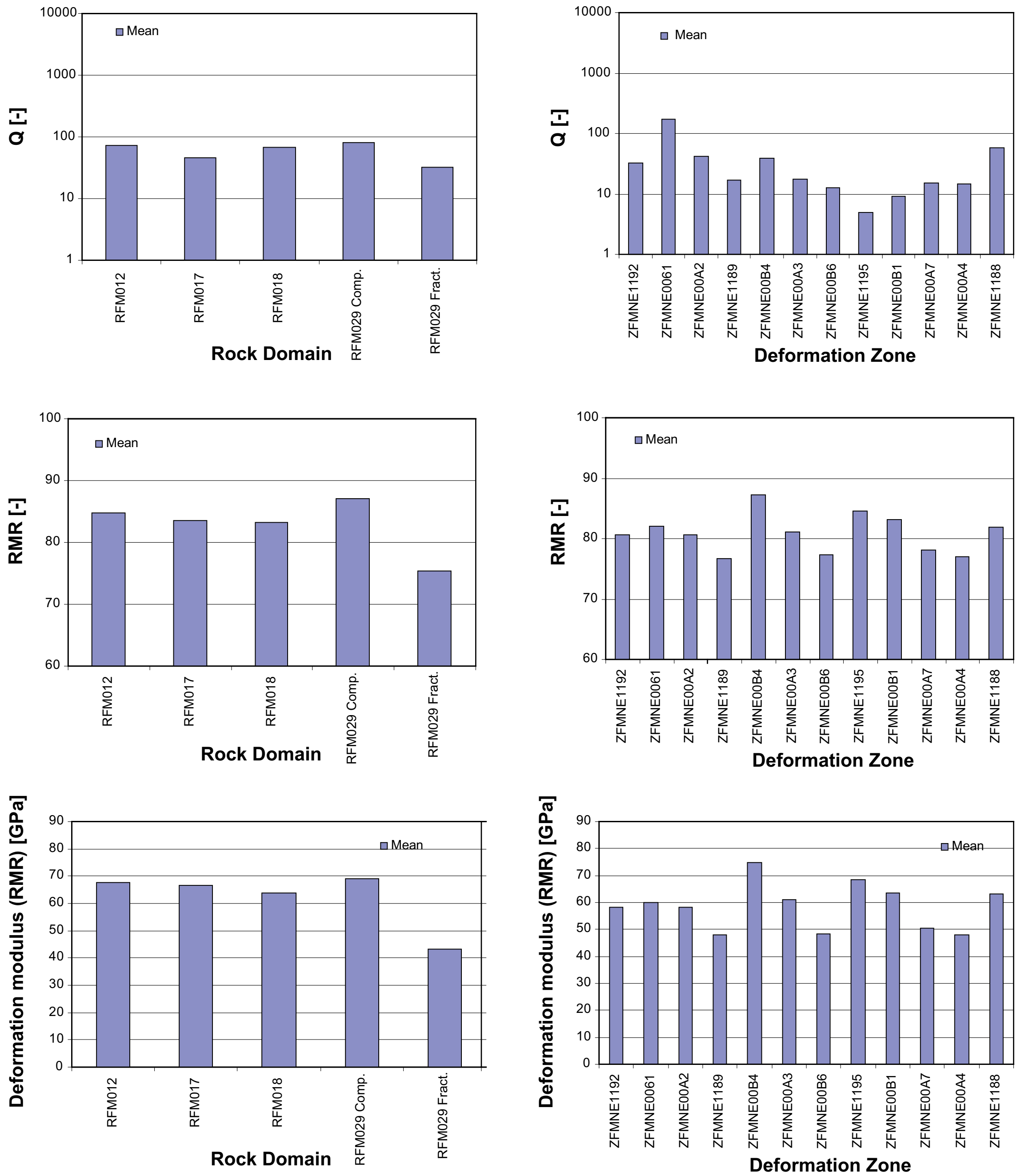

Figure A1-1. *Comparison of Q, RMR and deformation modulus of the rock mass in the Rock Domains and Deformation zones.*

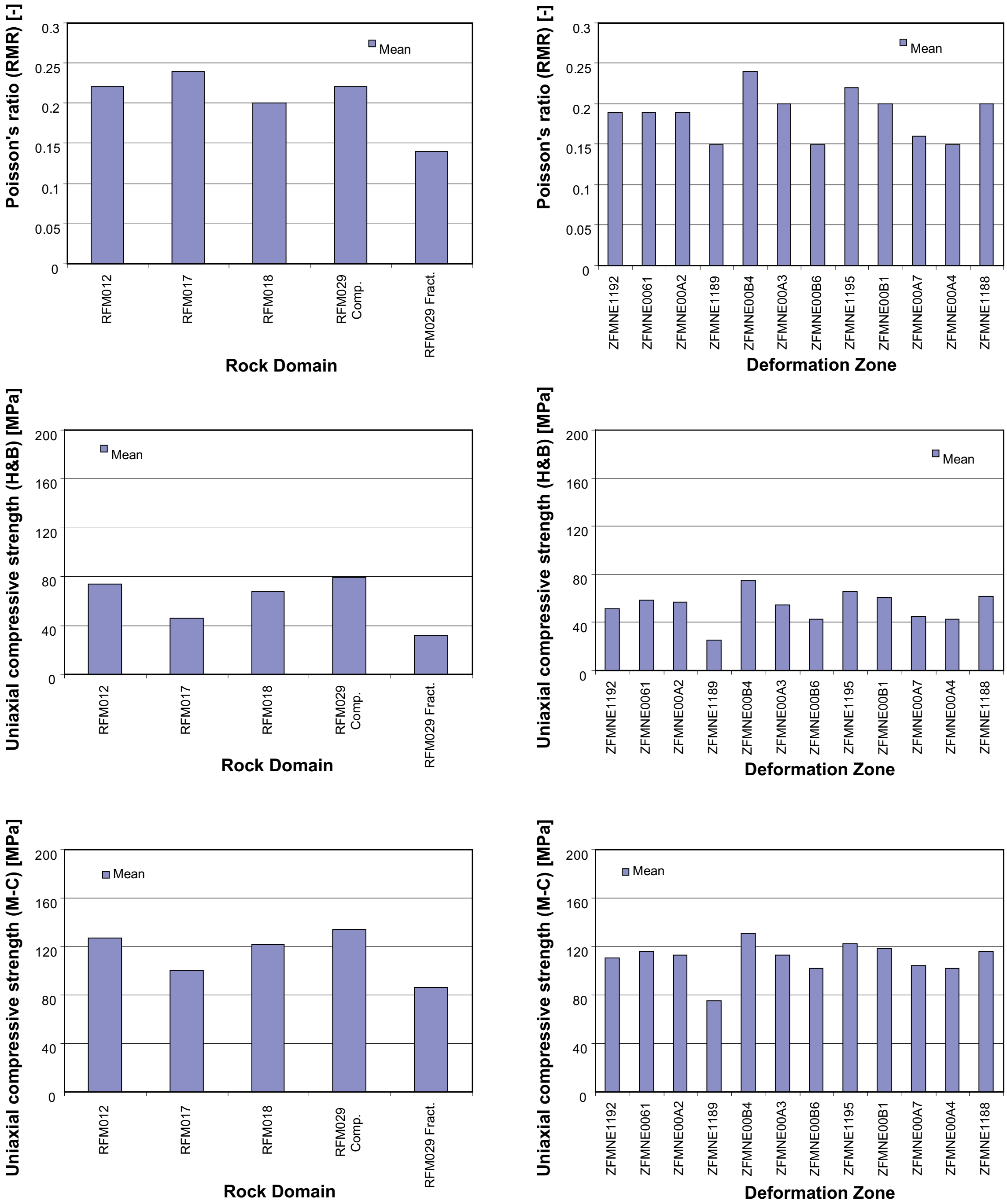

Figure A1-2. *Comparison of the Poisson's ratio, uniaxial compressive strength according to the Hoek & Brown's Criterion and Coulomb's Criterion of the rock mass in the Rock Domains and Deformation zones.*

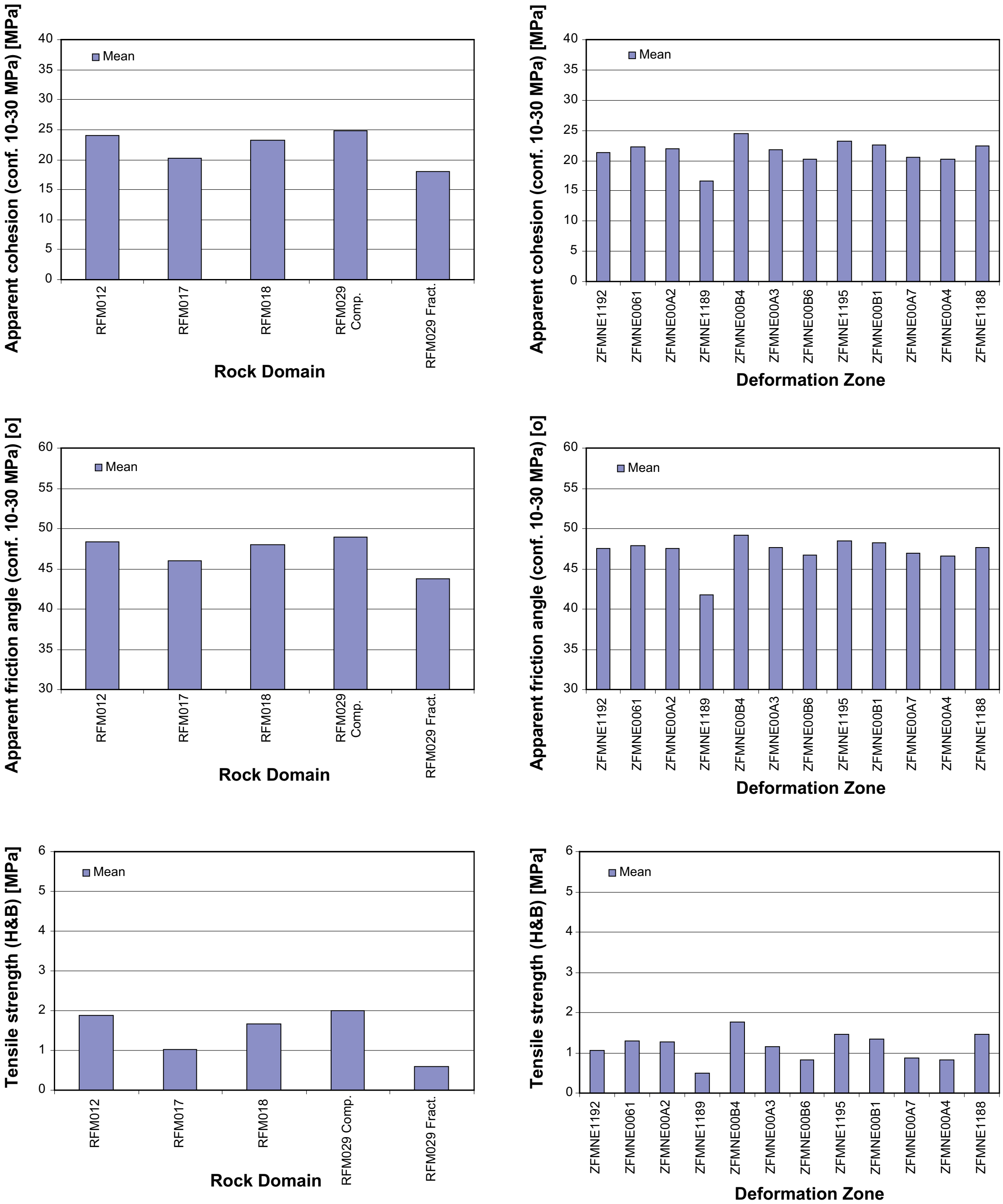

Figure A1-3. *Comparison of the cohesion, friction angle and tensile strength according to the Hoek & Brown's Criterion of the rock mass in the Rock Domains and Deformation zones.*

Histograms for rock domain RFM012

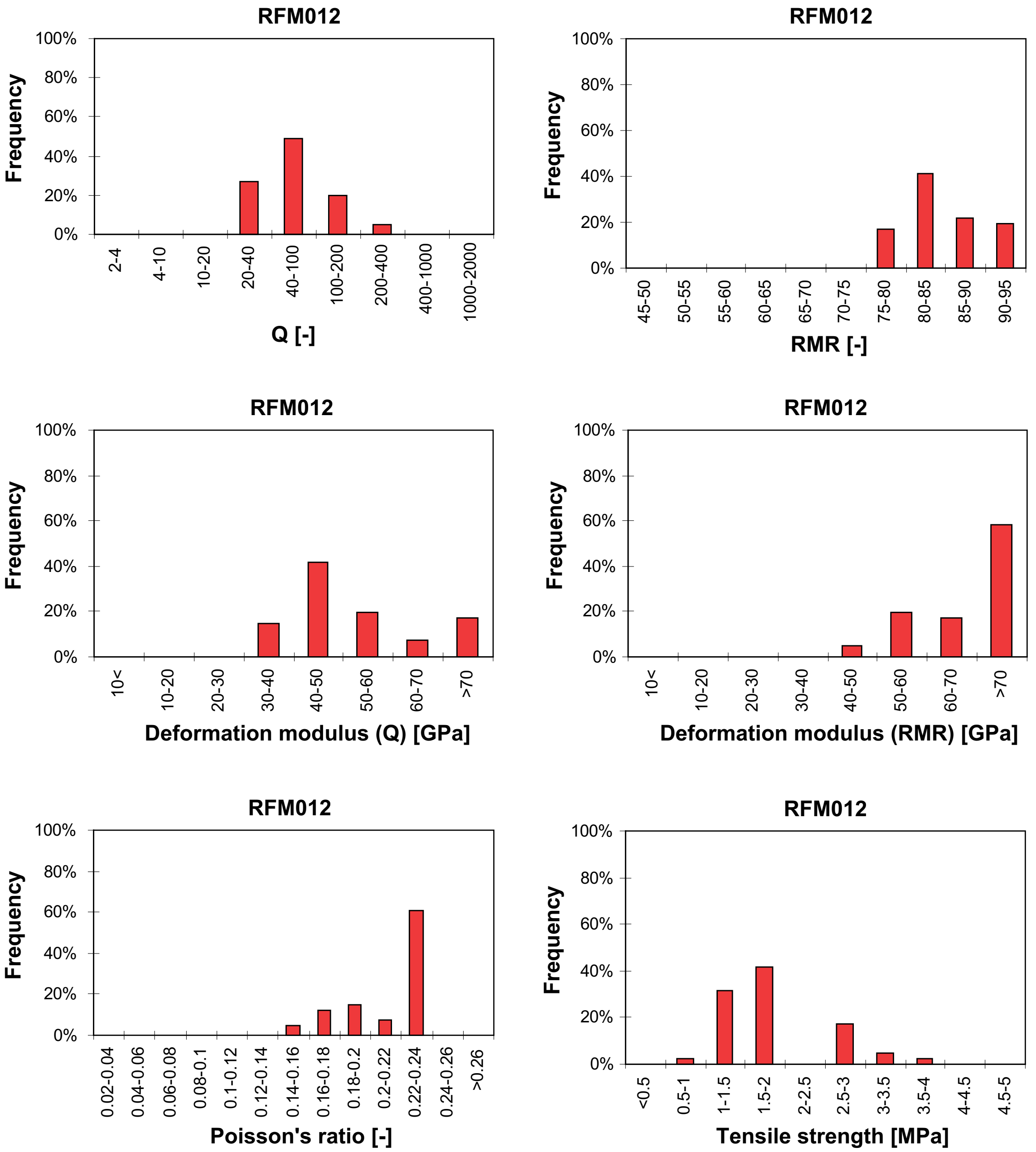

Figure A1-4. *Rock Domain RFM012: Histograms showing the results of RMR and Q and derived mechanical properties.*

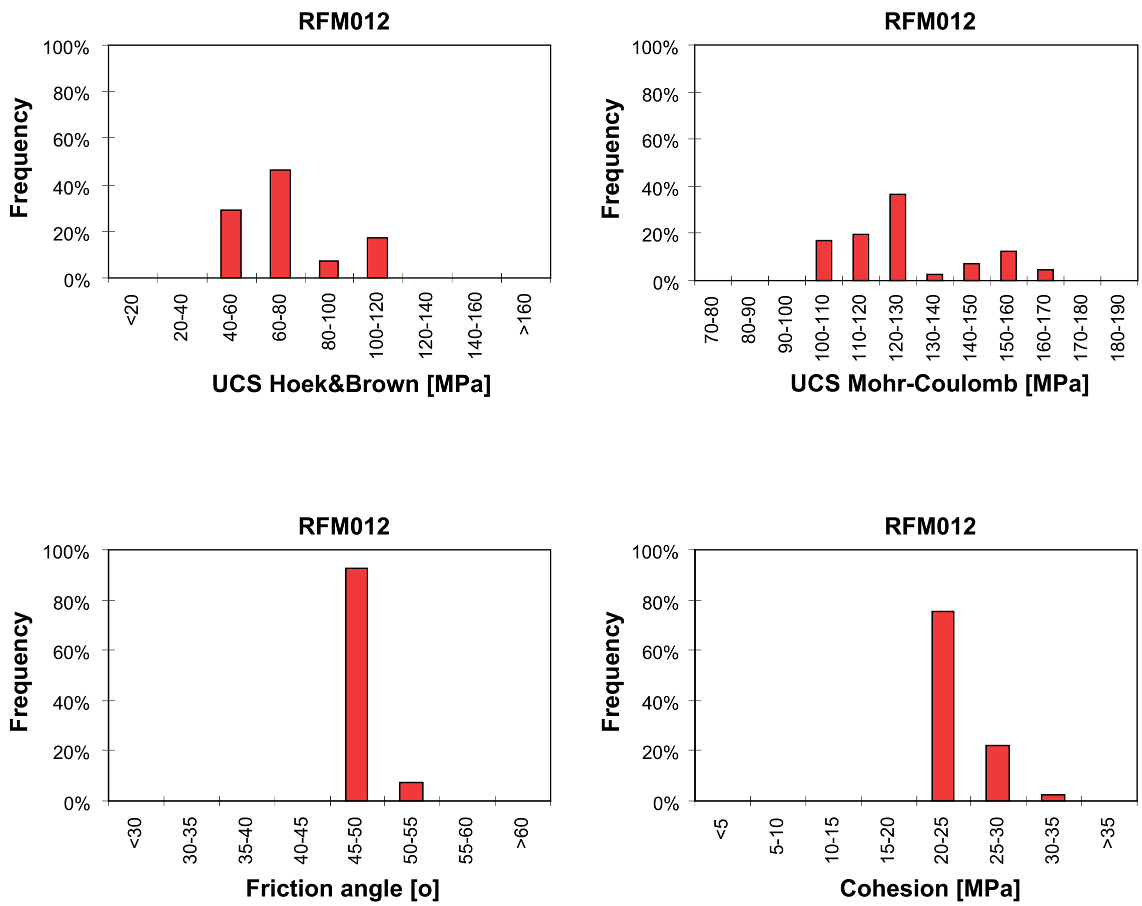

Figure A1-5. *Rock Domain RFM012: Histograms showing the mechanical properties derived from RMR.*

Histograms for rock domain RFM017

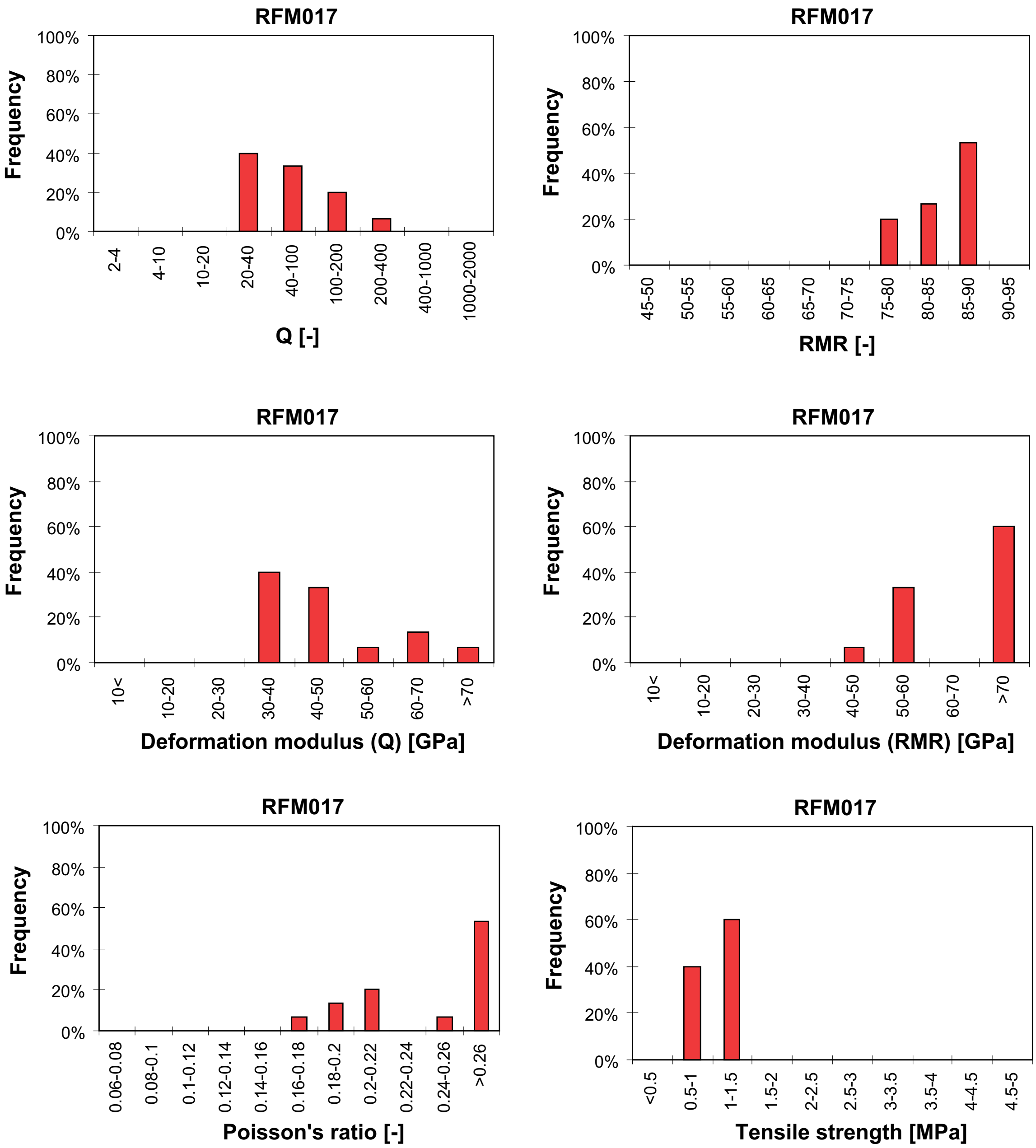

Figure A1-6. *Rock Domain RFM017: Histograms showing the results of RMR and Q and derived mechanical properties.*

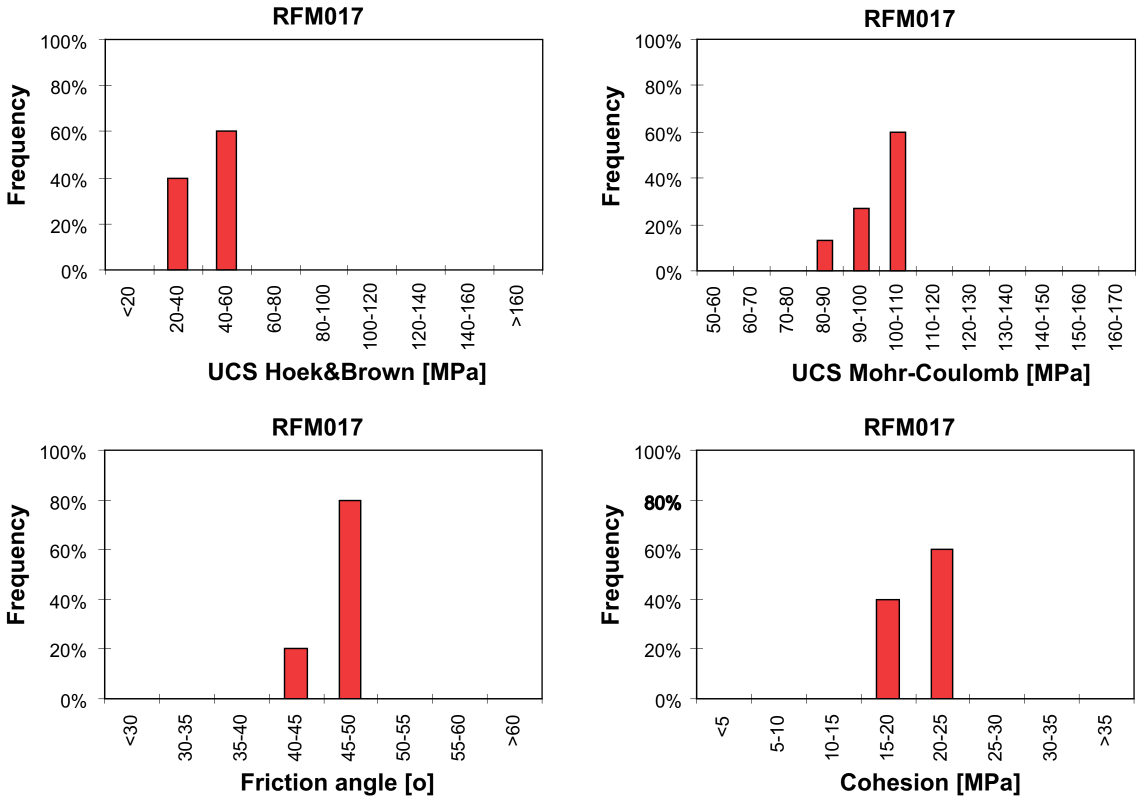

Figure A1-7. *Rock Domain RFM017: Histograms showing the mechanical properties derived from RMR.*

Histograms for rock domain RFM018

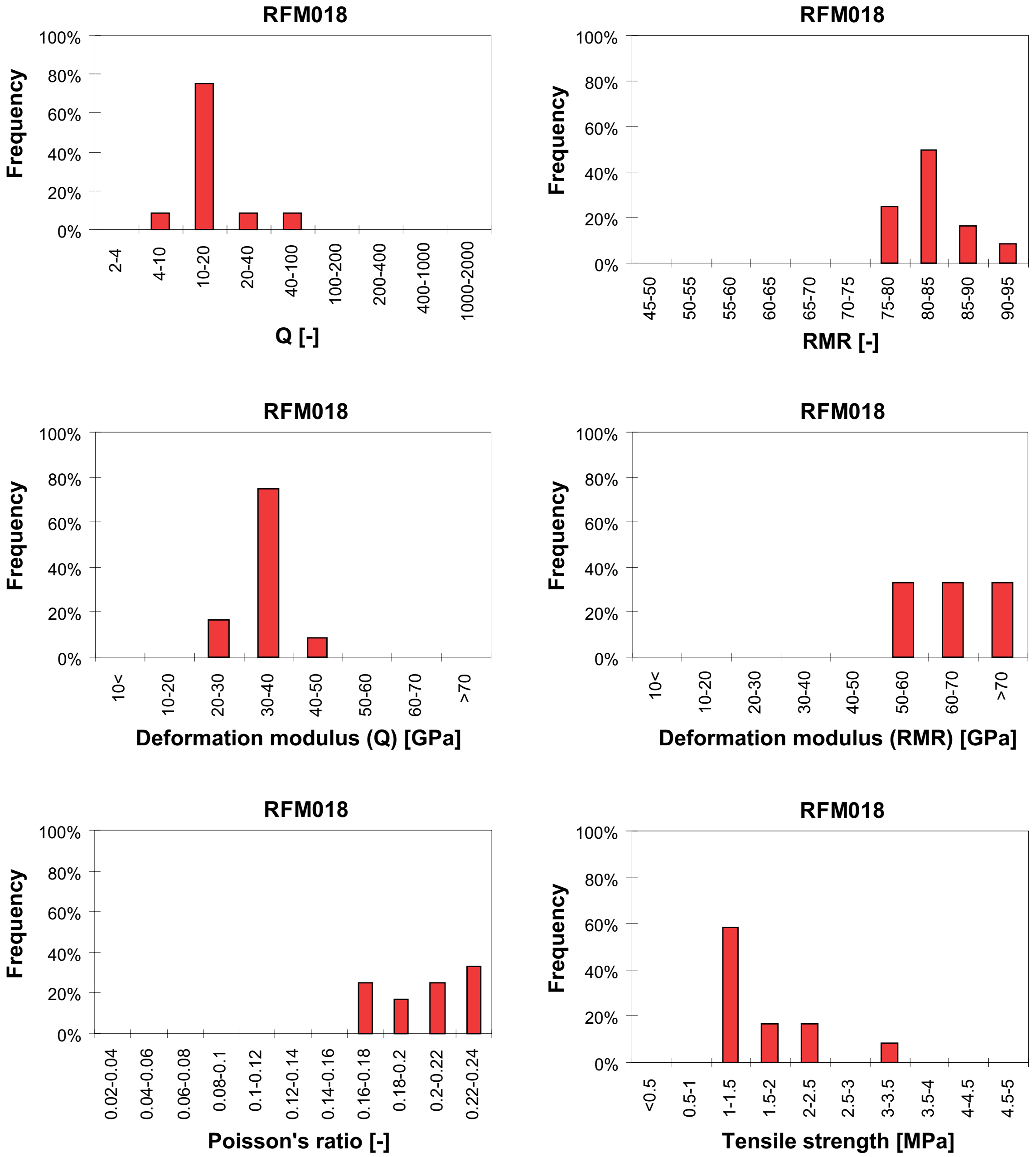

Figure A1-8. *Rock Domain RFM018: Histograms showing the results of RMR and Q and derived mechanical properties.*

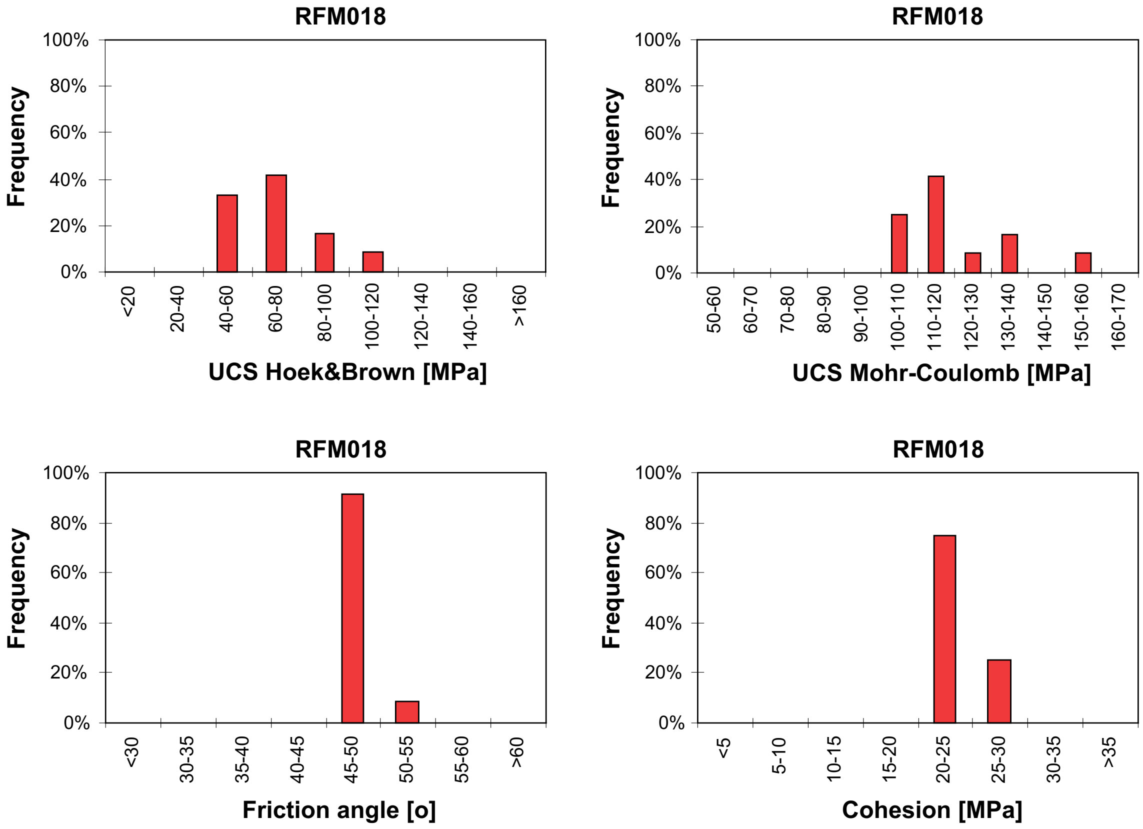

Figure A1-9. *Rock Domain RFM018: Histograms showing the mechanical properties derived from RMR.*

Histograms for rock domain RFM029

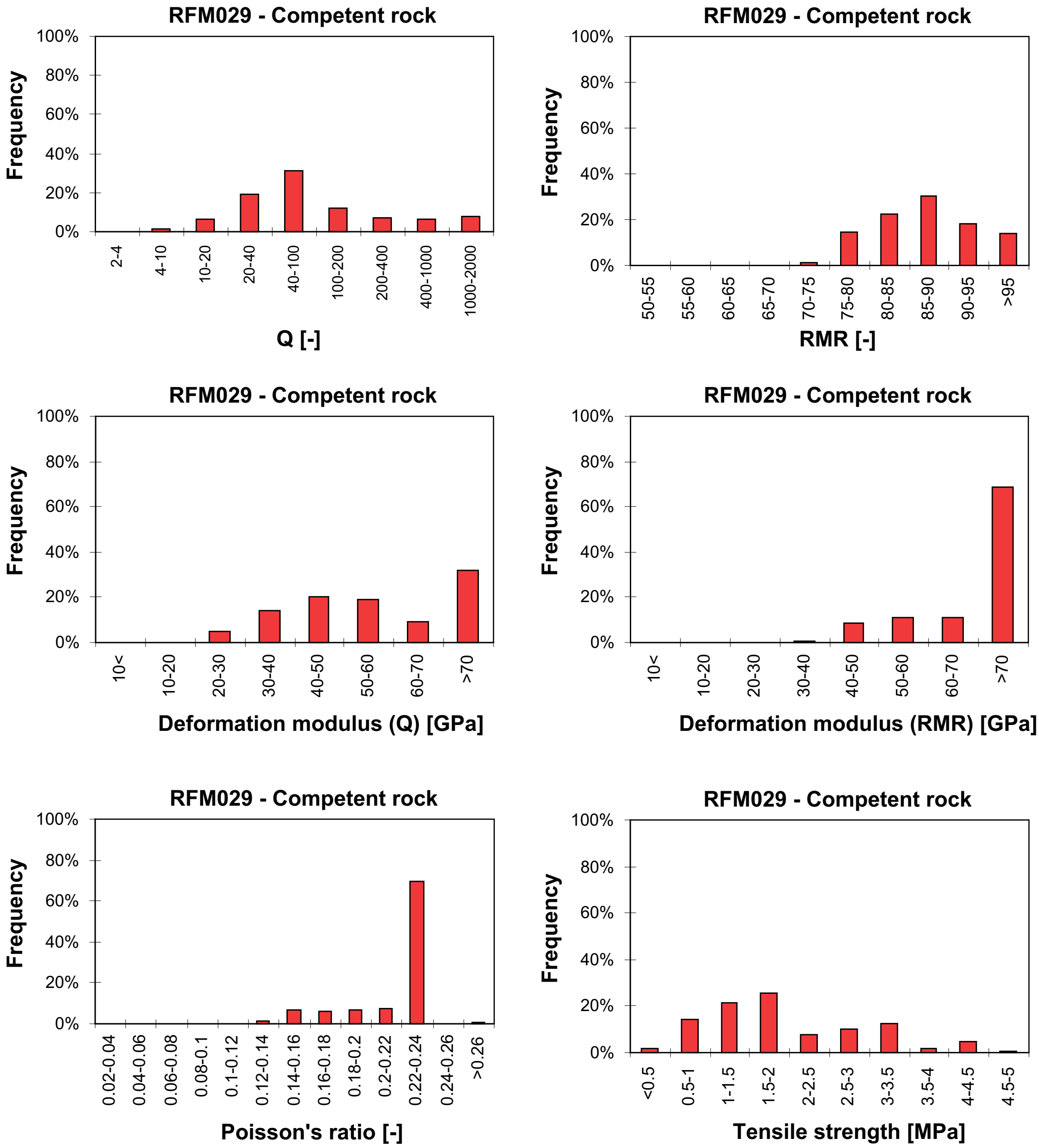

Figure A1-10. *Rock Domain RFM029 – Competent rock: Histograms showing the results of RMR and Q and derived mechanical properties.*

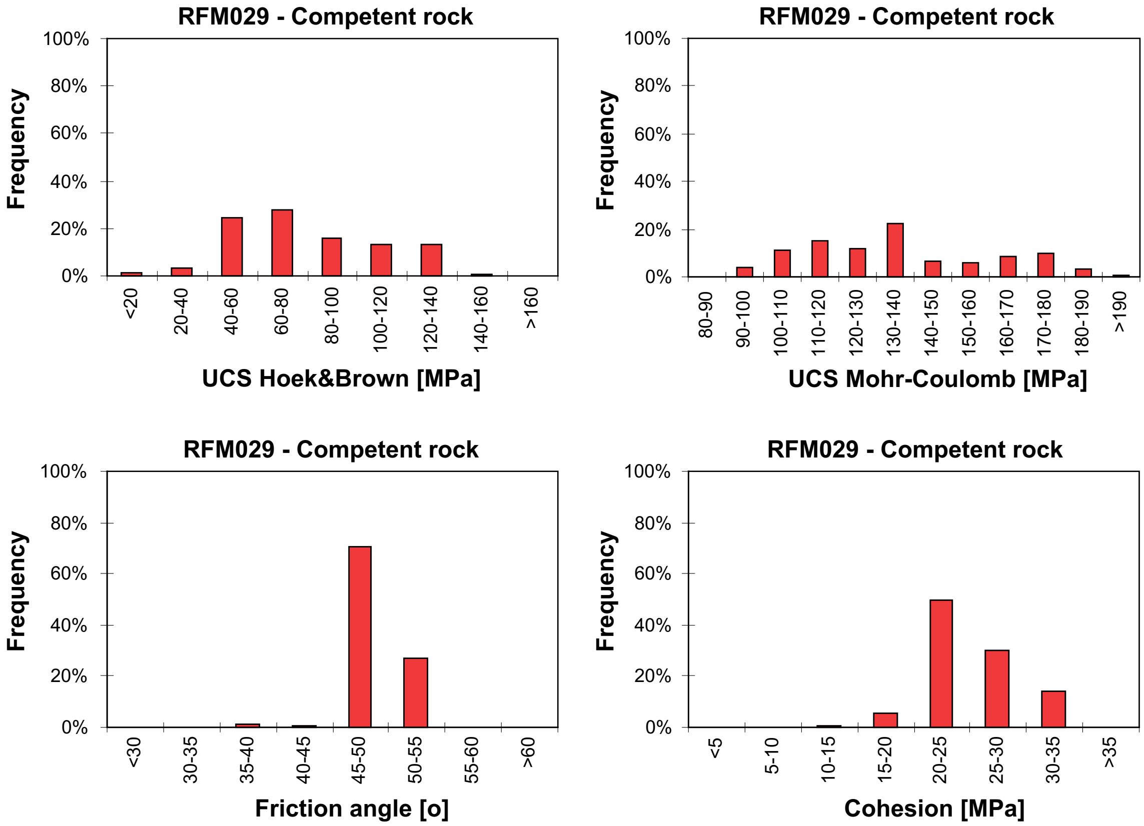

Figure A1-11. *Rock Domain RFM029 – Competent rock: Histograms showing the mechanical properties derived from RMR.*

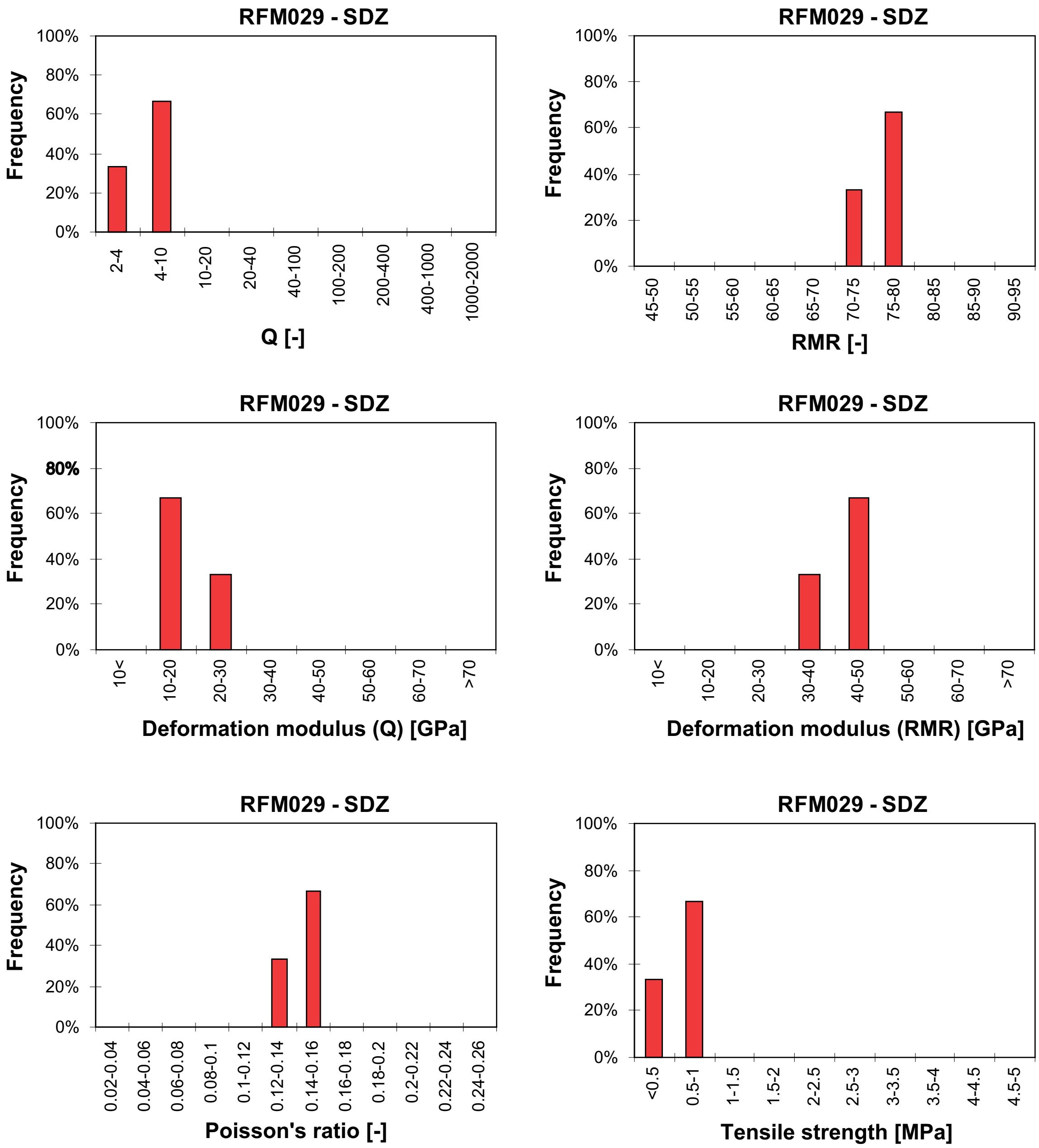

Figure A1-12. *Rock Domain RFM029 – Deformation zone (SDZ): Histograms showing the results of RMR and Q and derived mechanical properties.*

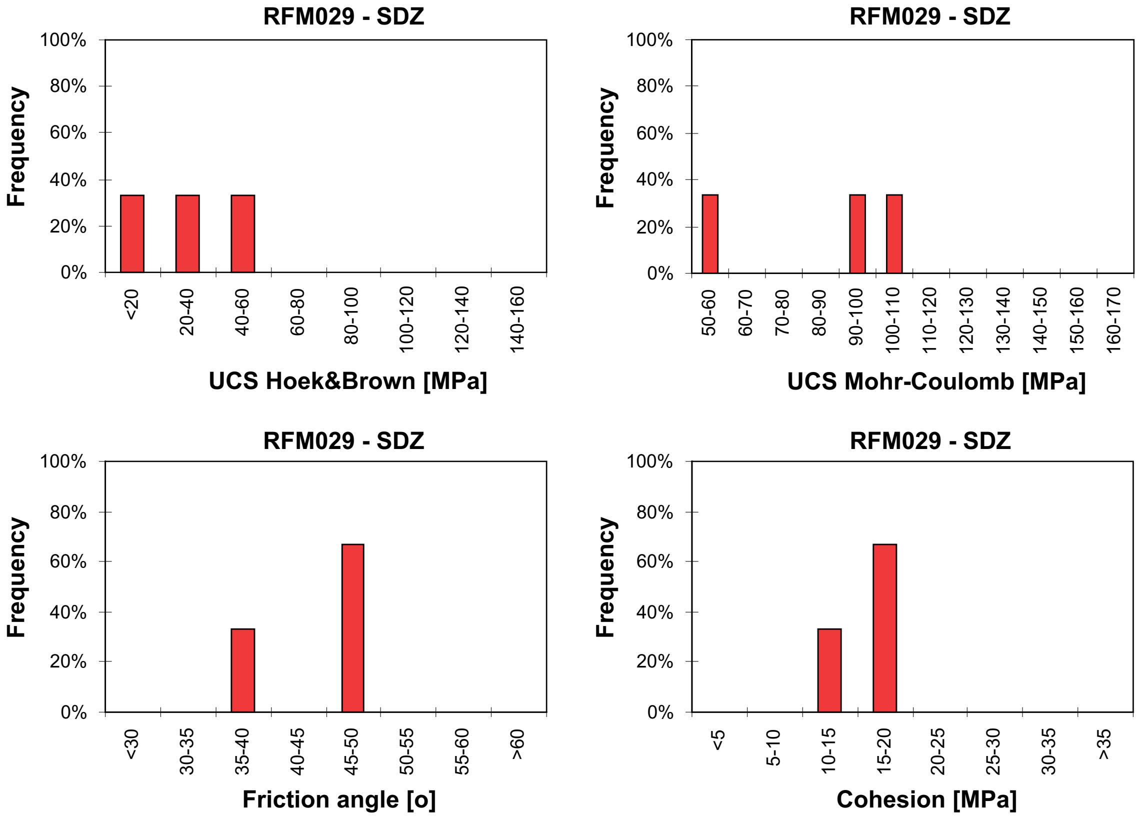

Figure A1-13. *Rock Domain RFM029 – Deformation zone (SDZ): Histograms showing the mechanical properties derived from RMR.*