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Rock mechanics characterisation of the rock mass – empirical approach

Preliminary site description Simpevarp subarea – version 1.2

Flavio Lanaro, Berg Bygg Konsult AB

June 2005

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Abstract

Five boreholes in the Simpevarp-Laxemar Area were analysed for the purpose of Rock Mechanics characterisation of the rock mass by means of empirical methods. The Q and RMR systems were applied to the geomechanical data delivered before the Data-freeze on April 7th, 2004. The mechanical properties of the rock mass were calculated based on the empirical relations with Q and RMR according to SKB's Methodology for the characterisation of the rock mass. The inferred mechanical properties of the rock mass were: deformation modulus, Poisson's ratio, uniaxial compressive and tensile strength, cohesion and friction angle. These properties were given for low confinement stress (deformation modulus, Poisson's ratio) or for stresses between 10 and 30 MPa (cohesion, friction angle).

The Rock Mechanics properties slowly increase with depth along borehole KSH01AB, KSH02 and KSH03A. Borehole KAV01 and KLX02 present deep deformation zones, thus, the mechanical properties decrease when the zones are approached.

The Lithological Model and the Deformation Zone Model divide the rock mass in the Simpevarp-Laxemar Area into pseudo-homogeneous Rock Domains and Deterministic Deformation Zones, which are characterised here from a Rock Mechanics point of view.

The deformation zones inside the Rock Domains seem to have very similar deformation modulus independently of the Rock Domain (except Zone ZSMNE024A. The deformation modulus of the deformation zones is on average 35% lower than the modulus of the competent rock that is around 35 GPa. The estimated Poisson's ratio for low confinement stress varies between 0.10 and 0.16 for the competent rock, and between 0.05 and 0.08 for the deformation zones, respectively. On average, it was found that all Rock Domains have very similar uniaxial compressive strength: around 30 MPa for the competent rock, around 20 MPa for the stochastic deformation zones and 12 MPa for Zone ZSMNE024A, respectively. The tensile strength, on the other hand, varies from Rock Domain to Rock Domain. Rock Domain RSMB01 has the highest tensile strength while RSMA01 and RSMC01 present almost the same values. This depends on the different rock types prevailing in the three Rock Domains. Also the cohesion and friction angle are very similar for RSMA01 and RSMC01. On average, the cohesion is about 17 MPa for the competent rock and 15 MPa for the deformation zones, while the friction angle is 45° for the competent rock and 40° for the deformation zones respectively. For RSMB01, there is not difference between the properties of the deformation zones and those of the competent rock: cohesion 15 MPa and friction angle 40° for the whole Rock Domain. The cohesion of ZSMNE024A is very close to that of the deformation zones inside the Rock Domains, but the friction angle is on average 39°.

Separated analyses of the data from the Simpevarp and Laxemar Areas show the possibility of better quality and mechanical properties of the rock mass at Laxemar compared to the rock mass at Simpevarp. However, this hypothesis should be verified by means of further site investigations.

The results presented in this report (Empirical Approach) and analogous results obtained by means of numerical simulation of the behaviour of the rock mass (Theoretical Approach) will be combined and harmonised into the Rock Mechanics Model of the Simpevarp Site v. 1.2.

Sammanfattning

I denna rapport beskrivs resultat av den bergmekaniska karakteriseringen av fem borrhål i Simpevarp och Laxemar områderna. Empiriska Q- och RMR-värden bestämdes baserat på geomekanisk data tillgänglig den 7:e April 2004 (Data-freeze). De mekaniska egenskaperna hos bergmassan beräknades baserad på Q och RMR, i enighet med SKB:s Metodbeskrivning för bergmekanisk karakterisering. De mekaniska egenskaperna är: deformationsmodul, Poisson-tal, enaxiella tryck- och draghållfasthet, kohesion och friktionsvinkel. Vissa egenskaper gäller för låga spännigsnivåer (deformationsmodul och Poisson-tal) medan andra gäller explicit för bergspänningar mellan 10 och 30 MPa (kohesion och friktionsvinkel).

De mekaniska egenskaperna visar sig öka svagt med djupet för borrhål KSH01AB, KSH02 och KSH03A medan i borrhål KAV01 och KLX02 påträffas djupa deformationszoner som gör att egenskaperna tenderar att minska med djupet på grund av det.

Bergmassan idealiseras som bergdomäner och deterministiska deformationszoner i den Lithologiska modellen och Deformationszon-modellen. I denna rapport kompletteras bergdomänerna och deformationszonerna med dess bergmekaniska egenskaper.

Deformationszonerna inom bergdomänerna har ungefär samma egenskaper oavsett vilken bergdomän de tillhör. Deformationsmodulen för deformationszonerna är i genomsnitt 35 % lägre än den för kompetent berg som varierar runt 35 GPa. Den uppskattade Poissons tal för låga bergspänningar varierar mellan 0,10 och 0,16 för kompetent berg resp. mellan 0,05 och 0,08 för deformationszoner. Alla bergdomänerna har väldigt lika enaxiell tryckhållfasthet: 30 MPa i kompetent berg och 20 i deformationszonerna. Den deterministiska deformationszonen ZSMNE024A har låg tryckhållfasthet (runt 12 MPa). Draghållfastheten varierar däremot från bergdomän till bergdomän. Den är högre för RSMB01 än för RSMA01 och RSMC01 på grund av skillnader i bergmaterialets egenskaper. I genomsnitt har bergdomänerna en kohesion runt 17 MPa resp. 15 MPa för kompetent berg och deformationszoner. Friktionsvinkeln är runt 45° i kompetent berg och 40° i deformationszoner. I RSMB01A är skillnaden mellan kompetent berg och deformationszon väldigt liten vilket gör att parametrarna liknar de övriga deformationszonerna. Zon ZSMNE024A har samma kohesion som alla andra deformationszoner men en genomsnitt friktionsvinkel på 39°.

Datan analyserades även separat för Simpevarp och för Laxemar. Jämförelsen antyder att bergmassan har bättre kvalité och egenskaper i Laxemar är i Simpevarp. Denna hypotes bör bekräftas med hjälp av ytterligare platsundersökningar.

Resultaten i denna rapport (Empirisk approach) kommer att kombineras och harmoniseras med resultaten från numeriska beräkningar av bergmassans beteende (Teoretisk approach) för att bygga den Bergmekaniska modellen för Simpevarp område v. 1.2.

Contents

1 Introduction

This report summarizes in the results of the empirical Rock Mechanics characterisation of the rock mass along five boreholes in Oskarshamn, at the Simpevarp and Laxemar Sites for setting up of an updated version of the former Site Descriptive model /SKB 2004/. The Rock Mechanics characterisation is performed along five boreholes, KSH01AB, KSH02, KSH03A, KAV01 and KLX02, with the geological information available at the Data-freeze Simpevarp v. 1.2 on April 7th, 2004 and the outcomes of the Geological Model v. 1.2. The "characterisation" is carried out for the purpose of quantifying the mechanical properties of the rock mass in its undisturbed state. Thus, the influence of the orientation and damage of the excavations and the effects of the water conditions have not been taken into consideration /Andersson et al. 2002, Röshoff et al. 2002/. These will be handled by the "Design" and "Safety Analyses" studies, where the behaviour of the rock mass will be evaluated considering the design geometries and the actual stress and water pressure boundary conditions at a certain depth.

In this report, the results of the empirical characterisation are firstly presented for each borehole. The parameters provided by the characterisation are:

- The deformation modulus and Poisson's ratio of the rock mass calculated by means of RMR. Some results by Q are also considered for comparison.
- The uniaxial compressive and tensile strength of the rock mass determined by means of RMR. In this case, the rock mass is considered as a continuum equivalent medium.
- The friction angle and cohesion of the rock mass according to the Coulomb's Criterion also determined by means of RMR.

The plots of the parameter along each borehole allow to compare of different boreholes and to highlight the variation with depth. For this purpose, the geological "single-hole interpretations" of the geological information for the boreholes are used. Some of the mechanical properties are explicitly given as functions of the rock stresses. In all other cases, the mechanical properties given here are to be considered under low confinement stress (about 1 to 2 MPa). The Rock Mechanics Model, which combines the present Empirical model with the Theoretical Model /Fredriksson and Olofsson 2006/, will provide a description of the variation of the mechanical properties with stress.

Secondly, the statistics of the mechanical properties are given for the Rock Domains identified by the Geological Model (POM version 1.2 by August 13th, 2004) for Simpevarp. In particular, the Empirical Model makes use of the Lithological, Rock Domain and Deformation Zone /SKB 2005/ Model for partitioning the boreholes into pseudo-homogeneous rock volumes, and also for combining data from different boreholes. The Distinct Fracture Network (DFN) Model /La Pointe and Hermansson 2006/ is also implicitly used for the analysis of the fracture sets in the Rock Domains.

1.1 Background

For the characterisation of the rock mass from a Rock Mechanics point of view, four cored boreholes drilled on the Simpevarp Peninsula were analysed (KSH01AB, KSH02, KSH03A and KV01). In addition, borehole KLX02 drilled in Laxemar was also considered (see Figure 1-1). All the boreholes except KSH03A are sub-vertical, and all of them, except KAV01, reach at least a depth of 1,000 m from the surface. In Table 1-1, the core length and the orientation of the boreholes are listed.

Figure 1-1. *Overview of the Simpevarp and Laxemar Sites with indication of borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02 used for the Rock Mechanics characterisation.*

Table 1-1. Length and orientation of borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02 considered for rock mechanics purposes.

Borehole	Core depth [m]	Bearing/ inclination
KSH01AB	5–1,003	174/–80
KSH02	80–1,001	330/–86
KSH03A	0–1,001	125/–59
KAV01	70–757	237/–89
KLX02	200–1,700*	009/–85

*The Rock Mechanics characterisation was carried out for the upper 1,005 m.

All the rock types occurring in Simpevarp and Laxemar can be ascribed to the Trans-Scandinavian Igneous Belt (about 1,800 Ma) /SKB 2005/. The dominating rock types show a composition between diorite to gabbro and granite. These rock types present a “recalculated quartz content” of about 11 to 20%. On the southern part of Simpevarp, fine-grained granite with a quartz content of about 5% was observed. These rock types were sorted into more comprehensive groups:

- Rock type A: a mixture of porphyritic granite to quartz monzodiorite (Ävrö Granite, SKB code 501044).
- Rock type B: fine-grained dioritoid (SKB code 501030).
- Rock type C: a mixture of porphyritic granite to quatz monzodiorite (Ävrö Granite) and quartz monzodiorite (SKB code 501036).
- Rock type D: quartz monzodiorite (SKB code 501036).

These four groups dominate the Local Model Volume of the Sites. However, in the Regional Model Volume, fine-grained and medium-grained to coarse-grained granite (Götemar type) and diorite to gabbro are also present. Fine-grained granite and pegmatite seem to be ubiquitous within the local and regional volumes. Traces of hydro-thermal alteration were also observed in all rock types.

An idealization of the rock mass at the Sites was carried out and pseudo-homogeneous rock volumes (Rock Domains) with one prevalent rock type among Rock Type A trough B were identified. This was carried out by using the information on the surface, along the drill-cores and along percussion boreholes. Also the “rock units” determined by the geological “single-hole interpretation of the boreholes were analysed.

From the study of the lineaments and from the inspection of the boreholes, the Deterministic Deformation Zones intersecting the Sites were recognised and classified. This led to the construction of a geological-geometrical model composed by Rock Domains and Deformation Zones. In this report, some of the Rock Domains and Deformation Zones in the Local Model Volume are going to be characterised (where information from the cored boreholes is available).

Geomechanical data are available only for Rock Domains in the Rock Types A, B and C. These Rock Domains are called RSMA01, RSMB01 and RSMC01 in the predominant Rock Type is A, B or C, respectively. The boreholes also cross two Deterministic Deformation Zones, respectively ZSMEW007A and ZMSNE024A.

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 Simpevarp Site.
- Provide rock mass quality and mechanical properties (empirically determined) for the three Rock Domains intercepted by the available drill-core boreholes.
- Provide rock mass quality and mechanical properties (empirically determined) for the Deformation Zones intercepted by the available drill-core boreholes.
- 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 data are not available.
- Supply the necessary information for the set up of the Rock Mechanics Model of the Simpevarp 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 background database for this study are the equivalent continuum mechanical properties of the rock mass calculated based on empirical relations with the rock mass quality (RMR and Q). 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 KSH01AB, KSH02, KSH03A, KAV01 and KLX02.
- A section summarizes the mechanical properties of Rock Domain RSMA01, RSMB01 and RSMC01. There are not boreholes in Rock Domain RSMD01. The Rock Mechanics Model will probably assign properties to this domain as well based on the outcomes for the other Domains.
- A section summarizes the mechanical properties of two deterministic deformation zones intercepting the boreholes at the Simpevarp and Laxemar Sites.
- Discussion of the results.
- Appendices.

2 Empirical characterisation of the rock mass

Borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02 were analysed from a strictly geological point-of-view in the “single-hole interpretation” of the drill-cores /Hultgren et al. 2004, Mattsson et al. 2004ab/. Each borehole was subdivided into:

- Rock units.
- Possible deformation zones.

The rock units were later grouped into larger sub-homogeneous volumes called 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 DFN Model. The rock outside the possible deformation zones is designated as “competent rock” in Table 2-1. This table also shows the length of borehole extending into each of the Rock Domains RSMA01, RSMB01 and RSMC01.

In Table 2-1, it can be observed that the average length of borehole in competent rock is about 82% of the total length while the deformation zones occupy on average 18% of the analyzed borehole length. Concerning the Rock Domains, RSMA01 is dominating in most of the boreholes (50% in length), while RSMB01 and RSMC01 share almost equally the remaining length. The Deterministic Deformation Zones correspond to only 2.5% of the total analyzed borehole length, letting about 15.5% of the borehole length to the described stochastically by the DFN Model. The fractured rock in borehole KSH03A corresponds to the Deterministic Deformation Zone ZSMNE024A.

Table 2-1. Percentage in length of competent, fractured rock and distribution of the three Rock Domains RSMA01, RSMB01 and RSMC01 along the boreholes.

Borehole	Extension in % of the borehole length				
	Competent rock	Deformation zones	Rock Domain RSMA01	Rock Domain RSMB01	Rock Domain RSMC01
KSH01AB (5–1,000 m)	78%	22%		31%	69%
KSH02 (80–1,000 m)	87%	13%		100%	
KSH03AB (0–1,000 m)	89%	11%*	73%		27%
KAV01 (70–750 m)	79%	21%	100%		
KLX02 (200–1,005 m)	73%	24%**	100%		
All boreholes (4,400 m)	82%	18%***	50%	28%	22%

* This value corresponds to the Deterministic Deformation Zone ZSMNE024A.

** KLX02 contains Zone ZSMEW007A, which extension is only 2 m along the borehole.

*** This value includes Zone ZSMNE024A and ZSMEW007A, which together correspond to about 2.5% of the total length of all the boreholes.

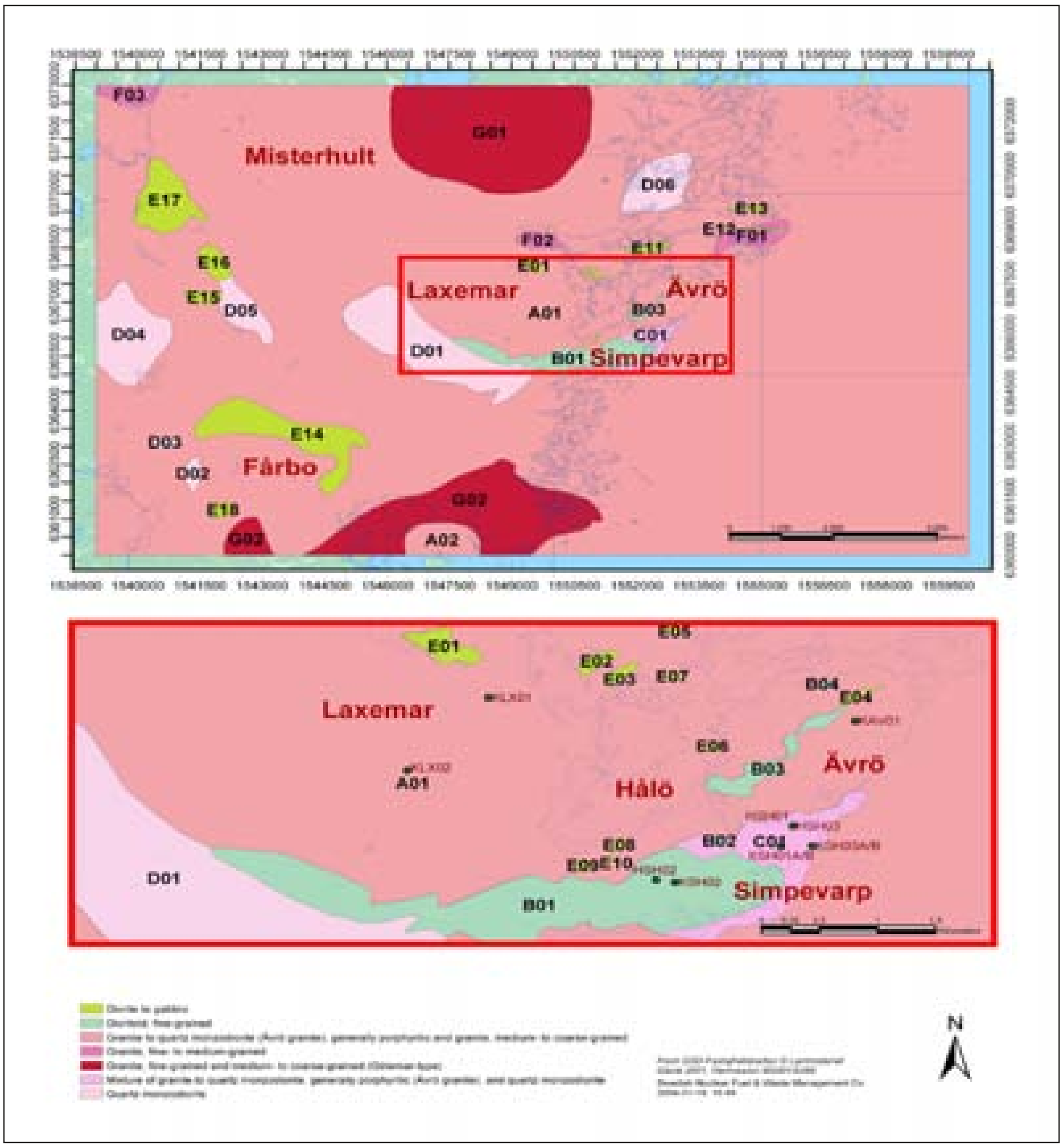

Figure 2-1. *Map of the Rock Domains in the Simpevarp v. 1.2 Regional and Local Model Volume. 36 Rock Domains appear in the Regional Model, of which 17 are included in the Local Model.*

2.1 Comparing the boreholes

A Rock Mechanics "single-hole interpretation" was carried out on borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02 /Lanaro 2005/. The single-hole interpretation consisted in the evaluation of the rock mass quality according to the widely used empirical methods Rock Quality Index (Q) /Barton 2002/, Rock Mass Rating (RMR) /Bieniawski 1989/ and Geological Strength Index (GSI) /Hoek and Brown 1998/. A series of empirical relations was also applied to estimate the mechanical properties of the rock mass based on its quality. The empirical relations provided the following properties of the rock mass:

- 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 between 10 and 30 MPa /Hoek et al. 2002/.

Figure 2-2 shows the comparison between the average deformation modulus of the competent rock and deformation zones for each borehole. Generally, all boreholes in Simpevarp and Ävrö (KSH01AB, KSH02, KSH03 and KAV01) have similar deformation modulus both for the competent and fractured rock. However, the deformation zones in KSH03A have the lowest deformation modulus of all boreholes. It is worth to point out that the deformation zone in KSH03A is the Deterministic Deformation Zone ZSMNE024A. Due to the short extension along borehole KLX02, the Deterministic Deformation Zone ZSMEW007A does not seem to produce an appreciable drop of the deformation modulus. KLX02 also exhibits the highest average deformation modulus of all boreholes.

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 fractured rock. In terms of strength, the boreholes in Simpevarp and Ävrö are rather consistent. The competent rock in KLX02 (Laxemar) is about 30% higher than for the other borehole. As expected, the lowest uniaxial compressive strength is attributed to the Deterministic Deformation Zone ZSMNE024A in KSH03A.

Figure 2-4 shows the average apparent friction angle for the competent and fractured rock. The friction angle for a confinement pressure between 10 and 30 MPa varies between 39° and 45° for the competent rock and between 38° and 42° for the deformation zones. The highest friction angles are estimated for borehole KSH01AB and KLX02. This can be explained by the fact that KSH01AB is dominated by Rock Type C, with a rather high friction angle of the intact rock (59.5°). On the other hand, the rock mass along KLX02 has better quality than the other boreholes. The friction angle is lowest for KSH02 both for competent and fractured rock. In fact, the dominant rock type in this borehole is B which has a friction angle of the intact rock of only 52.7°. For this borehole, the friction angle of the competent rock is very close to that of the deformation zones.

The cohesion of the competent rock is on average 15% larger than that of the fractured rock. Moreover, the results from the different boreholes are very consistent (Figure 2-5). The lowest cohesion is estimated for the Deterministic Deformation Zone in KSH03A (14.5 MPa).

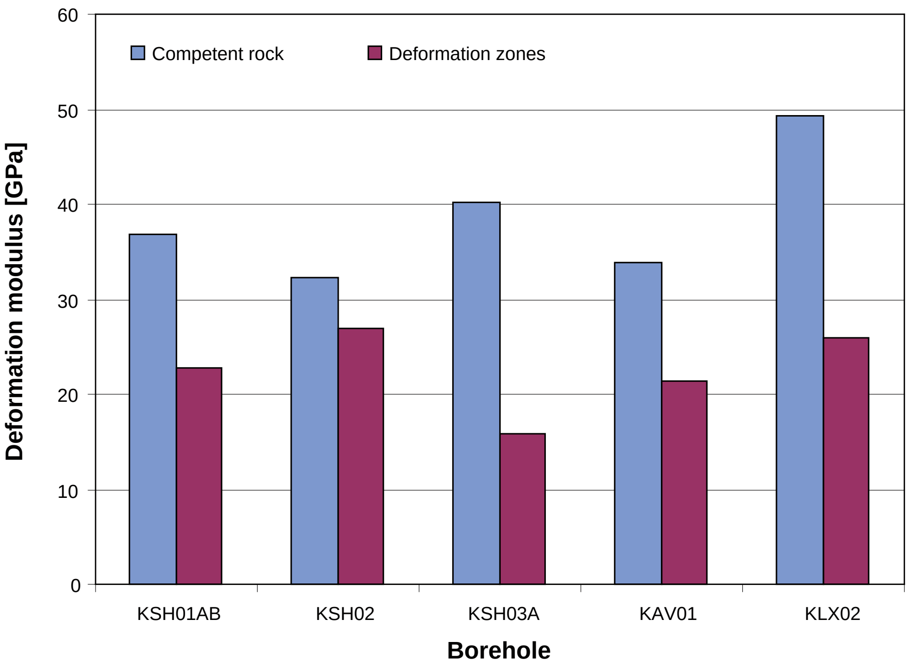

Figure 2-2. *Mean deformation modulus of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown. Please note that the fractured rock in KSH03AB corresponds to the Deterministic Deformation Zone ZMSNE024A.*

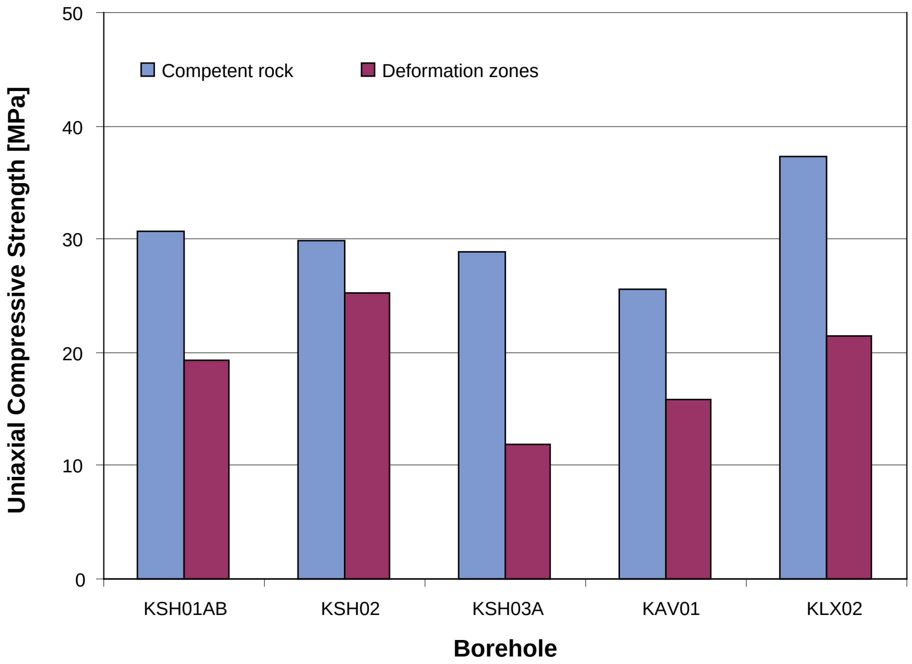

Figure 2-3. *Mean uniaxial compressive strength of the rock mass according to Hoek & Brown's Criterion for the analysed boreholes. The average values for competent rock and deformation zones are shown. Please note that the fractured rock in KSH03AB corresponds to the Deterministic Deformation Zone ZMSNE024A.*

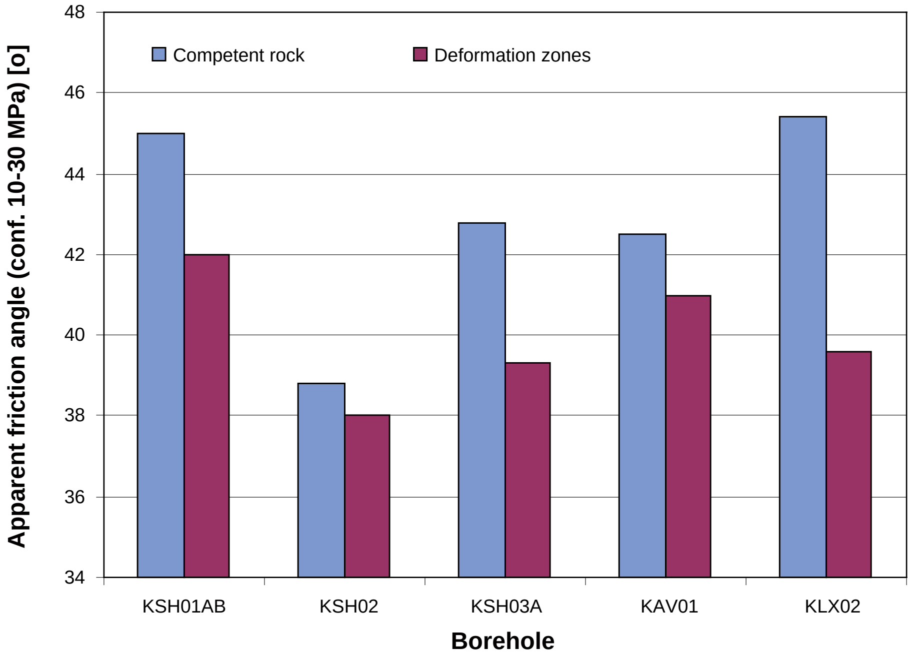

Figure 2-4. *Mean apparent friction angle of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown. The confinement stress is between 10 and 30 MPa. Please note that the fractured rock in KSH03AB corresponds to the Deterministic Deformation Zone ZMSNE024A.*

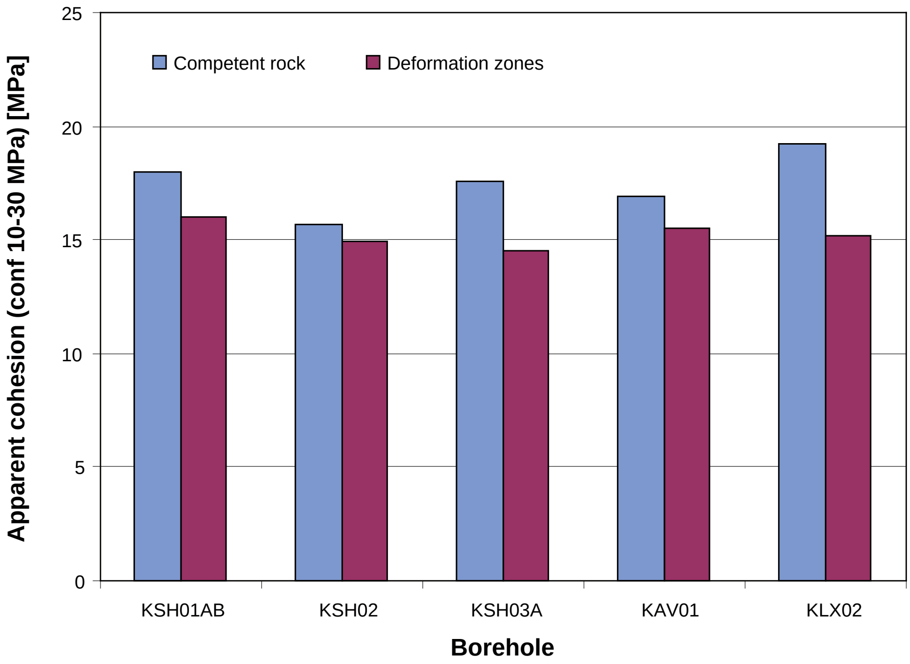

Figure 2-5. *Mean apparent cohesion of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown. The confinement stress is between 10 and 30 MPa. Please note that the fractured rock in KSH03AB corresponds to the Deterministic Deformation Zone ZMSNE024A.*

2.2 Variation along the boreholes

The mechanical properties are determined for the rock mass as if it were an equivalent continuous medium.

For characterisation, the deformation modulus of the rock mass is determined independently of the boundary conditions, e.g. water pressure and rock stresses. This means that, when nothing else is specified, the modulus applies for low confinement stress of the order of 1 to 2 MPa. This is because the empirical methods are not good in capturing the stress dependency of the rock mass properties. Moreover, any excavation induce a change of the rock stresses, thus, of the mechanical properties. The Rock Mechanics Model, build on the jointed results of the empirical and theoretical method, will provide such stress dependency of the parameters, which is not considered in this report.

Also the equivalent uniaxial compressive strength of the rock mass (zero confinement stress), and the “apparent” cohesion and friction angle according to Coulomb’s Criterion (for a confinement stress between 10 and 30 MPa) are reported here. Other confinement stress intervals would produce different apparent Coulomb’s parameters.

The following graphs show the range of variation of each parameter within each pseudo-homogeneous section of borehole (rock unit) identified in the “single-hole interpretation” of the borehole data. These ranges quantify 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 be sometimes dependent on depth and/or on the presence of the deformation zones.

When analysing the variation of the parameters along the boreholes, a weak increase with depth can be observed for KSH01AB, KSH02 and KSH03A. Borehole KAV01 and KLX02 both cross deep deformation zones, thus the mechanical properties of the rock mass even seem to decrease with depth approaching the deformation zones. The deformation zones that cause this phenomenon extend for more than 100 m along the boreholes.

Figure 2-6 through Figure 2-10 show the variation of the equivalent deformation modulus, uniaxial compressive strength, apparent cohesion and friction angle of the rock mass along borehole KSH01AB, KSH02, KSH03, KAV01 and KLX02, for each rock unit identified in the geological “single-hole interpretation”.

2.3 Variation with scale

For borehole KSH01AB, the rock mass characterisation was performed on core section lengths of 5 and 30 m to highlight possible scale dependence of the resulting rock quality and derived parameters. In Figure 2-11, the values of the deformation modulus obtained from RMR and Qc are compared for different scales. It is clear that the scale of the evaluation does not affect the result of the characterisation of this borehole. The only evident effect of scale is some smoothing of the lowest and highest values when passing from borehole sections of 5 m to those of 30 m. The difference in mean value for the deformation modulus from Qc is only 8%. This is probably due to the rather high degree of fracturing of the rock mass that makes the empirical systems rather independent of the borehole section length /Lanaro et al. 2004/. Thus, this conclusion could be extrapolated to all boreholes in the Simpevarp Area.

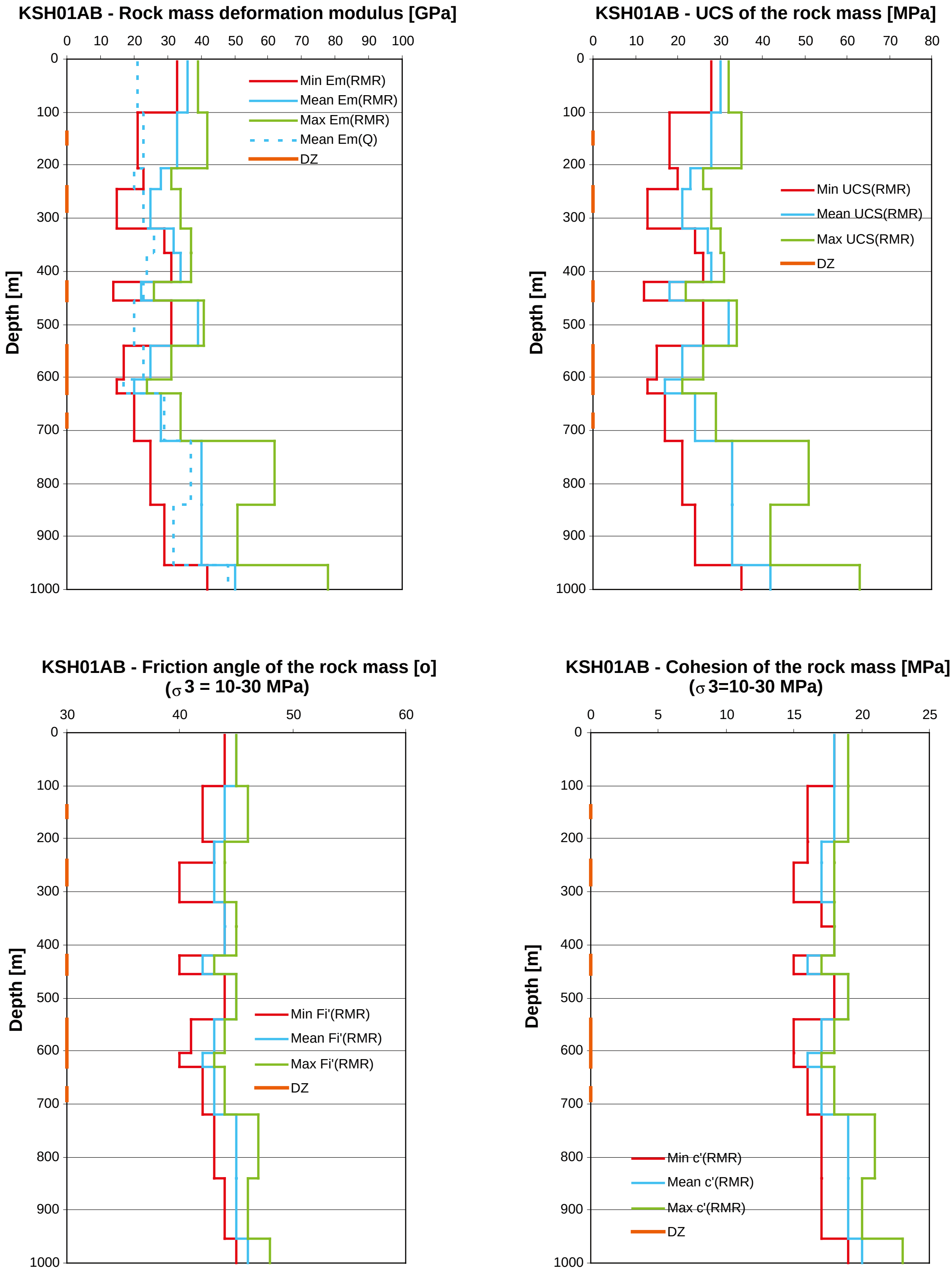

Figure 2-6. *KSH01AB: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

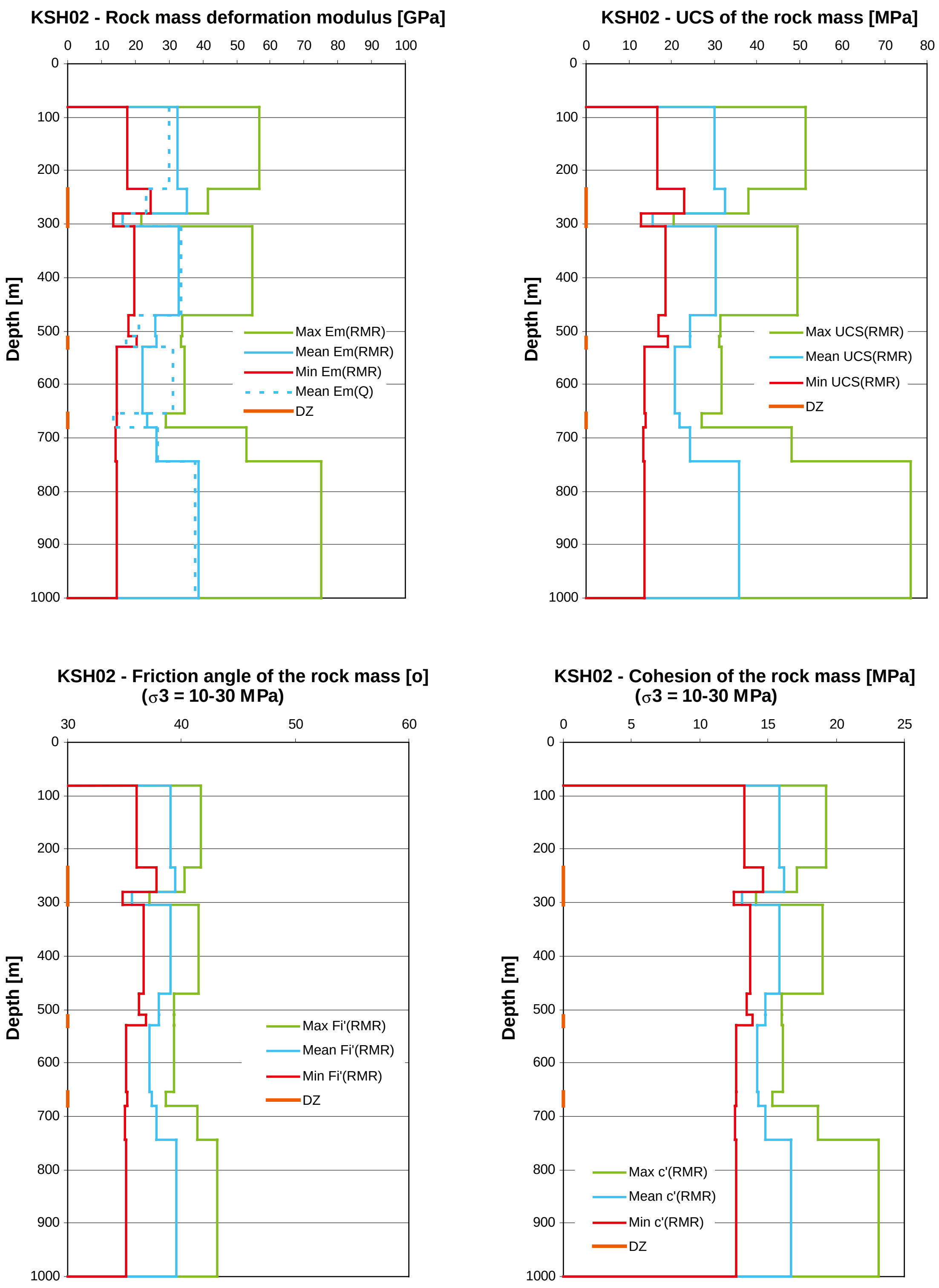

Figure 2-7. KSH02: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".

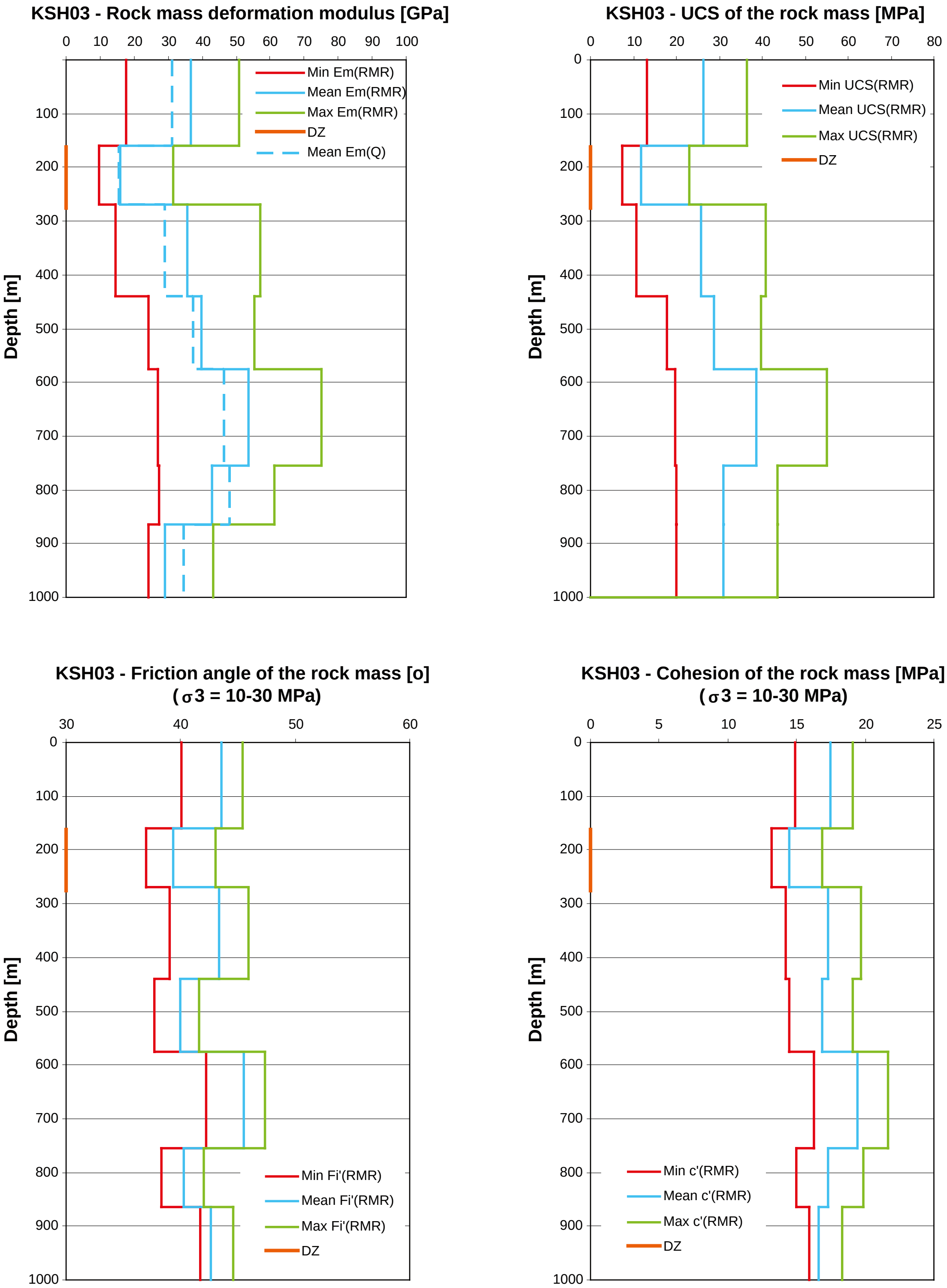

Figure 2-8. *KSH03A: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

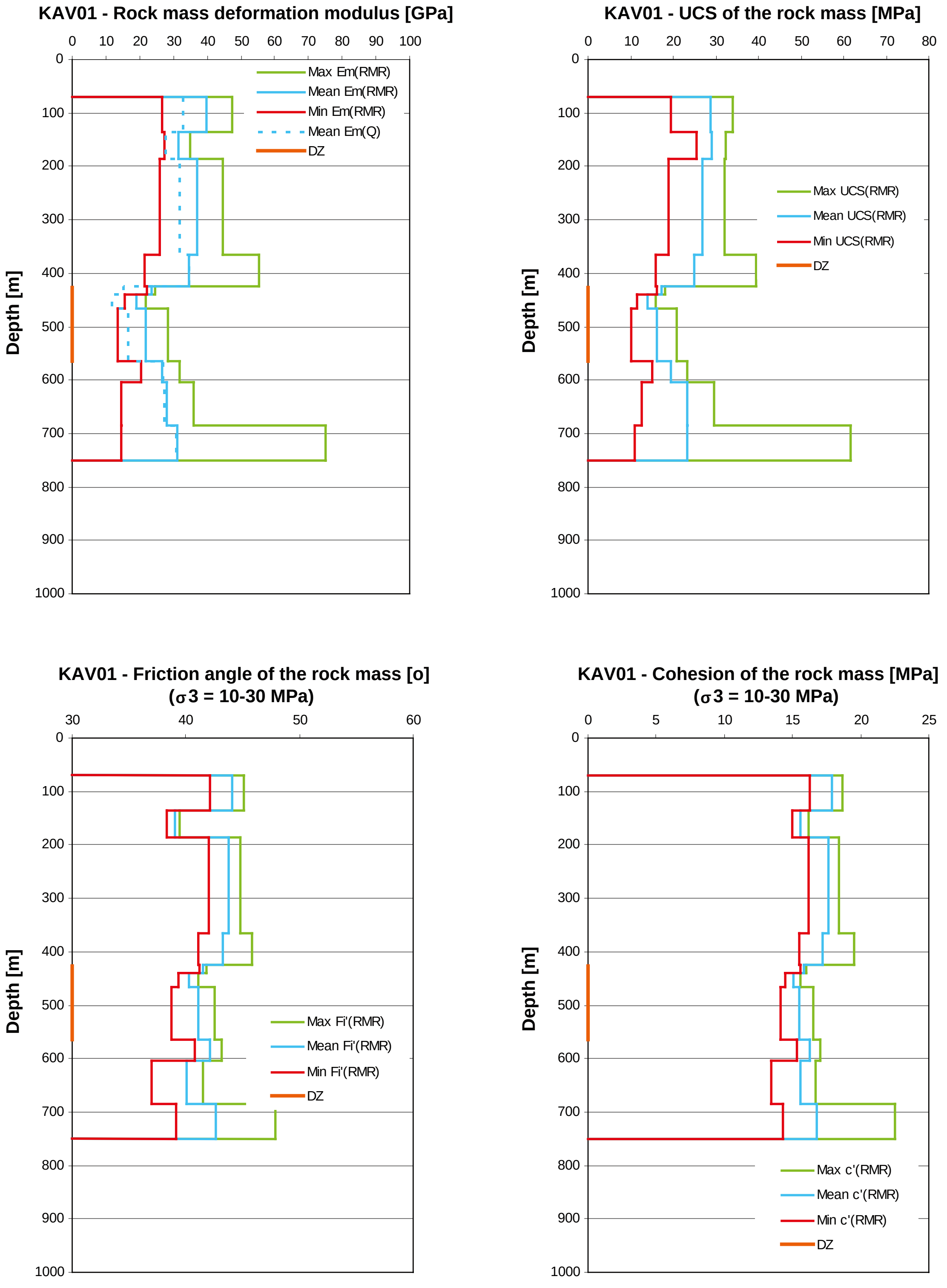

Figure 2-9. *KAV01: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

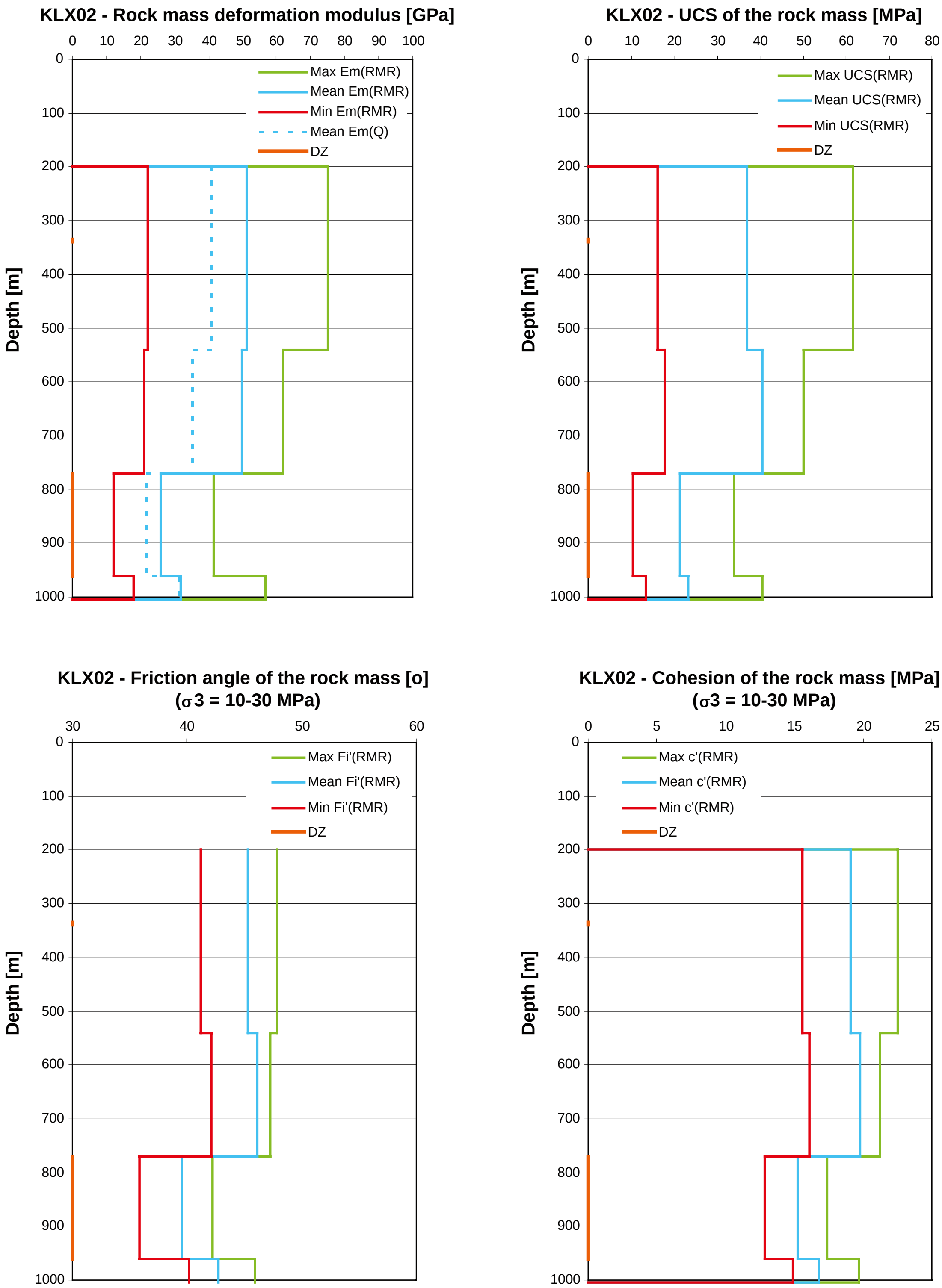

Figure 2-10. *KLX02: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

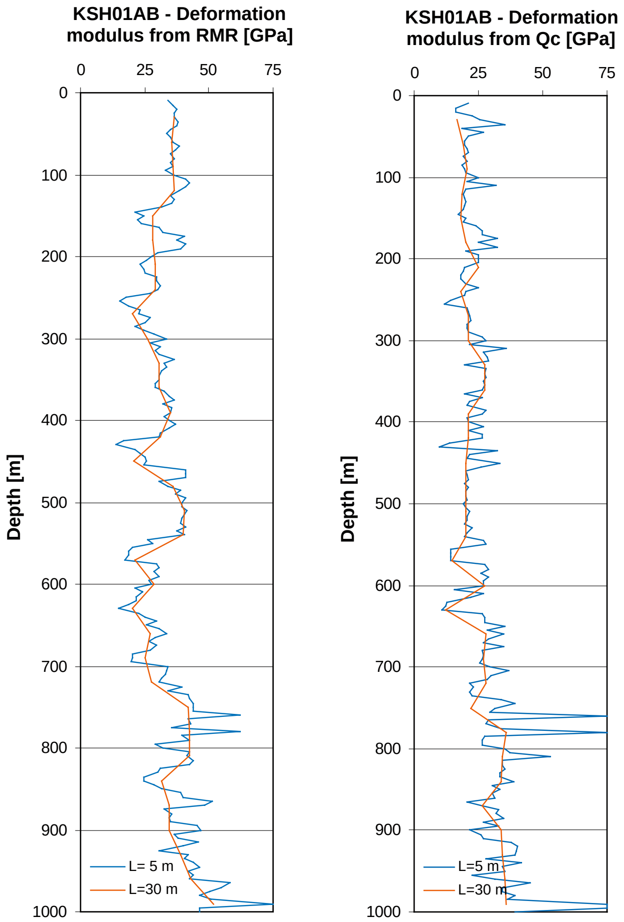

Figure 2-11. *KSH01AB: Variation of the deformation modulus from RMR (left) and Qc (right) depending on the core section length adopted for the rock mass characterisation. Results for core sections of 5 and 30 m are shown.*

3 Rock domains and deformation zones

In the following sections, summary tables for the Q index, RMR and the properties of the rock mass are provided as for an equivalent continuum medium. 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 also provided.

The mechanical properties are also summarised for all the boreholes in Simpevarp and Ävrö, and for borehole KLX02 in Laxemar.

These properties will be the basis for the Rock Mechanics Modelling for the Forsmark Descriptive Model Version 1.2. In Appendix, charts comparing the mechanical properties of the Rock Domains are also provided.

3.1 Geological model

36 Rock Domains are identified in the Regional Model Volume, of which, 17 belong to the Local Model Volume /SKB 2005/. The analysed boreholes intercept three of the Rock Domains in the Local Model, in particular (Figure 3-1):

- RMSA01 in Ävrö granite, the most extensive, is crossed by borehole KSH03, KAV01 and KLX02.
- RMSB01 in fine-grained dioritoid is intercepted by borehole KSH01A and KSH02.
- RMSC01, composed by a mixture of Ävrö granite and quartz monzodiorite, is crossed by borehole KSH01A and KSH03A.

In Figure 3-2, 22 Deterministic Deformation Zones identified with high confidence by the Geological Model, some of which crossing the boreholes, are indicated in red /SKB 2005/. Of them, Zone ZSMNE024A and ZSMEW007A are regional deformation zones in the Oskarshamn Area and intercept the boreholes. Zone ZSMNE024A strikes NE and has a dip of about 70°. This zone is composed by a brittle-ductile belt of zones following the East coast line of Ävrö and Simpevarp. Zone ZSMEW007A in borehole KLX02 is exaggerated in width in Figure 3-1. This zone extends only 2 m along the borehole. In the characterisation, a section of 5 m including the zone is considered to avoid length biases. In fact, all parameters are determined for borehole sections of 5 m length with no exceptions.

Table 3-1. Percentage in length of rock belonging to the Rock Domains RSMA01, RSMB01, RSMC01 and RSMDXX intercepted by borehole KSH01AB, KSH02, KSH03AB, KAV01 and KLX02.

Rock Domain	Extension in length	
	Competent rock	Fractured rock
RSMA01	85%	15%
RSMB01	80%	20%
RSMC01	89%	11%
RSMDXX*	–	–

* No Rock Domains intercepted for rock type D.

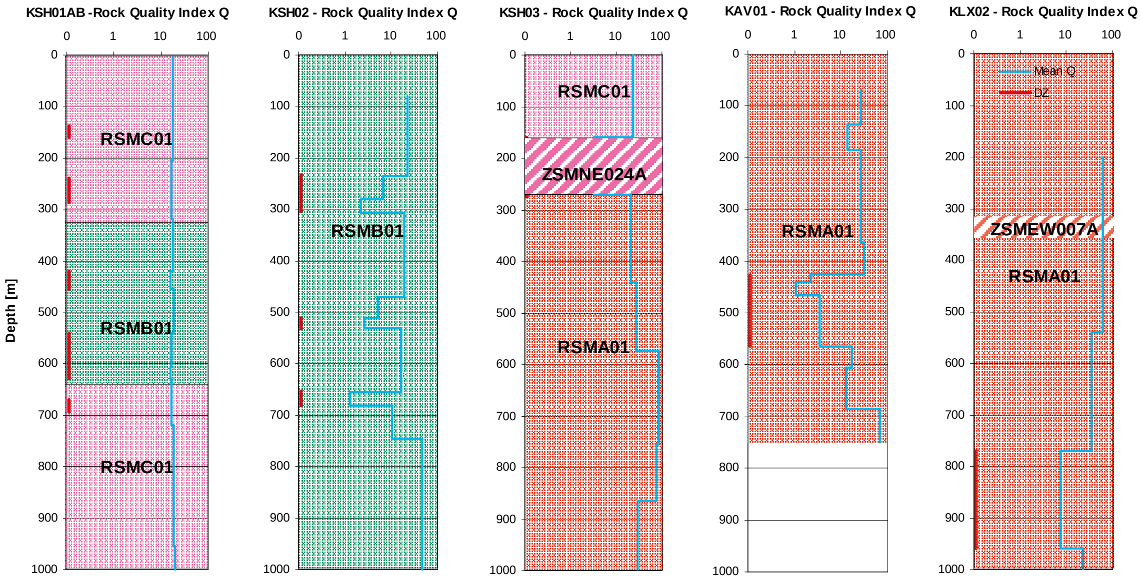

Figure 3-1. Partitioning of the boreholes into Rock Domains and Deformation Zones. The mean Q value is also plotted along the boreholes.

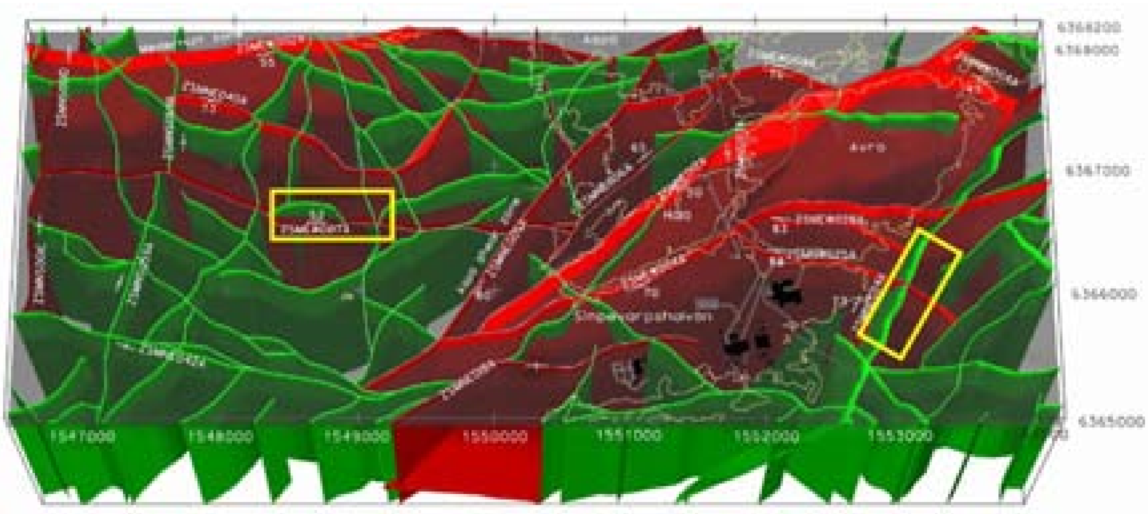

Figure 3-2. Simpevarp v. 1.2 Local Model Volume with the indication of the high confidence (in red) and possible (in green) Deterministic Deformation Zones. Zone ZSMNE024A and ZSMEW007A are highlighted in yellow.

3.2 Uncertainties

It was decided to correlate the uncertainty of each mechanical parameter P to the range of its possible values obtained at a certain depth (e.g. location of each core section of 5 m). This range of variation might depend on: i) uncertainty of 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. from the laboratory).

The spatial variability of the geological parameters within the section has to be filtered out because it should not affect the uncertainty of the mean value of P at a certain depth. To filter the spatial variability out, the differences between the maximum and mean P, and the minimum and mean P are evaluated at each 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:

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

where σ is the standard deviation of the parameter population and n is the number of values composing the sample. n is also the number of values on which the mean can be calculated (on average) 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:

$$u+_{conf\ mean} = \frac{P_{MAX} - P_{MEAN}}{\sqrt{n} \times P_{MEAN}}$$
$$u-_{conf\ mean} = \frac{P_{MEAN} - P_{MIN}}{\sqrt{n} \times P_{MEAN}} \qquad (2)$$

where P is the parameter with its possible maximum, minimum and mean value, and u + and u – are the upper and lower uncertainty limits of the mean P, respectively.

The mean value and standard deviation describe the statistical distribution of the parameters P. Moreover, the confidence intervals on the mean value quantify the reliability of the parameter determination, as illustrated in Figure 3-3. Here, the given minimum and maximum threshold values also rigidly translate when the uncertainty of the mean value of the parameter are considered.

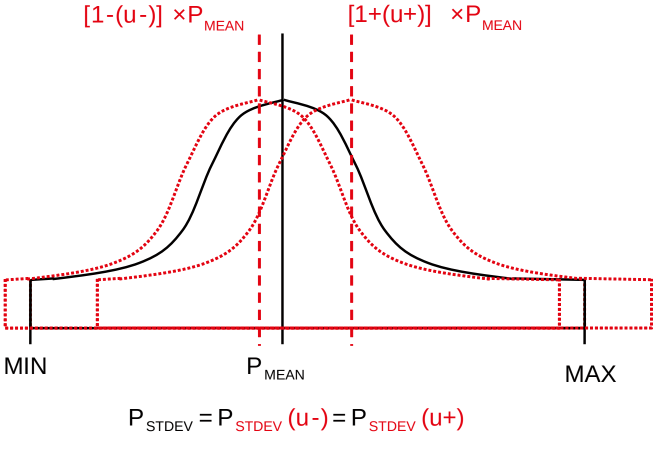

Figure 3-3. *Description of the statistical distribution and uncertainty of the Rock Mechanics parameters determined by means of the Empirical Approach.*

3.3 Rock quality index (Q)

Table 3-2 shows that the rock mass quality according to the Q-system is highest for the Rock Domain RSMA01 compared to the other two Rock Domains. Moreover, the portion of RSMA01 in Laxemar has better quality than that in Simpevarp and Ävrö, although this conclusion is drawn from just one borehole in Laxemar.

The Stochastic Deformation Zones have slightly better properties than the Deterministic Deformation Zones. ZSMNE024A presents rock among the poorest of all the deformation zones.

The uncertainty of the determination of the mean value of Q is summarised in Table 3-3 for the Rock Domains and Deformation Zones. The uncertainty of the mean Q for the competent rock is quite consistent for all Rock Domains. However, this is slightly asymmetric: the lower boundary is about –7% while the upper boundary is about +15%. The uncertainty of the mean Q value for the Deformation Zones is also asymmetric and larger than for the competent rock. The lower boundaries are about –13%. The upper boundaries vary between +60% and +198%. These large values can be explained by the fact that Q often spans over several order of magnitude within the same rock mass as soon as some heterogeneities are present due to the logarithmic nature of Q.

Table 3-2. Q values of the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

Q [–]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean [most freq.]**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	0.6	42.4 [23.8]	704.0	0.5	5.4 [3.1]	33.2
RSMA01 (Simpevarp)	0.6	39.3 [22.8]	704.0	0.5	2.8 [2.2]	9.9
RSMA01 (Laxemar)	0.9	48.8 [26.3]	528.0	0.7	7.3 [4.7]	33.2
RSMB01	1.5	22.6 [12.9]	352.0	0.5	5.6 [3.6]	20.4
RSMC01	2.4	25.3 [11.9]	352.0	0.9	6.4 [4.8]	22.4
ZSMNE024A				0.6	3.2 [1.2]	11.6
ZSMEW007A					5.5	

* The values within brackets are the most frequent Q.

Table 3-3. Uncertainty of the mean Q for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean Q value itself.

Uncertainty of the mean Q as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–5%	+14%	–13%	+64%*
RSMA01 (Simpevarp)	–5%	+15%	–13%	+69%*
RSMA01 (Laxemar)	–5%	+13%	–13%	+60%*
RSMB01	–7%	+25%	–23%	+175%*
RSMC01	–7%	+17%	–24%	+97%*
ZSMNE024A	–	–	–18%	+91%*
ZSMEW007A	–	–	–13%	+198%*

* The Q system spans over several order of magnitude.

3.4 Rock mass rating (RMR)

RMR also shows that the rock quality in Rock Domain RSMA01 and RSMC01 is on average slightly higher that for RSMB01. Also the quality of the rock mass in Rock Domain RSMA01 along KLX02 is better than for the other boreholes. According to RMR, the Deterministic Deformation Zone ZSMNE024A has markedly poorer properties compared to all the other deformation zones (–10%) and compared with the competent rock (–20%).

Table 3-4. RMR values of the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

RMR [–]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	56.3	73.8/5.8	87.7	53.3	64.5/4.8	74.7
RSMA01 (Simpevarp)	56.3	72.3/5.4	87.7	55.2	63.0/3.0	68.2
RSMA01 (Laxemar)	60.2	77.0/5.5	87.7	53.3	65.7/5.6	74.7
RSMB01	56.0	69.8/5.7	87.2	55.4	65.1/5.1	74.7
RSMC01	59.9	72.3/4.0	85.6	57.5	64.3/3.1	70.0
ZSMNE024A				49.7	57.3/4.8	69.9
ZSMEW007A				–	76.9	–

Table 3-5. Uncertainty of the mean RMR for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean RMR value itself.

Uncertainty of the mean RMR as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–2%	+1%	–4%	+4%
RSMA01 (Simpevarp)	–2%	+2%	–4%	+4%
RSMA01 (Laxemar)	–2%	+1%	–4%	+3%
RSMB01	–3%	+2%	–8%	+8%
RSMC01	–5%	+3%	–9%	+9%
ZSMNE024A	–	–	–6%	+6%
ZSMEW007A	–	–	–26%	+11%

The uncertainty of the mean RMR are much smaller than for Q because RMR is built on a "linear scale" while Q on a "logarithmic scale". The uncertainty of the mean RMR for the competent rock is quite small: the lower uncertainty (about 3%) is double compared to the upper uncertainty. The Deformation Zones have larger and more symmetric uncertainties of the mean RMR compared to the competent rock. Moreover, the Deterministic Deformation Zones show uncertainty comparable with the uncertainty calculated for the stochastic deformation zones. Zone ZSMEW007A has a wider uncertainty interval because RMR is determined based on a single value.

3.5 Deformation modulus of the rock mass

The equivalent deformation modulus of the rock mass determined by the empirical methods applies for low confinement stress (around 1 to 2 MPa). In Table 3-6, the minimum, maximum, mean deformation modulus and its standard deviation are summarised for the Rock Domains and Deformation Zones. For the competent rock, the maximum value always corresponds to the Young's modulus of the intact rock matrix, that for the rock types in Simpevarp and Laxemar is around 75–85 GPa. The mean deformation modulus of the competent rock for Rock Domain RSMA01 is highest (41 GPa), with lower values in Simpevarp and Ävrö and higher values in Laxemar. The lowest mean deformation modulus occurs in Rock Domain RSMB01, which is about 22% lower than for RSMA01. RSMC01 has deformation modulus similar to RSMA01. The stochastic deformation zones inside the Rock Domains have an average deformation modulus between 21 and 25 GPa, which is between 24% and 47% lower than the deformation modulus for the competent rock. This difference is largest for RSMA01 in Laxemar and smallest for RSMB01. The Deterministic Deformation Zone ZSMNE024A has the lowest calculated mean deformation modulus (15.9 GPa).

Table 3-7 contains the uncertainty determination for the mean deformation modulus. It can immediately be observed that, although Zone ZSMEW007A has a high mean deformation modulus, the uncertainty is the largest of all deformation zones. This mirrors the fact that only one value of deformation modulus was available for the evaluation of the uncertainty for this zone. Concerning the stochastic deformation zones, the uncertainty of the mean deformation modulus of RSMA01 is smaller than for the other Rock Domains. This can be explained with the fact that the zones in RSMA01 are larger on average, thus there are more data from the same zone for the evaluation of the uncertainty. This also applies to Zone ZSMNE024A. The opposite effect is seen for Zone ZSMNE007A that has obviously the largest uncertainty because only one observation is available.

Table 3-6. Predicted deformation modulus E_m of the rock mass for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model (low confinement).

E_m [GPa]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	14.4	41.5/13.4	75.0*	12.1	24.0/6.6	41.5
RSMA01 (Simpevarp)	14.4	37.8/11.9	75.0*	13.5	21.4/3.5	28.5
RSMA01 (Laxemar)	18.0	49.3/13.1	75.0*	12.1	25.9/7.6	41.5
RSMB01	14.1	32.8/11.1	75.0*	13.6	24.9/7.3	41.4
RSMC01	17.7	37.0/8.6	75.0*	15.4	23.1/4.1	31.6
ZSMNE024A				9.8	15.9/5.0	31.5
ZSMEW007A				–	47.0	–

* The maximum deformation modulus is assumed to be very similar to the Young's modulus of the intact rock matrix that ranges between 75 and 85 GPa.

Table 3-7. Uncertainty of the mean deformation modulus E_m of the rock mass for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean E_m value itself.

Uncertainty of the mean E_m as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–6%	+8%	–10%	+21%
RSMA01 (Simpevarp)	–6%	+9%	–10%	+21%
RSMA01 (Laxemar)	–6%	+5%	–10%	+21%
RSMB01	–7%	+13%	–20%	+51%
RSMC01	–12%	+16%	–23%	+54%
ZSMNE024A	–	–	–13%	+35%
ZSMEW007A	–	–	–68%	+60%

3.6 Poisson's ratio of the rock mass

The Poisson's ration of the competent rock and deformation zones is listed in Table 3-8. The mean Poisson's ratio varies, for the competent rock, between 0.10 and 0.16, and, for the deformation zones, around 0.08, respectively. Zone ZSMEW007A exhibit a Poisson's ratio comparable with the best competent rock in RSMA01 in Laxemar.

The uncertainties of the mean Poisson's ratio ν_m for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Volume Model are similar to the uncertainties calculated for the rock mass deformation modulus E_m due to the way ν_m is calculated (see Table 3-7). The Poisson's ratio is directly obtained from the deformation modulus of the rock mass divided by the Young's modulus and multiplied by the Poisson's ratio of the intact rock.

Table 3-8. Predicted Poisson's ratio ν_m of the rock mass for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

ν_m [–]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	0.05	0.13/0.04	0.24	0.04	0.08/0.02	0.14
RSMA01 (Simpevarp)	0.05	0.12/0.04	0.24	0.04	0.07/0.01	0.09
RSMA01 (Laxemar)	0.06	0.16/0.04	0.24	0.04	0.08/0.02	0.14
RSMB01	0.04	0.10/0.03	0.23	0.04	0.08/0.02	0.13
RSMC01	0.06	0.12/0.03	0.25	0.05	0.08/0.01	0.10
ZSMNE024A				0.03	0.05/0.02	0.10
ZSMEW007A				–	0.15	–

3.7 Uniaxial compressive strength of the rock mass

The equivalent uniaxial compressive strength of the rock mass is here obtained from the Hoek & Brown Strength Criterion determined via RMR/GSI. The uniaxial compressive strength, which corresponds to a convex strength criterion, is independent of the confinement. This parameter does not coincide with the "apparent" compressive strength that can be obtained from the Coulomb's Strength Criterion (see Section 3.8).

The competent rock in the three Rock Domains has very similar uniaxial compressive strength, around 31 MPa (Table 3-9). The part of RSMA01 in Laxemar seems to exhibit a higher value of about 37 MPa than the part in Simpevarp, which is around 29 MPa. The deformation zones inside the Rock Domains have a uniaxial compressive strength ranging between 16 and 22 MPa. The highest parameter is estimated in RSMB01 and is probably due to the high uniaxial compressive strength of the intact rock matrix there (about 205 MPa). The lowest compressive strength of about 12 MPa is estimated for Deformation Zone ZSMNE024A.

In Table 3-10, the uncertainties of the mean uniaxial compressive strength of the rock mass are summarised. These uncertainties are directly affected by the variability of the uniaxial compressive strength of the intact rock matrix. In fact, RSMA01, in quatz-monzonite to monzodiorite, and RSMB01, in fine-grained dioritoid, have lower uncertainty than RSMC01 that is a mixture of the two rock types. The uncertainty doubles for the deformation zones inside the Rock Domains. Zone ZSMNE024A has uncertainties of the mean uniaxial compressive strength comparable with the zones inside the Rock Domains. On the other hand, ZSMEW007A has much larger uncertainties depending on the uncertainty of RMR for this small zone where little geological information is available.

Table 3-9. Predicted uniaxial compressive strength of the rock mass $UCS_{H\&B}$ according to the Hoek & Brown's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

$UCS_{H\&B}$* [MPa]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	10.8	32.0/10.5	61.6	10.1	19.1/5.7	34.1
RSMA01 (Simpevarp)	10.8	29.4/9.6	61.6	10.1	15.8/2.5	20.8
RSMA01 (Laxemar)	13.4	37.4/10.2	61.6	10.3	21.5/6.1	34.1
RSMB01	13.5	29.9/10.2	76.1	12.1	22.2/6.8	38.0
RSMC01	13.1	30.0/7.0	63.0	13.2	19.6/3.4	26.4
ZSMNE024A				7.5	11.8/3.6	22.9
ZSMEW007A				–	33.8	–

* Equivalent strength for zero confinement pressure.

Table 3-10. Uncertainty of the mean uniaxial compressive strength of the rock mass $UCS_{H\&B}$ determined according to the Hoek & Brown's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean $UCS_{H\&B}$ value itself.

Uncertainty of the mean $UCS_{H\&B}$* as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	Min	Max	Min	Max
RSMA01 (Total)	–7%	+11%	–12%	+26%
RSMA01 (Simpevarp)	–7%	+14%	–12%	+29%
RSMA01 (Laxemar)	–7%	+7%	–12%	+23%
RSMB01	–9%	+21%	–24%	+78%
RSMC01	–15%	+20%	–30%	+61%
ZSMNE024A	–	–	–16%	+46%
ZSMEW007A	–	–	–78%	+96%

* Equivalent strength for zero confinement pressure.

3.8 Mohr-Coulomb's strength criterion of the rock mass

The curvilinear Hoek & Brown's Strength Criterion can be determined by means of RMR through GSI and considering the mechanical properties of the intact rock matrix in each Rock Domain. From this Criterion, a linear approximation for stresses for example, between 10 and 30 MPa is performed to obtain the simpler parameters of the linear Coulomb's Strength Criterion (i.e. can be apparent cohesion, friction angle and uniaxial compressive strength). Another set of parameters is obtained if the range of stresses is changed. This is why the parameters in this paragraph are called "apparent".

The apparent cohesion of the competent rock mass in the Rock Domains varies between 16 and 19 MPa, thus the variation are only about 20% from the minimum to the maximum value. Analogously, the range of variation of the cohesion is between 14 and 19 MPa in the deformation zones, were the extreme values are taken by the Deterministic Deformation Zones where ZSMNE024A present the lowest cohesion.

Table 3-11. Predicted apparent cohesion c' of the rock mass according to the Mohr-Coulomb's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

c'* [MPa]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA01 (Total)	13.4	17.9/1.8	22.5	12.8	15.3/1.0	17.4
RSMA01 (Simpevarp)	13.4	17.3/1.5	22.5	14.1	15.5/0.6	16.5
RSMA01 (Laxemar)	14.9	19.2/1.6	22.5	12.8	15.2/1.2	17.4
RSMB01	12.6	16.2/2.0	23.1	12.5	15.7/1.4	17.5
RSMC01	14.9	18.1/1.1	22.8	15.0	16.4/0.7	17.7
ZSMNE024A				13.2	14.5/0.9	16.9
ZSMEW007A				–	18.7	–

* Linear envelope between 10 and 30 MPa.

The uncertainties of the apparent cohesion are summarised in Table 3-12. As for other parameters, the uncertainty of the mean cohesion of the competent rock (around 5%) is about half the uncertainty of the mean cohesion of the deformation zones (around 11%). The lack of data is mirrored in the uncertainty of Zone ZSMEW007A which is the largest. The uncertainty intervals are often symmetrical. As explained before, the uncertainty for the zones in RSMB01 and RSMC01 is slightly larger due to the fact that these zones are smaller and more numerous.

Table 3-12. Uncertainty of the mean apparent cohesion of the rock mass c' for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as the percentage of the mean c' value itself.

Uncertainty of the mean c' as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–3%	+3%	–6%	+6%
RSMA01 (Simpevarp)	–3%	+4%	–5%	+6%
RSMA01 (Laxemar)	–3%	+2%	–6%	+6%
RSMB01	–5%	+6%	–12%	+15%
RSMC01	–7%	+5%	–14%	+13%
ZSMNE024A	–	–	–7%	+8%
ZSMEW007A	–	–	–36%	+27%

Table 3-13. Predicted apparent friction angle of the rock mass φ' according to the Mohr-Coulomb's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

φ'* [°]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	37.0	43.5/2.4	47.9	35.9	40.2/1.5	42.5
RSMA01 (Simpevarp)	37.0	42.6/2.2	47.9	38.7	41.0/0.9	42.5
RSMA01 (Laxemar)	40.2	45.4/1.6	47.9	35.9	39.6/1.6	42.2
RSMB01	35.0	39.9/2.7	45.3	34.8	40.2/2.6	43.9
RSMC01	40.1	44.5/1.2	48.2	40.3	42.4/0.9	44.0
ZSMNE024A				37.0	39.3/1.4	43.0
ZSMEW007A				–	45.0	–

* Linear envelope between 10 and 30 MPa.

In Table 3-14, the apparent friction angle of the rock mass for stresses between 10 and 30 MPa is reported. The mean value of the friction angle of the competent rock varies around 43°, except Rock Domain RSMB01 that has only 40° in fine-grained dioritoid. In fact, this rock type matrix has lower friction angle (around 53°) than the other rock types (around 60°).

For the deformation zones, the mean friction angle also spans between 39° and 41°. Zone ZSMEW007A has a friction angle comparable to the competent rock.

Table 3-14 shows that the uncertainty of the apparent friction angle is rather low. This means that the mean friction angle of the competent rock is estimated within an interval of about ± 2%. For the deformation zones this value slightly more than doubles. Zone ZSMEW007A has high uncertainty due to the scarcity of geological data. It is worth to remind here that a small variation of the friction angle can produce not negligible over- or underestimations of the rock mass strength with increasing continuent stress.

By means of the apparent cohesion and friction angle, the apparent uniaxial compressive strength of the rock mass for a stress confinement between 10 and 30 MPa can be determined. This is done for the sake of comparison with the results that will be obtained by the Theoretical Approach, which are expressed in terms of apparent uniaxial compressive strength of the rock mass. On average, the apparent compressive strength of the competent rock and deformation zones is between 80 MPa and 70 MPa, respectively. ZSMNE024A has the lowest apparent compressive strength of 61 MPa.

The uncertainties of the mean apparent uniaxial compressive strength are very similar to those for the equivalent uniaxial compressive strength in Section 3.7.

Table 3-14. Uncertainty of the mean apparent friction angle of the rock mass φ' for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean φ' value itself.

Uncertainty of the mean φ' as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–2%	+1%	–5%	+3%
RSMA01 (Simpevarp)	–2%	+1%	–4%	+3%
RSMA01 (Laxemar)	–2%	+1%	–5%	+2%
RSMB01	–3%	+2%	–9%	+6%
RSMC01	–5%	+2%	–10%	+6%
ZSMNE024A	–	–	–5%	+4%
ZSMEW007A	–	–	–24%	+10%

Table 3-15. Predicted apparent uniaxial compressive strength UCS_m of the rock mass according to the Mohr-Coulomb's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

Apparent UCS_{M-C}* (Mohr-Coulomb)	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	53.7	84.1/13.0	116.9	50.3	66.3/6.2	78.6
RSMA01 (Simpevarp)	53.7	79.4/10.9	116.9	58.6	68.0/3.9	75.2
RSMA01 (Laxemar)	64.3	94.1/11.3	116.9	50.3	65.0/7.3	78.6
RSMB01	48.6	69.8/12.6	106.9	48.0	68.0/9.5	82.5
RSMC01	63.9	86.7/7.9	119.5	65.0	74.3/4.6	83.2
ZSMNE024A				52.8	61.2/5.9	77.9
ZSMEW007A				–	90.2	–

* Linear envelope between 10 and 30 MPa.

Table 3-16. Uncertainty of the mean UCS_m of the rock mass according to the Mohr-Coulomb's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean UCS_m (Mohr-Coulomb) value itself.

Uncertainty of the mean UCS_{M-C} (Mohr-Coulomb) as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–5%	+5%	–8%	+9%
RSMA01 (Simpevarp)	–5%	+6%	–8%	+10%
RSMA01 (Laxemar)	–4%	+3%	–8%	+9%
RSMB01	–6%	+9%	–16%	+24%
RSMC01	–10%	+8%	–19%	+21%
ZSMNE024A	–	–	–10%	+13%
ZSMEW007A	–	–	–50%	+42%

3.9 Tensile strength of the rock mass

The equivalent tensile strength of the rock mass is determined from the Hoek & Brown's Strength Criterion determined via RMR/GSI. According to the Hoek & Brown's Criterion, the tensile strength of the competent rock spans between 0.5 and 1 MPa, while the tensile strength of the deformation zones ranges between 0.2 and 0.7 MPa, respectively. The differences between Rock Domain RSMB01 and the other two Rock Domains depends on the Hoek & Brown's parameter m_i for the intact rock that is around 14 for the fine-grained dioritoid in RSMB01, and about 31 for the quatz monzonite to monzodiorite in the other two Rock Domains, respectively.

The uncertainties of the mean tensile strength are very close to those of the equivalent uniaxial compressive strength in Section 3.7 because they are determined in a very similar way.

Table 3-17. Preliminarily predicted tensile strength TS_m of the rock mass according to the Hoek & Brown's Criterion for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model.

TS_m [MPa]	Competent rock			Stochastic or deterministic deformation zones		
Rock Domain/ Deformation Zone	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA01 (Total)	0.13	0.69/0.38	2.24	0.12	0.38/0.19	0.89
RSMA01 (Simpevarp)	0.13	0.68/0.43	2.24	0.12	0.23/0.05	0.33
RSMA01 (Laxemar)	0.18	0.72/0.26	1.43	0.18	0.48/0.18	0.89
RSMB01	0.33	1.02/0.49	3.45	0.31	0.70/0.27	1.34
RSMC01	0.18	0.53/0.17	1.43	0.17	0.29/0.07	0.44
ZSMNE024A				0.08	0.16/0.07	0.37
ZSMEW007A				–	0.63	–

Table 3-18. Uncertainty of the mean TS_m of the rock mass for the Rock Domains and Deterministic Deformation Zones of the Simpevarp Area Model. The uncertainty of the mean is expressed as percentage of the mean TS_m value itself.

Uncertainty of the mean TS_m as % of the mean value itself	Competent rock		Stochastic or deterministic deformation zones	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA01 (Total)	–7%	+13%	–12%	+33%
RSMA01 (Simpevarp)	–8%	+16%	–13%	+39%
RSMA01 (Laxemar)	–7%	+9%	–12%	+28%
RSMB01	–9%	+19%	–18%	+67%
RSMC01	–16%	+23%	–31%	+77%
ZSMNE024A	–	–	–16%	+66%
ZSMEW007A	–	–	–82%	+114%

4 Conclusions

This report contains the delivery of the rock mass characterisation by means of the Empirical Approach to the Simpevarp 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 Simpevarp Site.

The characterisation was carried out based on the geomechanical information available from five boreholes (KSH01AB, KSH02, KSH03, KAV01 and KLX02). The data used was included in the delivery from the Data-freeze on April 7th, 2004.

The Lithological Model (also called Rock Domain Model) provides the partitioning of the rock mass into Rock Domains according to geological criteria including rock types, weathering and age. The five boreholes constituting the base of the present Rock Mechanics characterisation intercept three of the 36 Rock Domains inside the Regional Model Volume.

- RMSA01 in Ävrö granite.
- RMSB01 in fine-grained dioritoid.
- RMSC01 in a mixture of Ävrö granite and quartz monzodiorite.

For each of these Rock Domains, the rock quality was determined based on the well-known empirical systems Q and RMR. By means of the empirical relations between the rock mass quality and the mechanical properties of the rock mass available in the literature, the deformation modulus was determined based on the two methods. By comparing the results, it was concluded that the two methods gave rather similar results (Figure 4-1). Based on this, it was decided to obtain the mechanical properties of the rock mass based on RMR only because a wider range of formula are available to relate RMR values with the Hoek & Brown's and Mohr-Coulomb's Strength Criteria for the rock mass.

The following Rock mechanics parameters were determined for rock mass in each Rock Domain and Deterministic Deformation Zone: a) equivalent deformation modulus (for low stress); b) Poisson's ratio (for low stress); c) equivalent uniaxial compressive strength; d) equivalent tensile strength; e) apparent cohesion (for stresses between 10 and 30 MPa); apparent friction angle (for stresses between 10 and 30 MPa); f) apparent uniaxial compressive strength (from the cohesion and friction angle for stresses between 10 and 30 MPa).

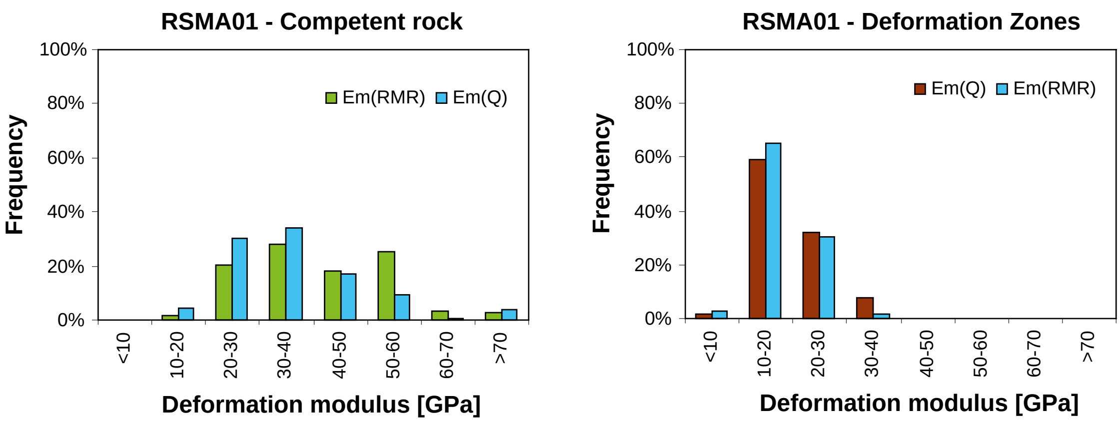

Figure 4-1. *Histogram of the deformation modulus of the rock mass determined from Q and RMR for the competent rock (left) and fractured rock/deformation zones (right) in Rock Domain RSMA01 in Simpevarp SDM v. 1.2.*

A comparison of the characterisation results at different scales (5 and 30 m) showed that the RMR and Q systems are rather insensitive to the length of the borehole sections on which they are applied. In fact, the deformation modulus of the rock mass decreases only 8% by passing from 5 to 30 m /Lanaro et al. 2004/.

The deformation zones in the Simpevarp SDM v. 1.2 represent, on average, 18% of the borehole length. Some of the deformation zones identified by the geological "single-hole interpretation" were promoted to Deterministic Deformation Zones in the Deformation Zone Model for Simpevarp SDM v. 1.2. The remnant 15.5% consists of so-called "stochastic deformation zones" that are modelled as stochastic features by the Distinct Fracture Network Model for Simpevarp SDM v. 1.2. Because they were recognised as rock sections of worse properties compared to the adjacent rock mass, the stochastic deformation zones inside the Rock Domains are studied per se.

The Rock Mechanics properties weakly increase with depth along borehole KSH01AB, KSH02 and KSH03A. Borehole KAV01 and KLX02, where deep deformation zones are present, do not show clear variation of the parameters with depth. The deformation zones that cause this phenomenon extend for more than 100 m along the boreholes and the rock mass quality tend to decrease when approaching them.

The comparison of deformation modulus of the three Rock Domains and of the two Deterministic Deformation Zones is shown in Figure 4-2. It can be observed that the competent rock in RSMA01 has the highest deformation modulus, while RSMB01 has the lowest. The deformation zones in the Rock Domains seem to have almost the same deformation modulus independently of the Rock Domain (around 35 GPa). The deformation modulus of the deformation zones is on average 35% smaller than the modulus of the competent rock (around 25 GPa).

The possible spatial variability of the properties for Rock Domain RSMA01 should get a particular mention. In fact, this Rock Domain is penetrated by three boreholes, two of which are in Simpevarp and one in Laxemar. If the properties are separately illustrated for the two areas of the model some differences can be observed (Figure 4-3). In fact, it seems that the rock mass in Laxemar has better mechanical properties than that in Simpevarp. However, this observation is based only on one borehole in Laxemar, thus, it has to be confirmed by more investigations.

The two Deterministic Deformation Zones are very different. ZSMNE024A, which extends about 110 m along borehole KSH03A, has deformation modulus about 57% smaller than that for the average competent rock, and lower than the deformation modulus of the zones in the

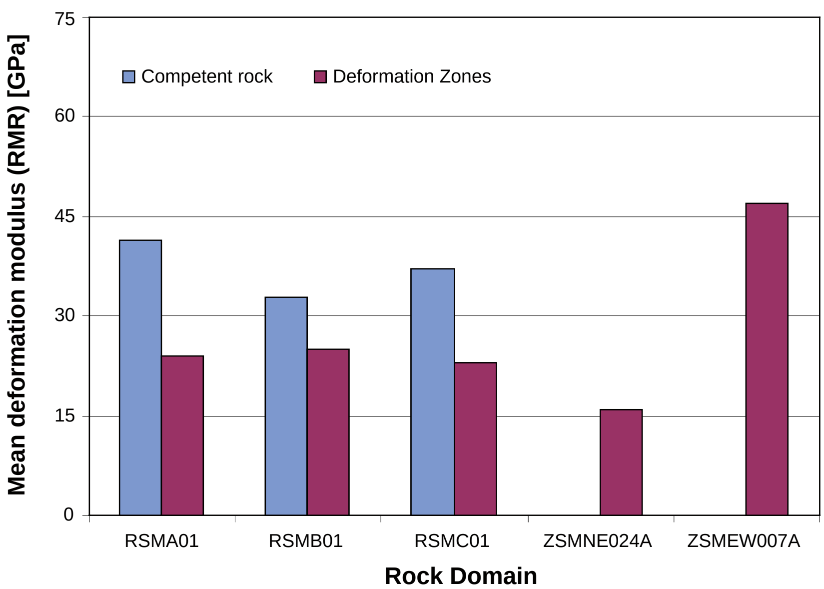

Figure 4-2. *Mean deformation modulus from RMR of the rock mass in Rock Domain RSMA01, RSMB01 and RSMC01 ("competent" and "deformation" zones) and for Deterministic Deformation Zone ZSMNE024A and ZSMEW007A in Simpevarp SDM v. 1.2.*

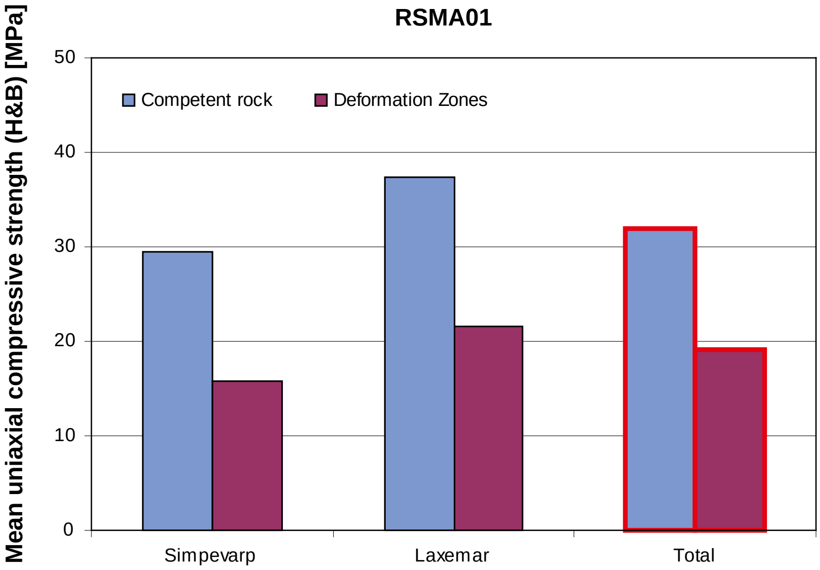

Figure 4-3. *Equivalent uniaxial compressive strength of the rock mass in Rock Domain RSMA01 for Simpevarp, Laxemar, and for the whole Model Volume.*

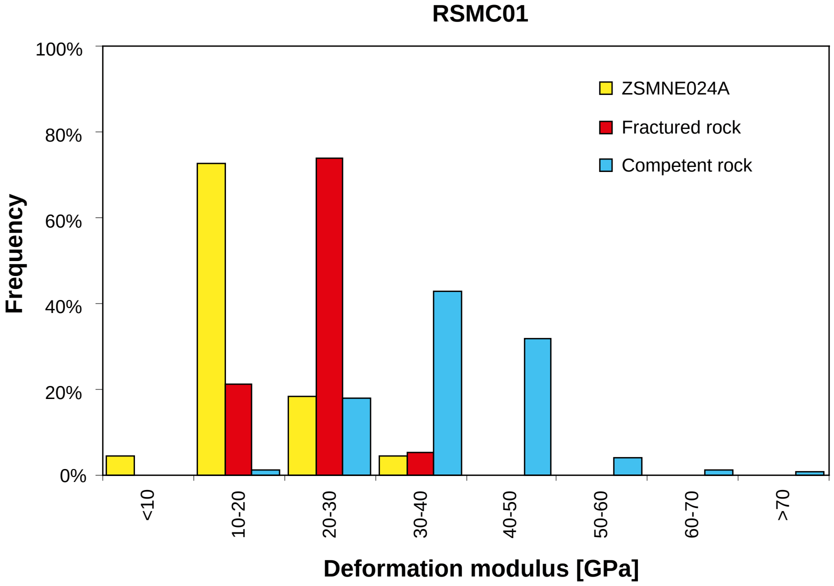

Figure 4-4. *Histogram of the deformation modulus of the rock mass in Rock Domain RSMC01 (competent and fractured rock/deformation zones) and Deterministic Deformation Zone ZSMNE024A.*

Rock Domains (Figure 4-4). On the other hand, ZSMEW007A extends only 2 m along KLX02, and for this reason has no particular Rock Mechanics importance. The deformation modulus of ZSMEW007A is estimated to be even better than the average modulus in Rock Domain RSMA01 to which this zone belongs.

The equivalent uniaxial compressive and tensile strength of the rock mass were determined based on RMR/GSI and the Hoek & Brown's Criterion. On average, it was found that all Rock Domains have very close uniaxial compressive strength: around 30 MPa for the competent rock and around 20 MPa for the stochastic deformation zones. Zone ZSMNE024A has a mean estimated uniaxial compressive strength of only about 12 MPa. The estimated tensile strength, on the other hand, varies from Rock Domain to Rock Domain. RSMB01 has the highest tensile strength of about 0.75 MPa and 1 MPa for the deformation zones and competent rock, respectively. RSMA01 and RSMC01 present almost the same tensile strength of about 0.3 MPa and 0.6 MPa for the deformation zones and competent rock, respectively. The difference between RSMB01 and the other Rock Domains depend on the mechanical properties of the intact rock matrix. Zone ZSMNE024A exhibits an average tensile strength of 0.15 MPa.

Apparent cohesion and friction angle for stresses between 10 and 30 MPa are also very similar for Rock Domain RSMA01 and RSMC01. On average, for the competent rock the cohesion is 17 MPa and for the deformation zones 15 MPa, while the friction angle is 45° for the competent rock and 40° for the deformation zones respectively. For RSMB01, the properties of the deformation zones and competent rock almost coincide and are, on average: cohesion 15 MPa and friction angle 40°. The cohesion of ZSMNE024A is very close to that of the deformation zones inside the Rock Domains, while the friction angle is on average 39°.

The uncertainties of 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, the ranges of variation of the laboratory results on rock properties were also explicitly considered. The following uncertainties of the mean values of the Rock Mechanics properties were quantified for the competent rock in all Rock Domains:

- Deformation modulus and the Poisson's ratio (low stress): –7%/+10%.
- Uniaxial compressive and tensile strength: –9%/+15.
- Apparent cohesion (confinement 10–30 MPa): ± 4%.
- Apparent friction angle (confinement 10–30 MPa): –3%/+1%.

The following uncertainties of the mean value of the Rock Mechanics parameters were quantified for the fractured rock in all Rock Domains and for Deterministic Deformation Zone ZSMNE024A:

- Deformation modulus and the Poisson's ratio (low stress): –15%/+35%.
- Uniaxial compressive and tensile strength: –18%/+46%.
- Apparent cohesion (confinement 10–30 MPa): ± 9%.
- Apparent friction angle (confinement 10–30 MPa): –7%/+20%.

Zone ZSMEW007A is not representative as deformation zone because of the scarcity of data available.

After the "harmonization", the mechanical properties of the rock mass will be applied in the calculations for design and safety analysis of the deep repository at the Simpevarp and Laxemar Candidate Site. To build a complete Rock Mechanics Model of the site, however, the knowledge of the boundary conditions in terms of rock stresses and water pressure is necessary. In fact, most of the mechanical properties of the rock mass included in this report are stress-dependent.

5 References

Andersson J, Christiansson R, Hudson JA, 2002. Site Investigations Strategy for Rock Mechanics Site Descriptive Model, SKB TR-02-01, Svensk Kärnbränslehantering AB.

Barton N, 2002. Some new Q-value correlations to assist in site characterisation and tunnel design, I.J. Rock Mech. & Min. Eng., Vol. 39, p. 185–216.

Bieniawski ZT, 1989. Engineering rock mass classifications. John Wiley & Sons.

Fredriksson A, Olofsson I, 2006. Rock mechanics characterisation of the rock mass – theoretical approach. Preliminary site description Simpevarp subarea version 1.2, SKB R-05-87, Svensk Kärnbränslehantering AB.

Hoek E, Brown 1998. Practical estimates of rock mass strength, Int. J. Rock Mech. Min. Sci. Vol. 34, p. 1165–1186.

Hoek E, Carranza-Torres C, Corkum B, 2002. The Hoek-Brown Failure Criterion – 2002 Edition. 5th North American Rock Mechanics Symposium and 17th Tunneling Association of Canada Conference: NARMS-TAC, p. 267–271.

Hultgren P, Stanfors R, Wahlgren C-H, Carlsten S, Mattsson H, 2004. Geological single-hole interpretation of KSH03A, KSH03B, KLX02, HAV09 and HAV10. Oskarshamn site investigation, Revised June 2006, SKB P-04-231, Svensk Kärnbränslehantering AB.

Lanaro F, Bäckström A, 2005. Rock mechanics characterisation of borehole KSH01A and B, KSH02, KSH03A and B, KAV01 and KLX02. Oskarshamn site investigation, SKB P-05-283, Svensk Kärnbränslehantering AB.

La Pointe P R, Hermanson J, 2006. Statistical model of fractures and deformation zones. Preliminary site description Simpevarp subarea - version 1.2, SKB R-05-28, Svensk Kärnbränslehantering AB.

Mattsson H, Stanfors R, Wahlgren C-H, Stenberg L, Hultgren P, 2004a. Geological single-hole interpretation of KSH01A, KSH01B, HSH01, HSH02 and HSH03. Oskarshamn site investigation, SKB P-04-32, Svensk Kärnbränslehantering AB.

Mattsson H, Stanfors R, Wahlgren C-H, Carlsten S, Hultgren P, 2004b. Geological single-hole interpretation of KSH02 and KAV01. Oskarshamn site investigation, Revised June 2006, SKB P-04-133, Svensk Kärnbränslehantering AB.

Lanaro F, Christiansson R, Röshoff K, 2004. Effects of scale on rock mass empirical characterisation, Proc. Euro-Conference on Rock Physics and Geomechanics – Scaling laws in space and time, Potsdam, Germany, 2004, p 51.

Lanaro F, 2005. Rock Mechanics characterisation of borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02, Simpevarp Site Investigations, SKB P-04-CC in preparation, Svensk Kärnbränslehantering AB.

Peebles PZ jr, 1993. Probability, random variables and random signal functions, McGraw p. 401.

Röshoff R, Lanaro F, Jing L, 2002. Strategy for a Rock Mechanics Site Descriptive Model. Development and testing of the empirical approach, SKB R-02-01, Svensk Kärnbränslehantering AB.

Serafim JL, Pereira JP, 1983. Consideration of the geomechanics classification of Bieniawski, Proc. Int. Symp. Eng. Geol. & Underground Constr., p. 1133–1144.

SKB, 2004. Preliminary site description – Simpevarp Area – Version 1.1, SKB R-04-25 Svensk Kärnbränslehantering AB.

SKB, 2005. Preliminary site description. Simpevarp subarea - version 1.2, SKB R-05-08, Svensk Kärnbränslehantering AB.

A1 Summary of the results of the empirical approach

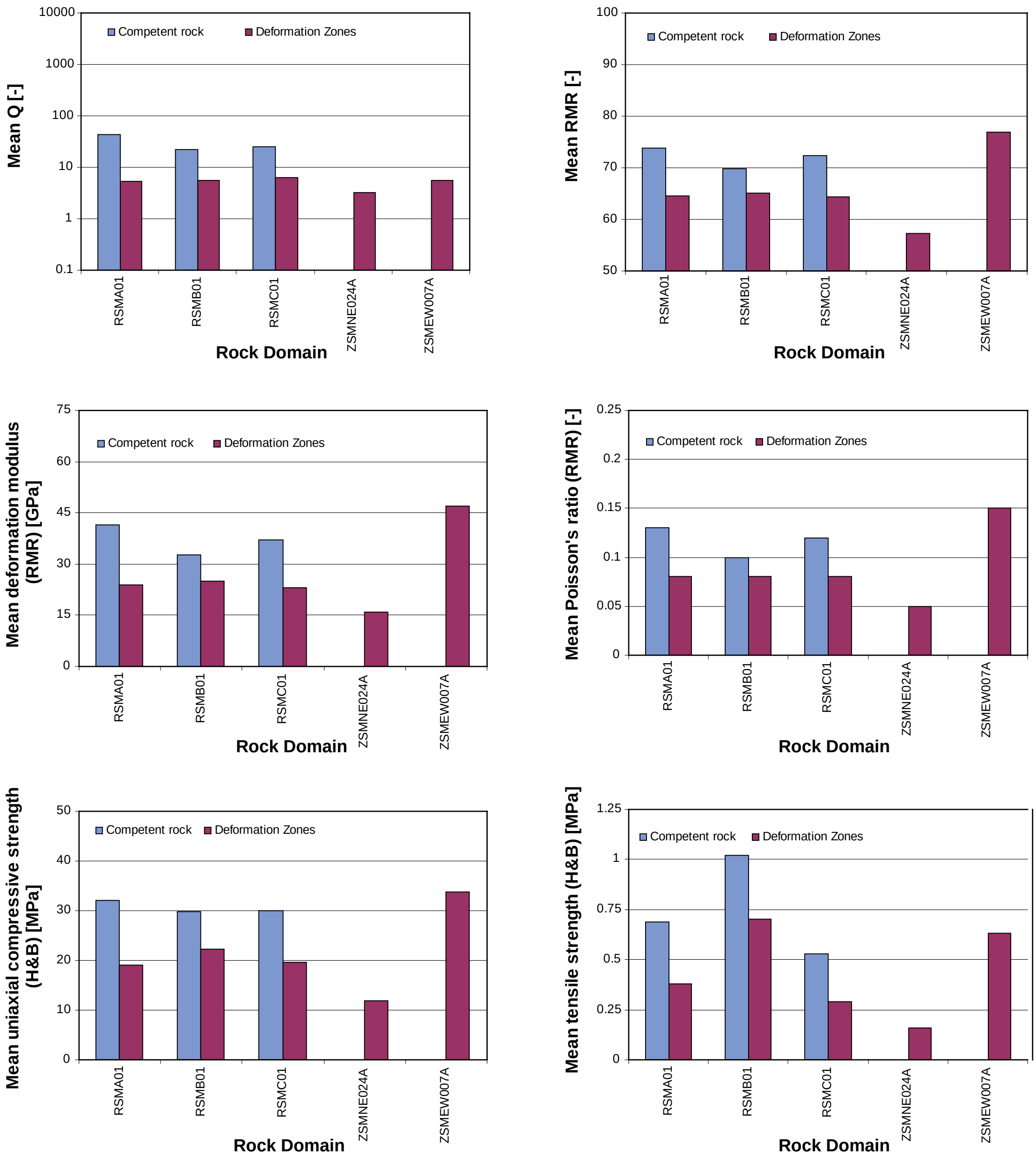

Figure A1-1. *Rock Mechanics properties of the Rock Domains and Deformation Zones for Simpevarp Site Descriptive Model v. 1.2. The mean Q and RMR values, the deformation modulus and Poisson's ratio, the uniaxial and tensile strength according to Hoek & Brown's Criterion are illustrated for the competent and fractured rock mass.*

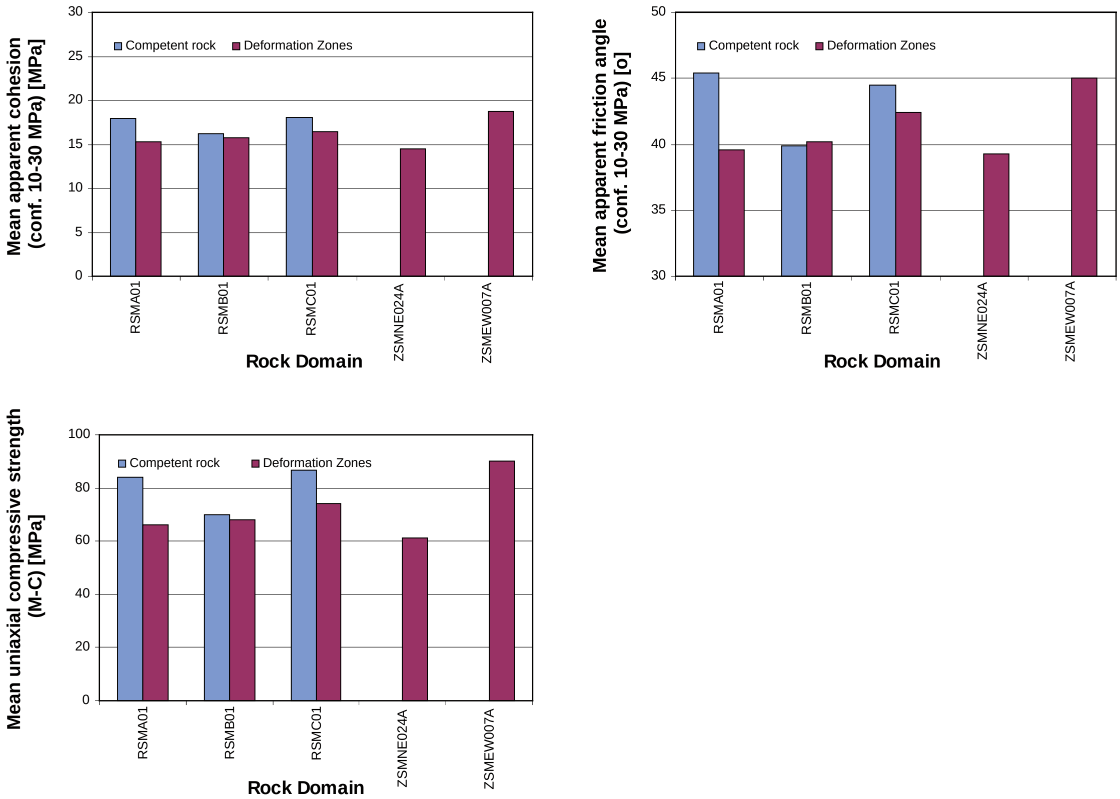

Figure A1-2. *Rock Mechanics properties of the Rock Domains and Deformation Zones for Simpevarp Site Descriptive Model v. 1.2. The mean apparent cohesion, friction angle and uniaxial compressive strength of the rock mass according to Mohr-Coulomb's Criterion are illustrated.*

A2 Properties of rock domain RMSA01 in Simpevarp, Laxemar and both sites

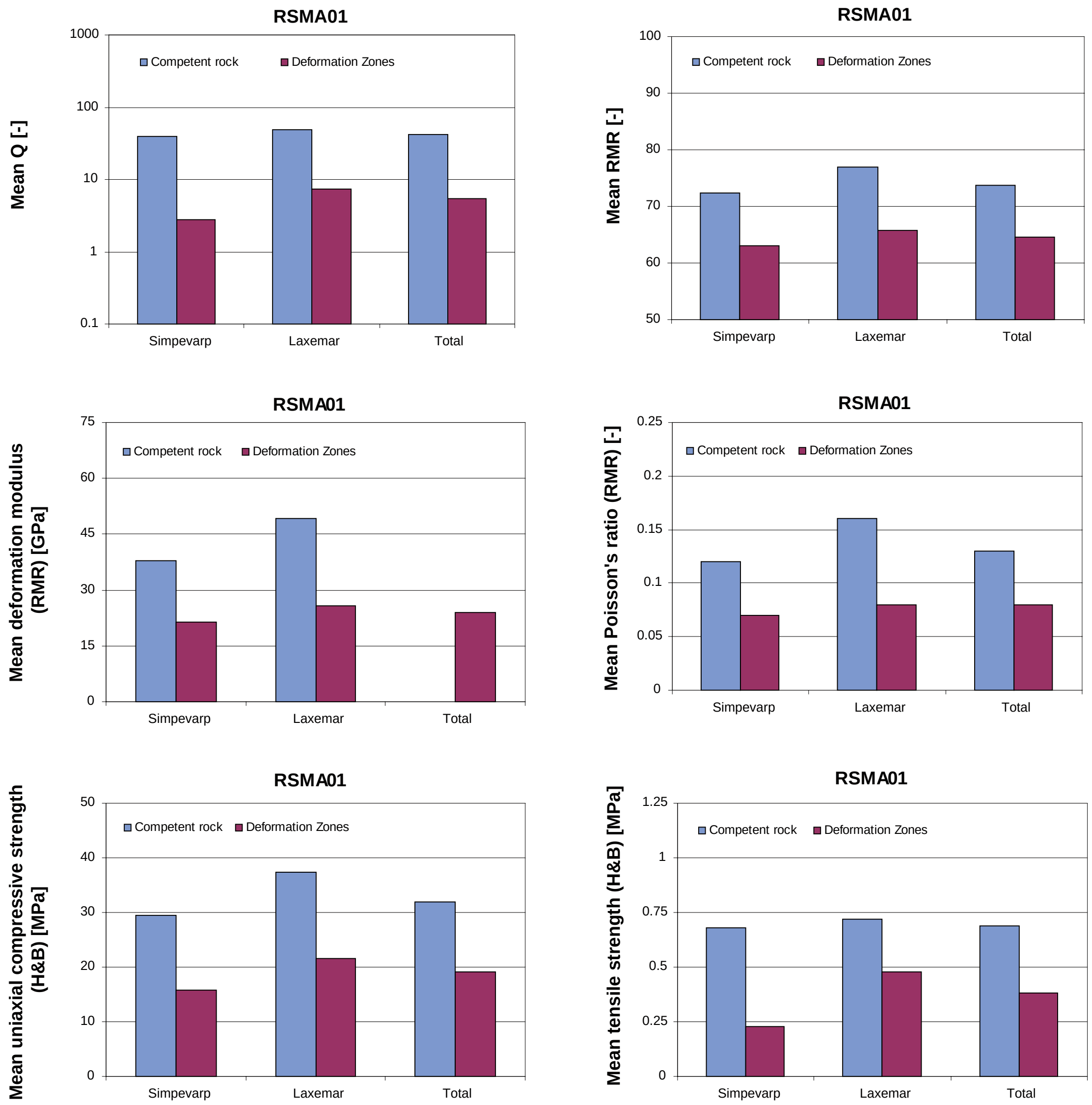

Figure A1-3. *Rock Mechanics properties of the competent rock and deformation zones for Rock Domain RSMA01 of Simpevarp Site Descriptive Model v. 1.2. The mean Q and RMR values, the deformation modulus and Poisson's ratio, the uniaxial and tensile strength according to Hoek & Brow's Criterion are illustrated for the competent and fractured rock mass.*

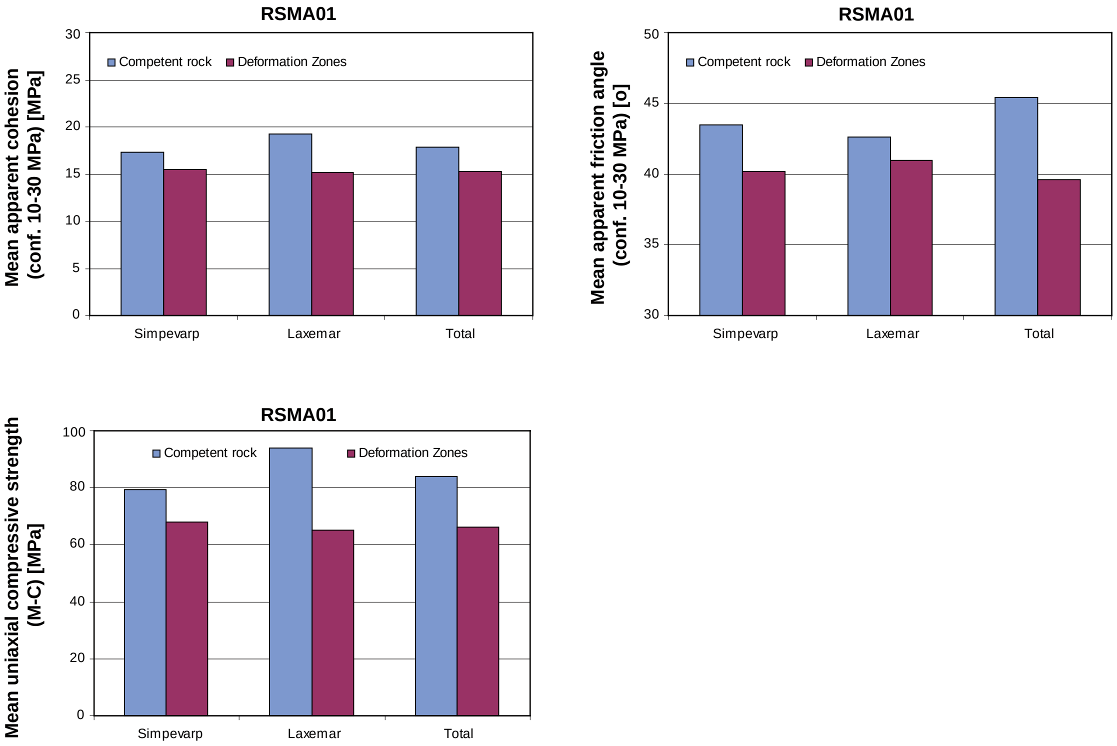

Figure A1-4. *Rock Mechanics properties of the competent rock and deformation zones for Rock Domain RSMA01 of Simpevarp Site Descriptive Model v. 1.2. The mean apparent cohesion, friction angle and uniaxial compressive strength of the rock mass according to Mohr-Coulomb's Criterion are illustrated.*

A3 Histograms for rock domain RSMA01

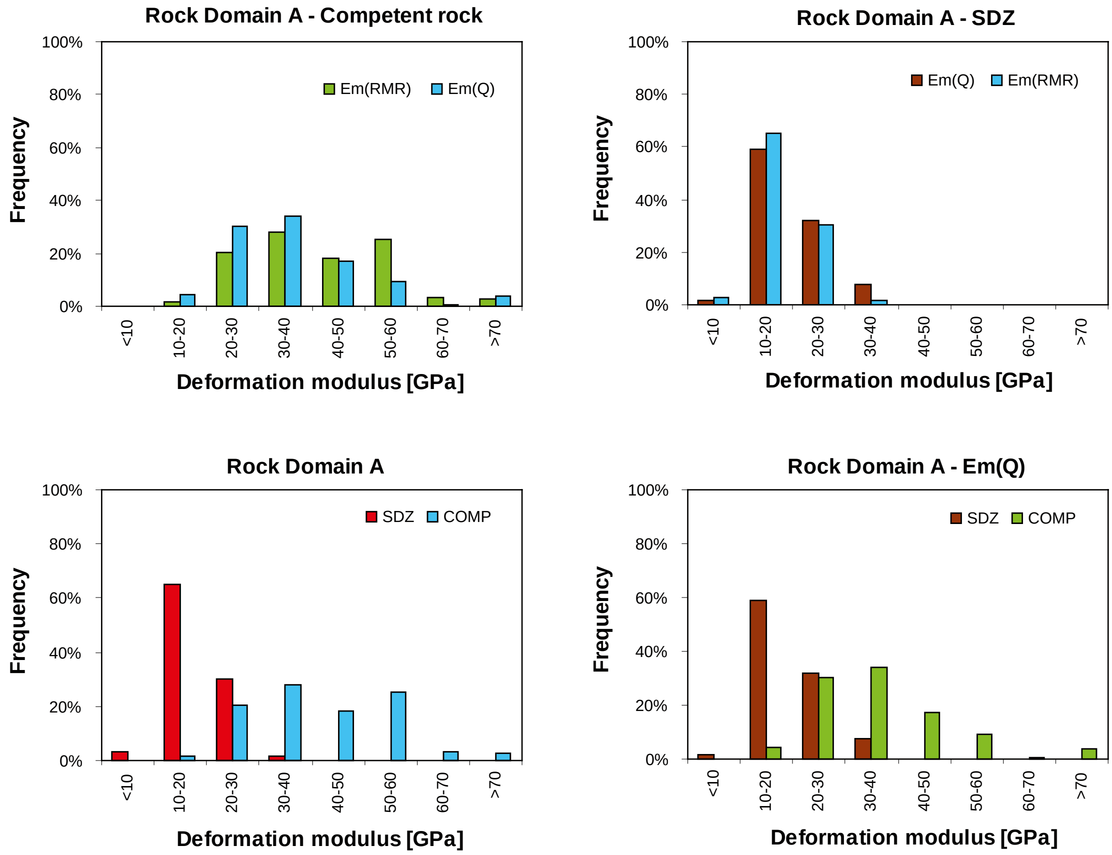

Figure A1-5. *Rock Domain RSMA01: Histograms showing the comparison of the results from RMR and Q for the competent rock (COMP) and fractured rock (SDZ), respectively. In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

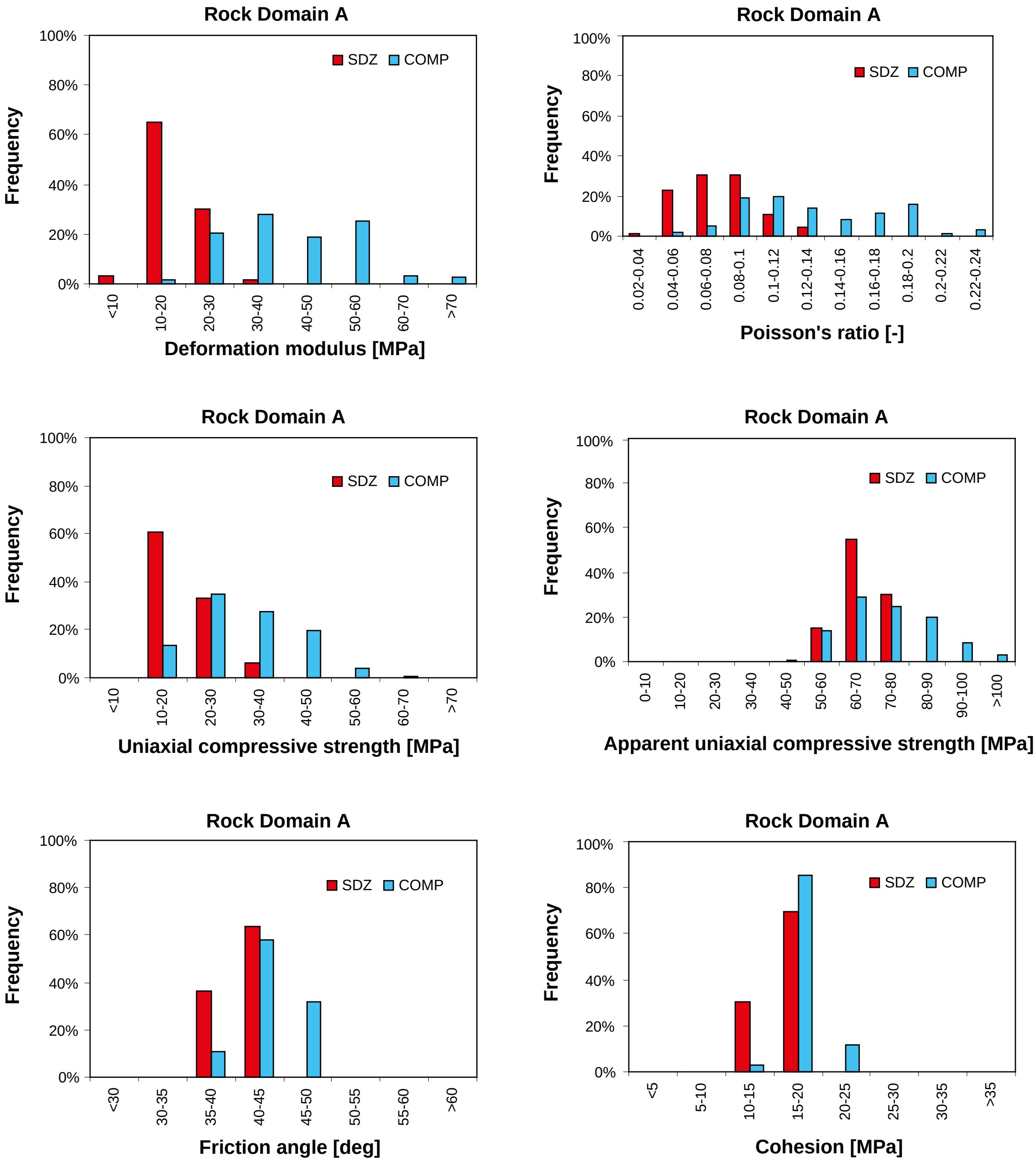

Figure A1-6. *Rock Domain RMSA01: Histograms of the deformation modulus, uniaxial compressive strength, apparent uniaxial compressive strength, friction angle and cohesion of the rock mass determined by means of RMR for the competent rock (COMP) and fractured rock (SDZ). In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

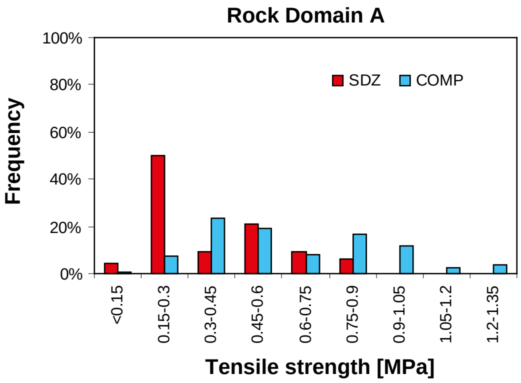

Figure A1-7. *Rock Domain RMSA01: Histogram of the tensile strength of the rock mass determined by means of RMR for the competent rock (COMP) and fractured rock (SDZ). In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

A4 Histograms for rock domain RSMB01

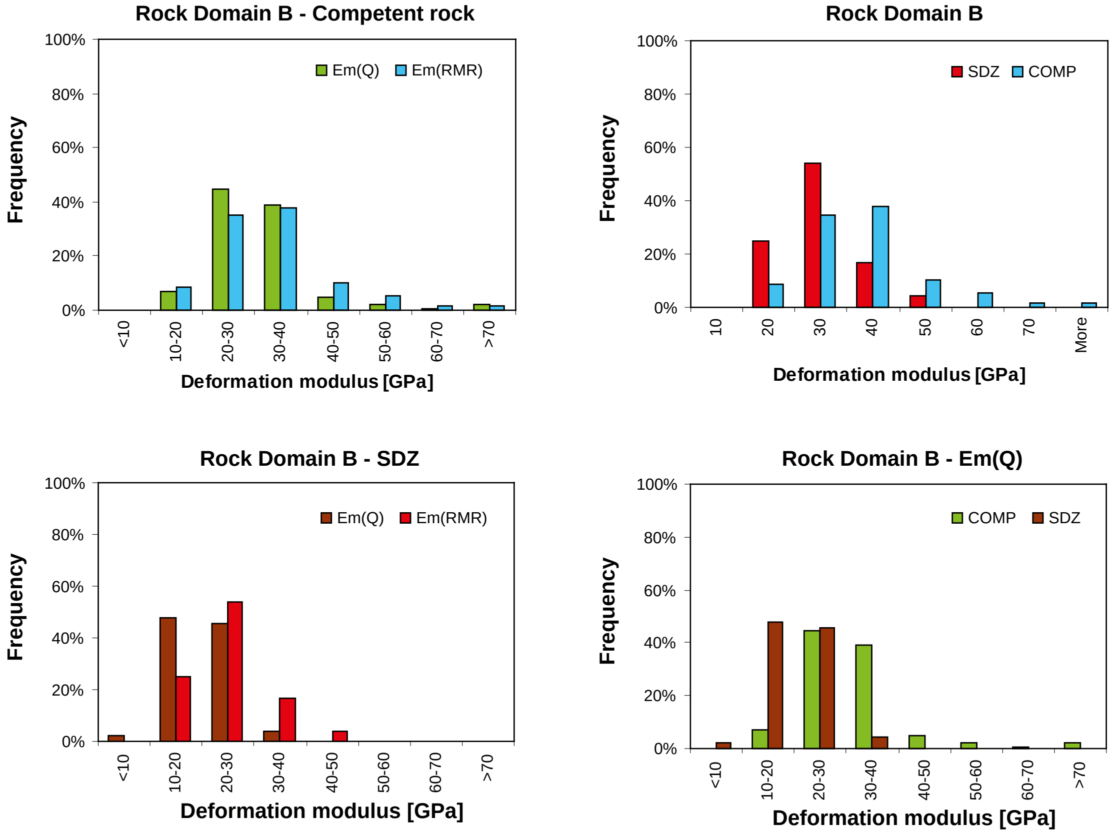

__Figure A1-8.__ Rock Domain RSMB01: Histograms showing the comparison of the results deformation modulus from RMR and Q for the competent rock (COMP) and fractured rock (SDZ), respectively. In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.

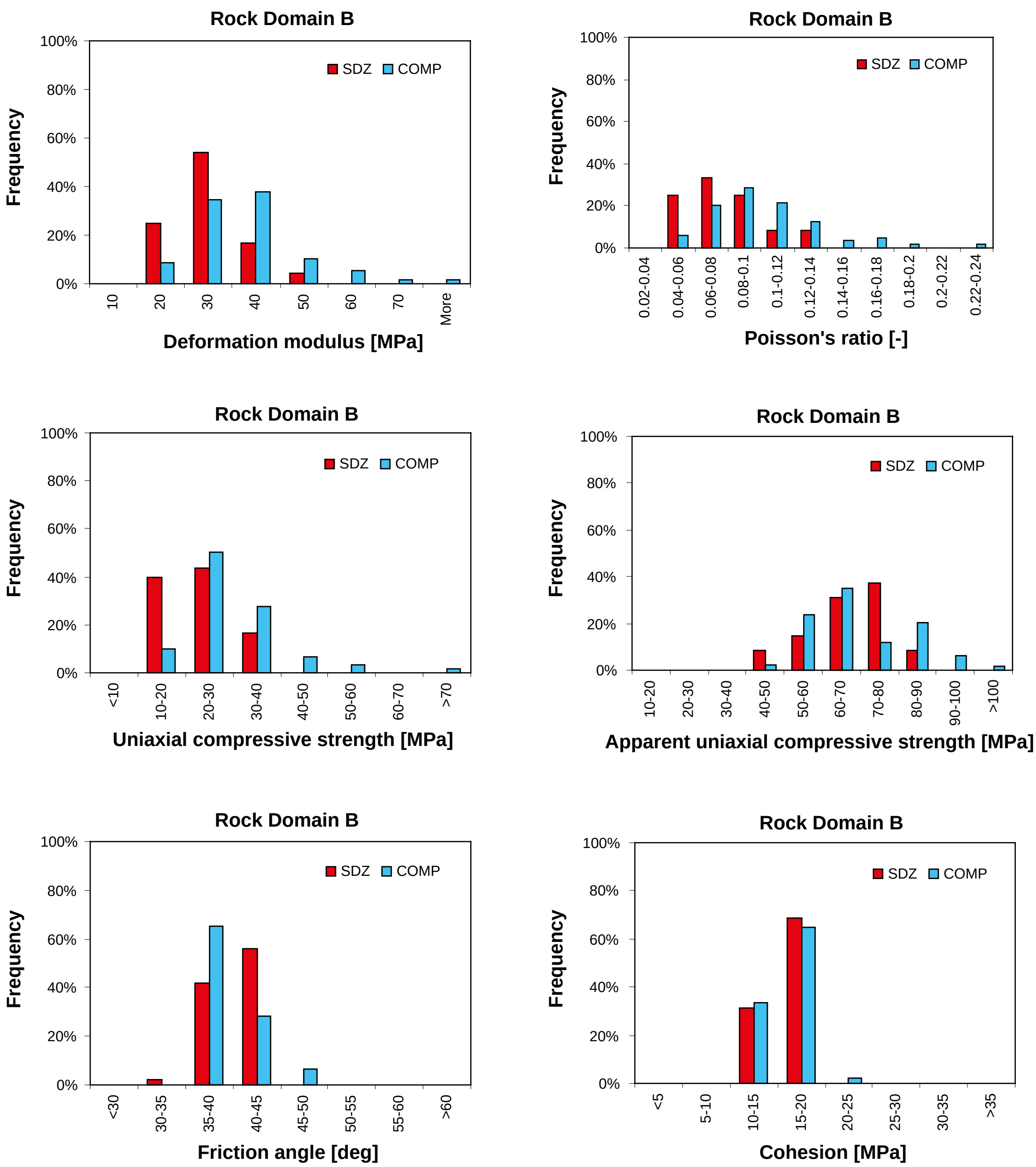

Figure A1-9. *Rock Domain RSMB01: Histograms of the deformation modulus Poisson's ratio, uniaxial compressive strength, apparent uniaxial compressive strength, friction angle and cohesion of the rock mass determined by means of RMR for the competent rock (COMP) and fractured rock (SDZ). In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

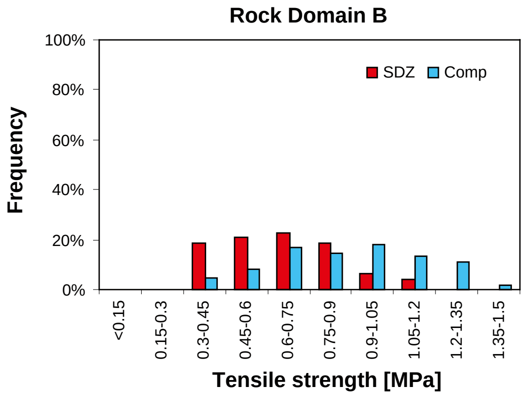

Figure A1-10. *Rock Domain RSMB01: Histogram of the tensile strength of the rock mass determined by means of RMR for the competent rock (COMP) and fractured rock (SDZ). In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

A5 Histograms for rock domain RSMC01

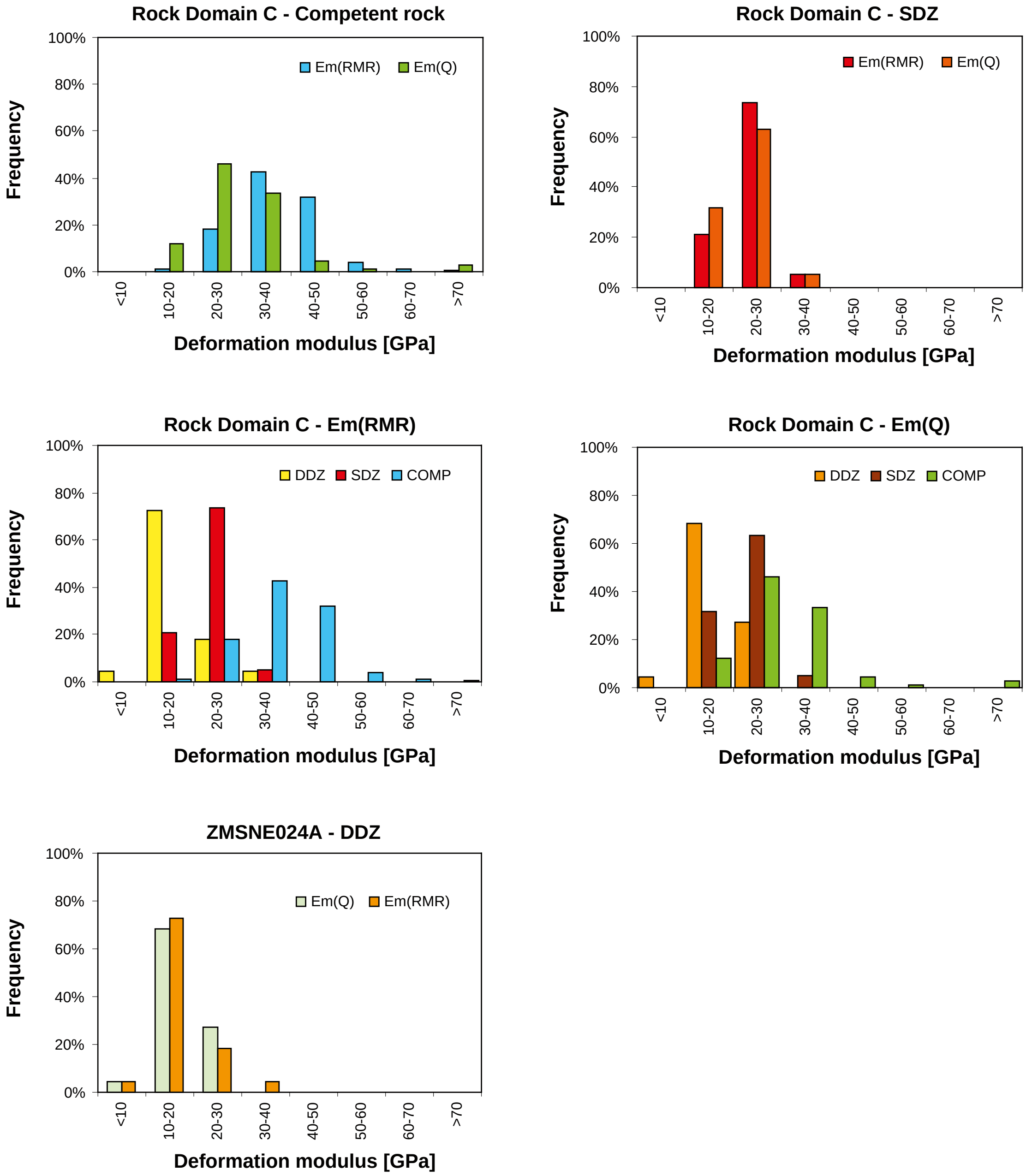

Figure A1-11. *Rock Domain RSMC01: Histograms showing the comparison of the results of deformation modulus from RMR and Q for the competent rock (COMP), fractured rock (SDZ) and the deterministic Deformation Zone (DDZ) ZMSNE024A, respectively. In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

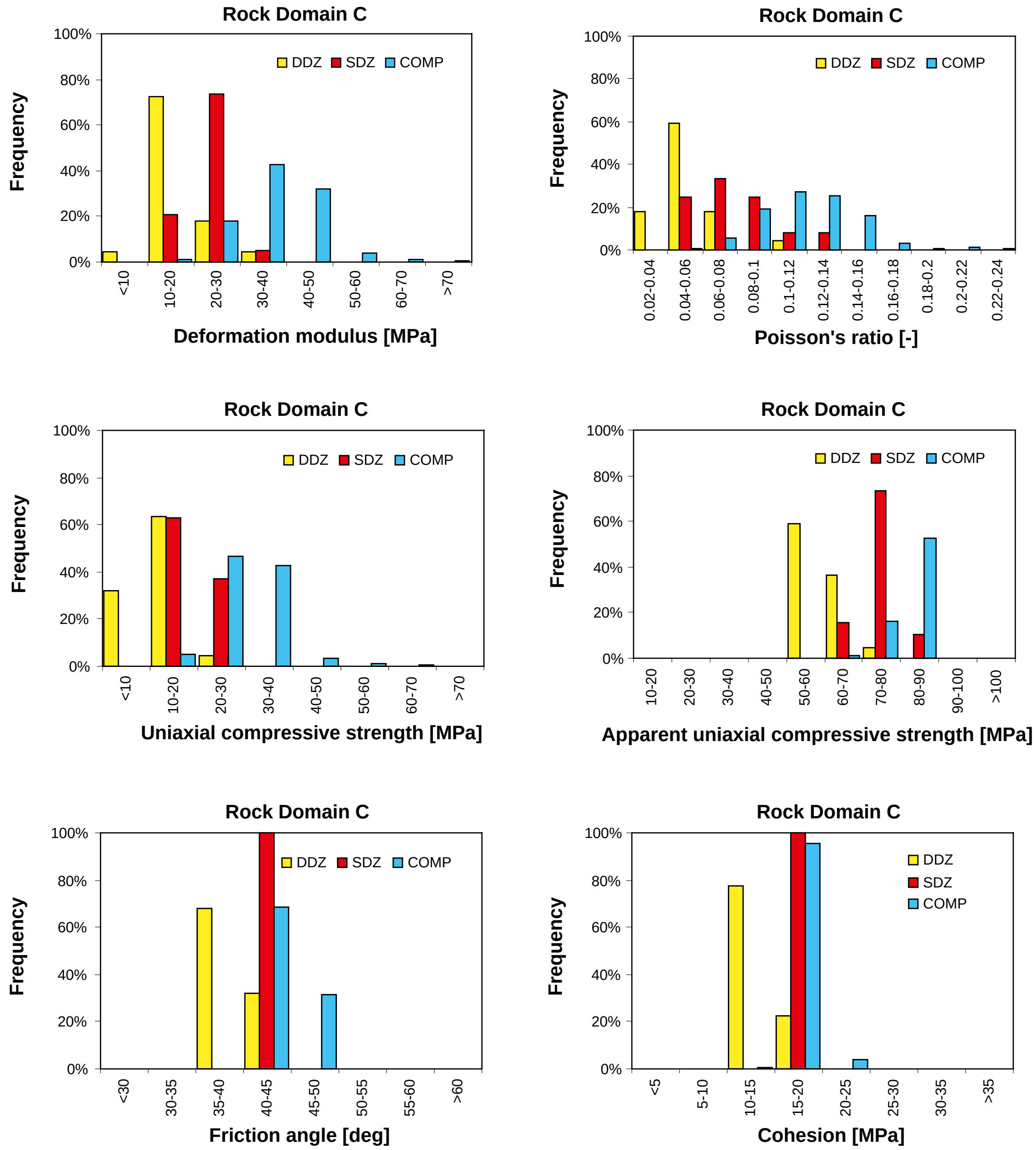

Figure A1-12. *Rock Domain RSMC01: Histograms of the deformation modulus Poisson's ratio, uniaxial compressive strength, apparent uniaxial compressive strength, friction angle and cohesion of the rock mass determined by means of RMR for the competent rock (COMP), fractured rock (SDZ) and the deterministic Deformation Zone (DDZ) ZMSNE024A. In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*

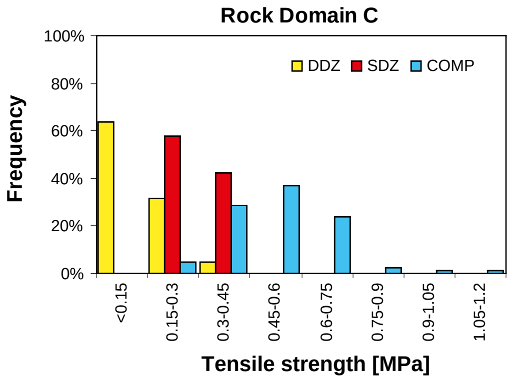

Figure A1-13. *Rock Domain RSMC01: Histogram of the tensile strength of the rock mass determined by means of RMR for the competent rock (COMP), fractured rock (SDZ) and the deterministic Deformation Zone (DDZ) ZMSNE024A. In this figure, the histograms for ZSMEW007A are not reported because they are only based on one value for each property.*