R-06-14

Rock mechanics modelling of rock mass properties – empirical approach

Preliminary site description Laxemar subarea – version 1.2

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September 2006

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This report concerns a study which was conducted for SKB. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

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Abstract

This report contains the results of the Empirical Approach for the characterisation of the rock mass in the Laxemar Site Descriptive Model Version 1.2. The geomechanical information available from nine boreholes (KSH01AB, KSH02, KSH03, KAV01, KAV04, KLX01, KLX02, KLX03 and KLX04) was used. The nine boreholes intercept six of the Rock Domains contained in the Regional Model Volume. For each of these Rock Domains, the rock quality was determined based on the well-known empirical systems Q and RMR system. From the Q and RMR values, the following Rock Mechanics parameters were determined for the rock mass in each Rock Domain and Deterministic Deformation Zone: a) equivalent deformation modulus (for low stresses); b) Poisson's ratio (for low stresses); c) equivalent uniaxial compressive strength from the Hoek & Brown's Criterion; 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 Coulomb's Criterion (from the cohesion and friction angle for stresses between 10 and 30 MPa).

The Rock Domains at Laxemar exhibit values of the deformation modulus ranging from 44 GPa to 71 MPa. The Rock Domain RSMD (quartz monzonite to monzodiorite) and RSMM (diorite and gabbro) seem to have the highest stiffness and strength: the average deformation modulus ranges between 66 GPa and 71 GPa. The equivalent cohesion and friction angle of the rock mass varies around the values of 20 MPa and 45°, respectively. The uncertainty range is about ± 4% of the mean value of the deformation modulus. Compared with the rock at the Simpevarp Peninsula, the rock mass in the Domain RSMA (Ävrö granite) at Laxemar seems to have better mechanical properties, although the rock type is the same.

Six Deterministic Deformation Zones were also analysed by means of the empirical methods: ZSMNE024A, ZSMNE031A, ZSMNE012A, ZSMEW007A, ZSMNW929A and ZSMNW932A. The length of these zones spans from 1,900 m to 11,600 m. An average deformation modulus of about 24 GPa, cohesion of 16 MPa and friction angle of 41° was estimated on average, respectively. Beside the Deterministic Deformation Zones, fractured rock within each Rock Domain was estimated between 1% and 3% in volume in the Laxemar Area (no correction for orientation bias). The average mechanical properties of the fractured rock can be assumed to be the same as for the Deterministic Deformation Zones.

The threshold values of Q equal to 4 and RMR equal to 60 were applied to obtain, independently from the Deformation Zone Model, the extension the deformation zones from a Rock Mechanics point of view. For the nine boreholes, the average volume of rock occupied by these "minor zones" was quantified to be between 0 and 13% of the rock mass. This result is in very good agreement with the studies conducted during the construction of the access tunnel of the Äspö HRL (about 9%). Considering that most of the deformation zones in the area occur at a rather steep angle (about 70°), this percentage could be reduced to about half (4.5% of the rock mass volume). The minimum thickness of these zones should be 5 m along the boreholes, or, after a correction for the estimated dip angle, about 2.5 m, which may be related to a zone length of about 250 m.

Sammanfattning

Empirisk karaktärisering av bergmassan i Laxemar redovisas i rapporten med fokus på bergdomänerna och sprickzonerna i den beskrivande modell för Laxemar, version 1.2. Geomekanisk information tillgänglig från nio borrhål användes (KSH01AB, KSH02, KSH03, KAV01, KAV04, KLX01, KLX02, KLX03 and KLX04). Dessa borrhål korsar sex bergdomäner inom Laxemars regionala volym. För varje bergdomän har bergkvalitén bedömts med hjälp av Q och RMR system. Från Q och RMR värden har följande ekvivalenta mekaniska egenskaper hos bergmassan beräknats: a) deformationsmodulen; b) Poissons tal; c) enaxiella tryckhållfastheten; d) draghållfastheten; e) kohesionen (bergspänningsnivån 10 MPa till 30 MPa); f) friktionsvinkeln (bergspänningsnivån 10 MPa till 30 MPa); g) skenbar enaxiella tryckhållfastheten från kohesionen och friktionsvinkeln.

Bergdomänerna i Laxemar visar ett deformationsmodulvärde mellan 44 GPa och 71 MPa. Bergdomänen RSMD (i kvartsmonzonit till monzodiorit) och RSMM (diorit och gabbro) har högst styvhet och hållfasthet: deformationsmoduls medelvärde ligger mellan 66 GPa och 71 GPa. Osäkerheten kvantifieras i ± 4 % av deformationsmodulens medelvärde. Den ekvivalenta kohesionen och friktionsvinkeln varierar runt 20 MPa respektive 45°. Jämfört med Simpevarp halvön verkar bergdomänen RSMA (i Ävrö granit) ha bättre mekaniska egenskaper trots att bergarten är den samma.

Sex deterministiska deformationszoner analyserades med empiriska metoder: ZSMNE024A, ZSMNE031A, ZSMNE012A, ZSMEW007A, ZSMNW929A och ZSMNW932A. Längden hos dessa zoner varierar mellan 1 900 m och 11 600 m. Den beräknade deformationsmodulen ligger runt 24 GPa, kohesionen runt 16 MPa och friktionsvinkeln runt 41°. Utöver de deterministiska deformationszonerna har även sprucket berg inom bergdomänerna kunnat kvantifieras till mellan 1 % till 3 % av bergsdomänernas volym (icke korrigerad för orienteringsbias). Även den spruckna bergmassan kan tilldelas samma egenskaper som de deterministiska deformationszonerna.

En analys med användning av Q och RMR med ett tröskelvärde på 4 respektive 60 visar att, oberoende av Deformationszonsmodellen kan även Bergmekaniken uppskatta en volym av ”sämre” berg i storleksordning mellan 0 och 13 %. Detta resultat stämmer bra med den geologiska uppskattningen och med tidigare erfarenheter under byggandet av tillfartstunneln till Äspö laboratorium i genomsnitt 9 %. Med tanke på att de flesta deformationszonerna i området lutar ganska brant kan man reducera detta procenttal till 4,5 %. De minsta undersökta zonerna sträcker sig 5 m längs borrhålen vilket motsvarar en zontjocklek på cirka 2,5 m. Denna tjocklek kan relateras till en längd på cirka 250 m.

Contents

1 Introduction

This report summarizes the results of the empirical Rock Mechanics characterisation of the rock mass along nine boreholes in Oskarshamn, at the Simpevarp and Laxemar Sites for the set up of an updated version of former Site Descriptive Model /SKB 2005/. The Rock Mechanics characterisation is performed along five boreholes, at Simpevarp and Ävrö (KSH01AB, KSH02, KSH03A, KAV01 and KAV04) and four boreholes at Laxemar (KLX01, KLX02, KLX03 and KLX04). The geological information available from the boreholes (Data-freeze Laxemar version 1.2 on November 1th, 2004) is combined with the outcomes of the Geological Model (i.e. Lithological, Deformation Zone and Discrete Fracture Network Model).

The "empirical characterisation" of the rock mass along the boreholes is carried out for the purpose of quantify the mechanical properties of the rock mass in its undisturbed state. Thus, the influence of the orientation, depth and damage of the excavations and the effects of the water conditions have not been taken into consideration /Andersson et el. 2002, Röshoff et al. 2002/. These will be handled by the "Design" and "Safety Analysis" 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 the single boreholes (Section 2). The parameters provided by the characterisation are:

- The deformation modulus and Poisson's ratio of the rock mass calculated by means of RMR. The obtained values for Q are also reported because useful for design analysis.
- 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.

Uncertainties of the rock mechanics properties of the rock mass are calculated as defined in Chapter 3.

Firstly, the plots of the quality and mechanics parameter of the rock mass along each borehole are compared for the different boreholes to highlight any significant variation in space or 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 (between 1 and 2 MPa). The Rock Mechanics Model, which combines the present Empirical model with the Theoretical Model /Fredriksson och Olofsson 2005/, 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 (Laxemar version 1.2 by May 4th, 2005). In particular, the empirical model makes use of the Lithological/Rock Domain Model and Deformation Zone Model /Wahlgren et al. 2005/ for partitioning the boreholes into pseudo-homogeneous rock volumes, and also for combining data from different boreholes. The Distinct Fracture Network (DFN) Model /Hermansson et al. 2005/ is also implicitly used for the empirical 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 and one on Ävrö Island (KSH01AB, KSH02, KSH03A, KV01 and KAV04) were analysed. On the mainland area Laxemar, four boreholes (KLX01, KLX02, KLX03 and KLX04) were also studied (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 ground surface. In Table 1-1, the available core length and the orientation of the boreholes are listed.

Table 1-1. Length and orientation of the borehole studied 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
KAV04	100–1,004	077/–85
KLX01	0–1,078	347/–85
KLX02	200–1,700*	009/–85
KLX03	101–1,000	199/75
KLX04	100–993	002/85

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

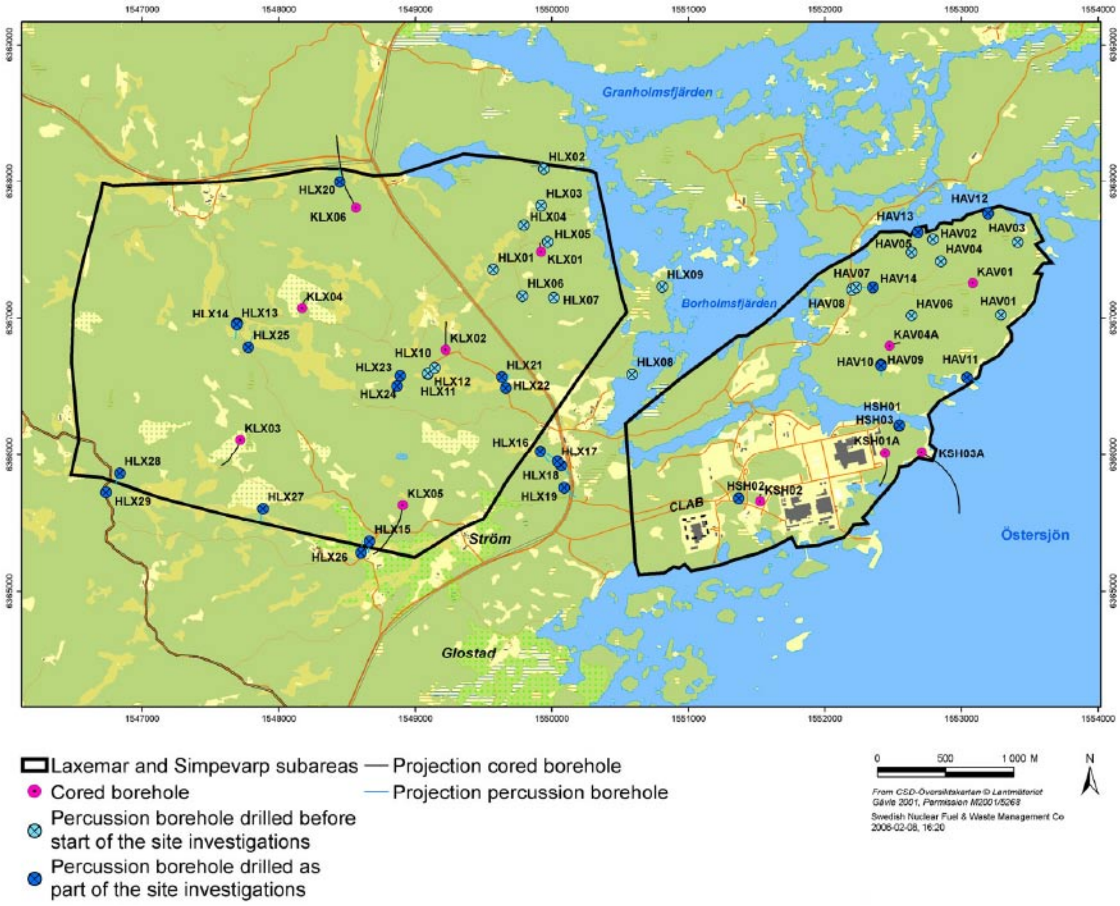

Figure 1-1. Overview of the Simpevarp and Laxemar Sites with indication of the borehole KSH01AB, KSH02, KSH03A, KAV01, KLX01, KLX02, KLX03 and KLX04 used for the Rock Mechanics characterisation.

1.1.1 The Lithological Model

All the rock types occurring at Simpevarp and Laxemar can be ascribed to the Trans-Scandinavian Igneous Belt (about 1,800 Ma) /Wahlgren et al. 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 and 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). It dominates the local area model both at Simpevarp and Laxemar and present a density of about 2,681 kg/m^3.
- Rock type B: fine-grained dioritoid (SKB code 501030). It dominates the Simpevarp Peninsula and the central part of the Ävrö Island and has an average density of about 2,803 kg/m^3.
- Rock type C: a mixture of porphyritic granite to quatz monzodiorite (Ävrö Granite, SKB code 501044) and quartz monzodiorite (SKB code 501036).
- Rock type D: quartz monzodiorite (SKB code 501036). It occurs on the western southern-most Laxemar and in association with Ävrö granite.
- Rock type E: diorite to gabbro (SKB code 501033). It is present in minor bodies in the Simpevarp, Ävrö and Äspö areas.

These five rock types dominate the Local Model Volume of the two 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; see also Figure 2-3) with one prevalent rock type, among Rock Type A through E, 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. The rock mass in the Rock Domains is characterised in Chapter 4.

1.1.2 The Deformation Zone Model

From the study of the lineaments and from the inspection of the boreholes, the Deterministic Deformation Zones intersecting the Sites were recognised and classified. A map of the deformation zones with their names is presented in Figure 1-2. The length and the thickness obtained in this Model are used in Section 4.2 and 5.2 to determine the thickness of the minor or "stochastic" deformation zones that might occur inside the Rock Domains. Seven Deterministic Deformation Zones were identified along the nine available boreholes. The rock inside these deformation zones is empirically characterised and the results shown in Chapter 5.

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 Laxemar and Simpevarp Site.
- Provide rock mass quality and mechanical properties (empirically determined) for the Rock Domains intercepted by the available core drill boreholes.
- Provide rock mass quality and mechanical properties (empirically determined) for the Deterministic Deformation Zones intercepted by the available drill-core boreholes.

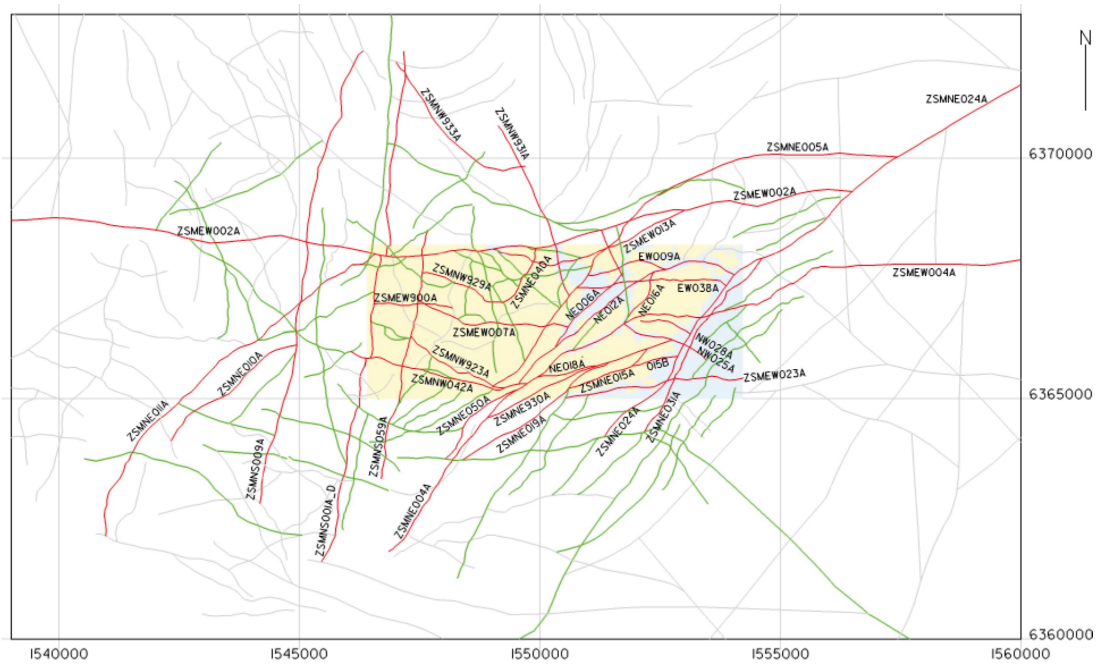

***Figure 1-2.** Surface map of the Deterministic Deformation Zones at the Simpevarp and Laxemar Sites with indication of name codes used for identification in Chapter 5.*

- Supply the necessary information for the set up of the Rock Mechanics Model of the Laxemar and Simpevarp Site.
- Infer the geometrical and mechanical properties of the "minor" deformation zones included in the Rock Domains and relevant for the Design of the deep repository.
- 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 continuum equivalent 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 data is also used for the characterization of the Rock Domains and Deterministic Deformation Zones at the Laxemar and Simpevarp Site. The uncertainties of the rock mass quality and mechanical properties are 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, KAV04, KLX01, KLX02, KLX03 and KLX04.
- A section summarizes the mechanical properties of Rock Domain RSMA, RSMB, RSMC, RSMD, RSMBA and RSMM. In this section, an attempt to identify some "minor" or "stochastic" deformation zones inside the Rock Domains based on their thickness was also performed.
- A section summarizes the mechanical properties of six deterministic deformation zones intercepting the boreholes at the Simpevarp and Laxemar Sites.
- Discussion of the results.
- Appendices.

2 Empirical characterisation of the rock mass

KSH01AB, KSH02, KSH03A, KAV01, KAV04, KLX01, KLX02, KLX03 and KLX04 were analysed from a strictly geological point-of-view in the "single-hole interpretation" of the drill-core geological information /Lanaro and Bäckström 2005ab/. Each borehole was subdivided into:

- rock units,
- possible deformation zones,

according to the geological "single-hole" interpretation of the borehole data.

A Rock Mechanics "single-hole interpretation" was carried out on borehole KSH01AB, KSH02, KSH03A, KAV01 and KLX02 /Lanaro and Bäckström 2005a/ and KLX01, KLX03, KLX04 and KAV04 /Lanaro and Bäckström 2005b/. 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 also the use of the 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/.

The geological data quality of borehole KLX01 was not as good as for the other boreholes since KLX01 was drilled much earlier than the other boreholes and the requirements on the geological logging were not the same. For this reason, some of the parameters (e.g. number of fracture sets) were not available and needed to be estimated. The results for this borehole, however, seem to be in line with the results of the characterization of borehole KLX03 and KLX04, also located at Laxemar.

The rock units in the single-hole interpretation were later grouped into larger sub-homogeneous volumes called Rock Domains in the Lithological Model /Wahlgren et al. 2005/. A surface map of the Lithological model is given in Figure 2-1. The possible deformation zones in the single-hole interpretation were either promoted to become Deterministic Deformation Zones (composing the Deformation Zone Model) /Wahlgren et al. 2005/, or incorporated in the Rock Domains where they were treated as stochastic features and incorporated into the Discrete Fracture Network Model /Hermansson et al. 2005/.

In the following sections, a distinction is made for the rock inside the Rock Domains whether the rock is outside ("competent rock") or inside the "possible deformation zones" obtained by the "single-hole interpretation" of the boreholes. Only in Section 4.2, no distinction is made between "competent" and "fractured rock" to be able to evaluate the impact of the fractured rock on the average properties of the Rock Domains.

In Table 2-1, an overview of the portioning of the borehole according to the geological "single-hole interpretation" and to the Lithological Model is given, respectively. It can be observed that the average length of borehole in competent rock is about 85% and 87% of the total length of borehole in the Simpevarp and Laxemar Area, respectively. The deformation zones occupies on average 15% and 12% of the total length of borehole in the Simpevarp and Laxemar Area, respectively. Table 2-1 summarised also how each borehole is divided into homogeneous Rock Domains according to the Lithological Model.

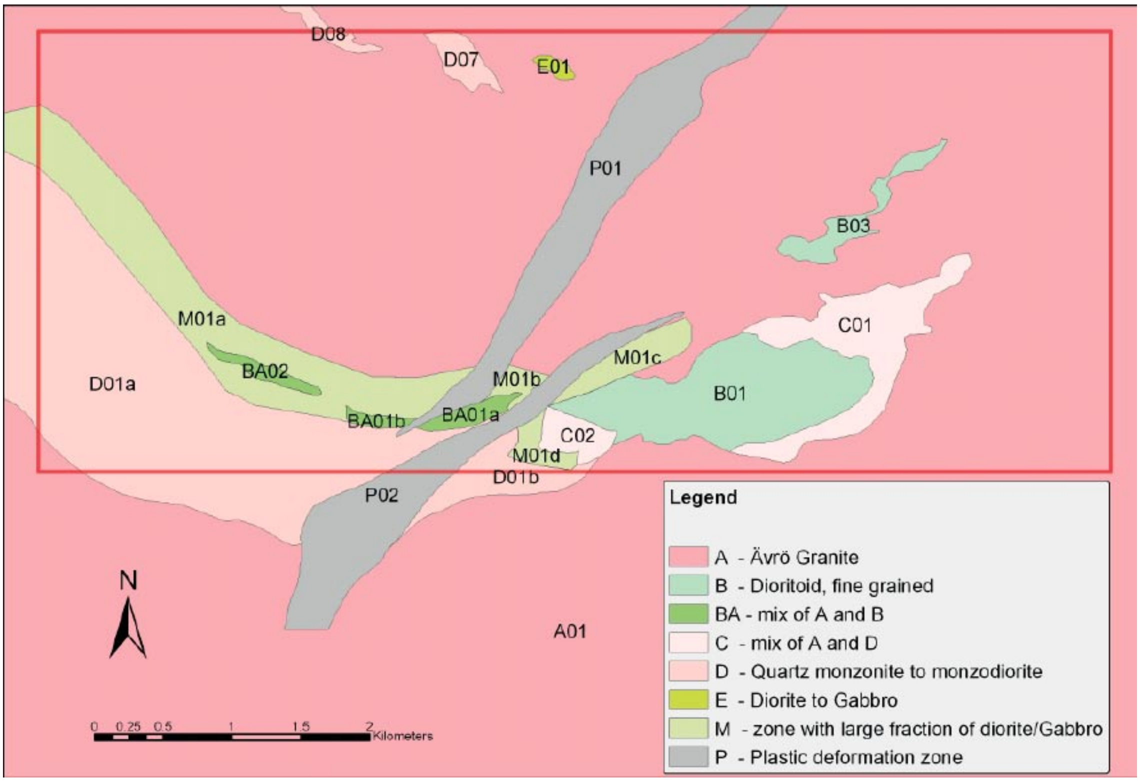

Figure 2-1. *Map of the Rock Domains in the Laxemar SDM version 1.2. The Rock Domains in the Local Model are shown /Wahlgren et al. 2005/.*

Table 2-1. Percentage in length along the boreholes of competent, fractured rock (according to the "single-hole interpretation") and distribution of the Rock Domains (according to the Lithological Model for Laxemar SDM 1.2).

Borehole	% of the borehole length							
	Competent rock	Fractured rock	RSMA	RSMB	RSMC	RSMBA	RSMD	RSMM
KSH01A (100–1,000 m)	76%	24%	–	34%	66%	–	–	–
KSH02 (80–1,000 m)	88%	12%	–	100%	–	–	–	–
KSH03AB (0–1,000 m)	87%	13%	81%	19%	–	–	–	–
KAV01 (70–750 m)	82%	18%	100%	–	–	–	–	
KAV04 (100–1,004 m)	93%	7%	42%	58%	–	–	–	–
KLX01 (0–1,078 m)	98%	2%	100%	–	–	–	–	–
KLX02 (200–1,005 m)	73%	25%	47%	–	–	53%	–	–
KLX03 (101–1,000 m)	90%	10%		–	–	–	25%	78%
KLX04 (100–993 m)	87%	13%	100%	–	–	–	–	–

2.1 Earlier studies

Many studies for the characterisation of the rock mass were conducted at the location of the Äspö Hard Rock Laboratory (Oskarshamn, Sweden). The Island of Äspö is included in the Regional Area of the Laxemar Site Descriptive Model version 1.2, but is outside the Local Area. Among these studies, the most relevant and comprehensive can be summarised as follows:

- Geological and rock mechanics pre-investigations on three boreholes drilled from the surface for the construction of the access tunnel to the Äspö HRL /Stille and Olsson 1990/.

- Rock mass classification of the access tunnel (section 431–2,875 m) during construction of the laboratory /Stille and Olsson 1996/.
- Äspö Test Case where empirical classification results from 57 boreholes and 718 m of tunnel in the deeper part of the Äspö HRL were summarised /Makurat et al. 2001/.

These studies provide, other than the order of magnitude of the empirically determined rock mass quality and mechanical properties of the rock mass, also interesting results about:

i) the relation between empirical results obtained from borehole cores, drilled and blasted tunnels and TBM tunnels,

ii) the evaluation of the rock mass volume occupied by “major” and “minor” deformation zones,

iii) the influence of the boundary conditions on the empirical results.

In the following sections, a short summary of these projects’ results is given where the topics interesting for the purposes of this report are highlighted.

2.1.1 Pre-investigations and characterisation of the access tunnel at Äspö HRL

During the pre-investigations for the construction of the access tunnel at Äspö HRL /Stille and Olsson 1990/, three deep boreholes (KAS02, KAS03 and KAS05) were characterised according to the RMR system /Bieniawski 1989/. A laboratory campaign on the mechanical properties of the intact rock was also conducted. The results of these pre-investigations were then compared with the results of an empirical classification of the rock mass performed during construction of the access tunnel /Stille and Olsson 1996/.

The comparison of the prognostic and the observed results is given in /Rhén et al. 1997/. Solid samples of four different rock types were tested in uniaxial loading conditions. By increasing the number of samples from 4 to about 14, the average mechanical properties such as uniaxial compressive strength and Young’s modulus showed non negligible differences that could not be explained other than with the fact that the number of samples was probably still too little to be representative for the different rock types. The first group of 4 samples was taken from the deep borehole cores while the second group of 9 to10 samples was collected from boreholes drilled from the tunnel.

The comparison of the rock mass classification results before and after construction is presented in Table 2-2. The differences can be explained by the fact that the prognostic classification is often voluntarily conservative, thus the best rock class is underestimated while the worse rock class overestimated. This second fact is determinant for the estimation of the construction costs. However, the estimation of the most extensive class was rather good.

Table 2-2. Comparison of the prognostic and observed results of the rock mass classification of the access tunnel of the Äspö HRL /Stille and Olsson 1996/.

RMR class	Prediction	Observation
> 72	23%	28%
60–72	50%	40%
40–60	19%	28%
< 40	8%	4%

In the analysed section of the access tunnel (Figure 2-2), a length of 225 m, which is about 9% of the total tunnel length, consisted of deformation zones larger than 5 m. The tunnel sections related to these zones required about 55% of the bolting and 77% of the shotcrete amount used for the total tunnel length. It is also worthwhile to add that, differently than for the reinforcement, 40% of the required grouting was performed outside the deformation zones and 16% in correspondence of minor deformation zones and single fractures (thickness less than 5 m). Outside the deformation zones, the frequency distribution of the obtained values of RMR is shown in Figure 2-3. The average RMR value obtained was close to 65 when all rock types were considered.

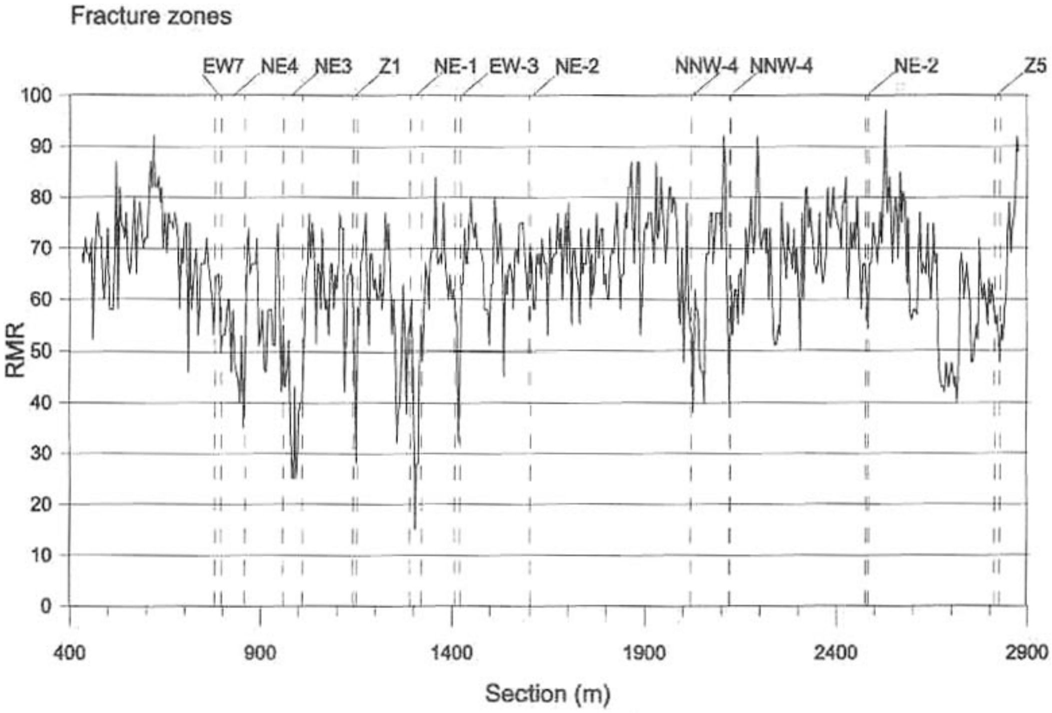

Figure 2-2. *Plot of the average RMR along the access tunnel at the Äspö HRL /Stille and Olsson 1996/.*

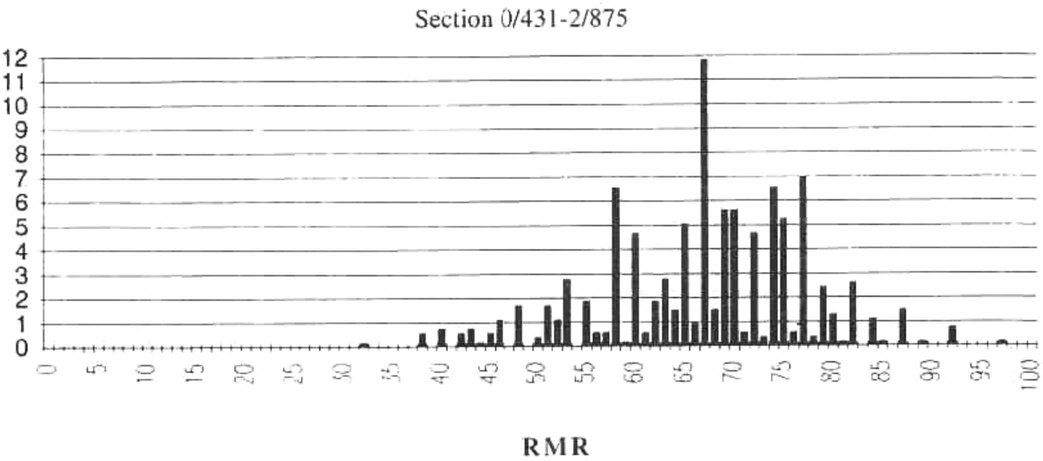

Figure 2-3. *Frequency distribution of the RMR values obtained outside the deformation zones for the access tunnel at the Äspö HRL /Stille and Olsson 1996/.*

2.1.2 Äspö Test Case

The Norwegian Geological Institute NGI /Makurat et al. 2001/ performed an empirical classification exercise based on the data available for the deeper part of the Äspö HRL (between 380 m and 500 m depth). The Q system /Barton et al. 1974/ and RMR system /Bieniawski 1989/ were applied. Their evaluation was based on newly logged boreholes (three for a total length 1,886 m) and previous results obtained by SKB. Based on the available data, they were able to compare the results of the classification obtained for the boreholes, drill & blast tunnels and one TBM tunnel. Table 2-3 shows that the classifications based borehole data give very close results to classification of the drill & blast tunnel. On the other hand, the classification performed on TBM tunnel data differs substantially from the other two. This was explained with the fact that the smooth walls of the TBM tunnel make it difficult to infer the fracture conditions and also lead to the underestimation of RQD. The same conclusions could be drawn from the SKB results obtained from the RMR classification of two parallel tunnels of about 400 m length (Table 2-4), one excavated by drill & blast and one by TBM technique.

Several deformation zones at Äspö were also studied (Table 2-5). Among them, sections of the Deterministic Deformation Zone ZSMEW013A (EW-1a) in the Laxemar SDM version 1.2 could also be studied.

Table 2-3. Comparison between the Q classification results obtained from borehole, drill & blast tunnel and TBM tunnel data after /Makurat et al. 2001/.

Q classes	Borehole data	Drill & blast tunnel data	TBM tunnel data
> 40	1%	0%	0%
10–40	62%	79%	100%
4–10	28%	21%	0%
1–4	8%	0%	0%
< 1	2%	0%	0%

Table 2-4. Comparison between the RMR classification results obtained from drill & blast tunnel and TBM tunnel data after /Makurat et al. 2001/.

RMR class	Drill & blast tunnel data	TBM tunnel data
> 80	10%	19%
60–80	64%	74%
40–60	17%	7%
20–40	9%	0%

Table 2-5. Classification of deformation zones by means of RMR and Q system at the Äspö HRL after /Makurat et al. 2001/.

Zone name	Thickness	RMR range*	Q range*
ZSMEW013A (EW-1a)	300 m	–	0.008–12.4 [2.4]*
NE-2	1–10 m	40–60	1.9–7.8 [5.0]
NE-1	60 m	–	0.01–12.4 [3.2]*
MWZ1, 2, 3	22 m	60–80	
MWZ 4	3–4 m	–	[5]*
MWZ 6	10 m	61–63	–
MZW7	10 m	40–60	
MZW 8	< 10 m	[57]*	–

* Average values between brackets.

2.1.3 Remarks

The following important aspects can be summarised from the experiences collected by the earlier studies:

- The earlier results listed here dealt with the "classification" of the rock mass, which means that the parameters taking into account the boundary conditions (water pressure and stress) and the geometry of the tunnels (orientation, size) were considered in the calculations. In this report, instead, the rock along the boreholes is "characterised", which means that the "undisturbed" rock mass is given material properties. To obtain the "classification" properties for all the Design applications from the "characterisation" properties, the influence of the water pressure, rock stress and tunnel geometry has to be added.

  Considering the rather high compressive strength of the intact rock compared to the in-situ stresses, and the fact that water leakage problems are often rather localized, it seems reasonable that the parameters for classification do not differ much from those for characterisation. For this reason, comparison between the old and the new data become possible.
- Figure 2-2 show that, although the authors affirm that the rock mass at the site is rather homogeneous, the calculated average RMR fluctuates quite much even outside the deformation zones.
- The earlier studies seem to agree on the fact that the rock mass might be defined as "fracture zones" or "deformation zones" when Q is below 4 and RMR below 60. This information will be used in Section 5.4 to localise all the possible deformation zones in the boreholes of the Laxemar Site.
- The earlier studies and this report focus on the deformation zones that have an extension along the boreholes or along the tunnels of at least 5 m. Thanks to this agreement, a comparison of the total extension of deformation zones in the boreholes and tunnels at the Laxemar Site will be possible.
- The earlier studies do not agree with each other on the fact that the classification results are dependent on the uniaxial compressive strength of the intact rock. In this report, the actual strength of the intact rock for each borehole section is used, when available, to avoid this uncertainty.

2.2 Characterisation by Q and RMR system

Figure 2-4 through Figure 2-9 show the plot of the Q and RMR empirical values with borehole length obtained for all the boreholes studied in this report. The figures contain the minimum, medium and maximum values of the empirically determined rock quality. Thus, for each "rock unit", the width of the interval between maximum and minimum gives a measure of the homogeneity of the rock mass.

The Q and RMR values, other than for determining equivalent mechanical properties of the rock mass as presented in Chapter 4 and 5, can also be directly used for the design of the shape, size and support requirement of the tunnels that can be constructed.

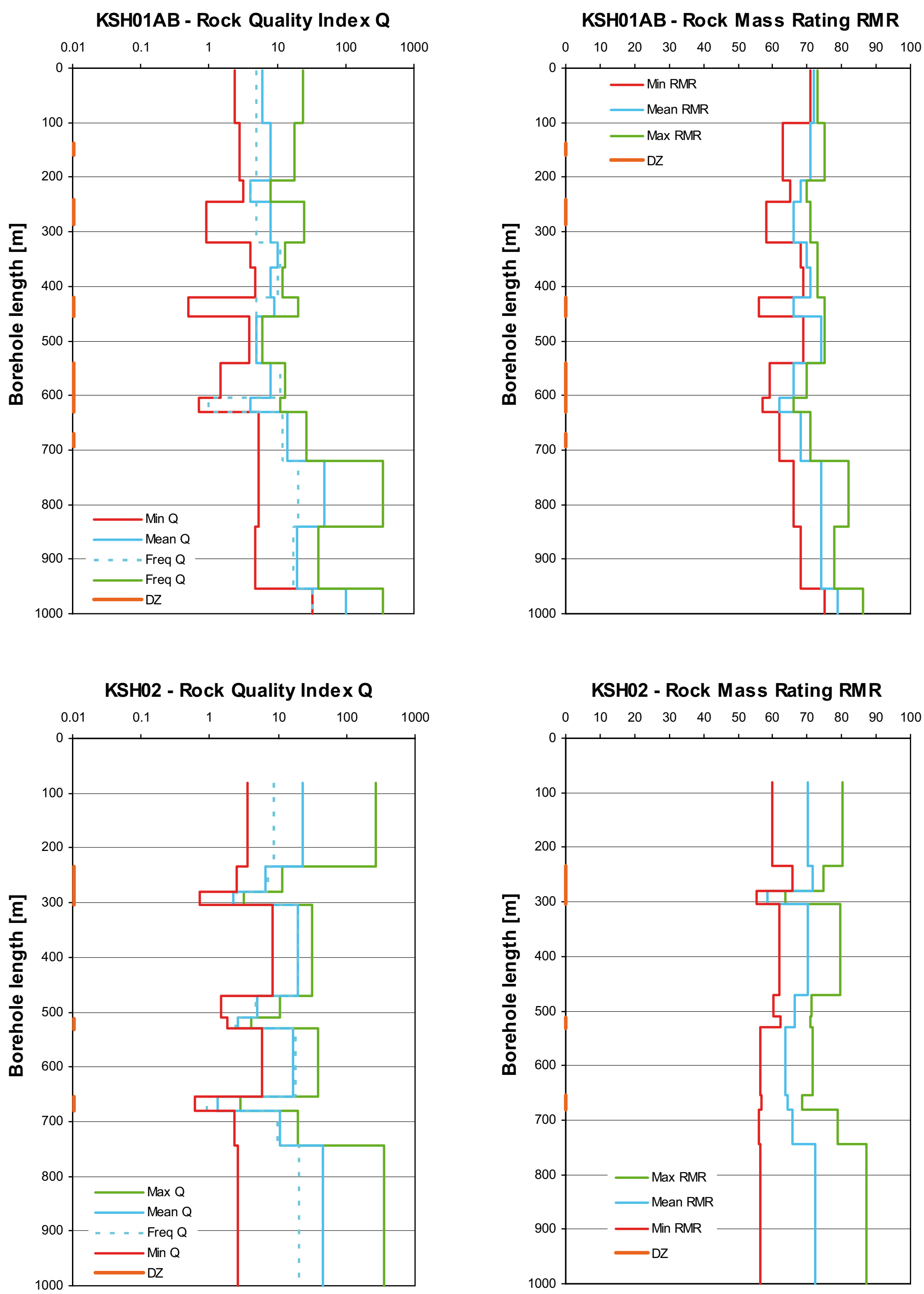

Figure 2-4. *Simpevarp Area: Variation of the Q and RMR with borehole lenght. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

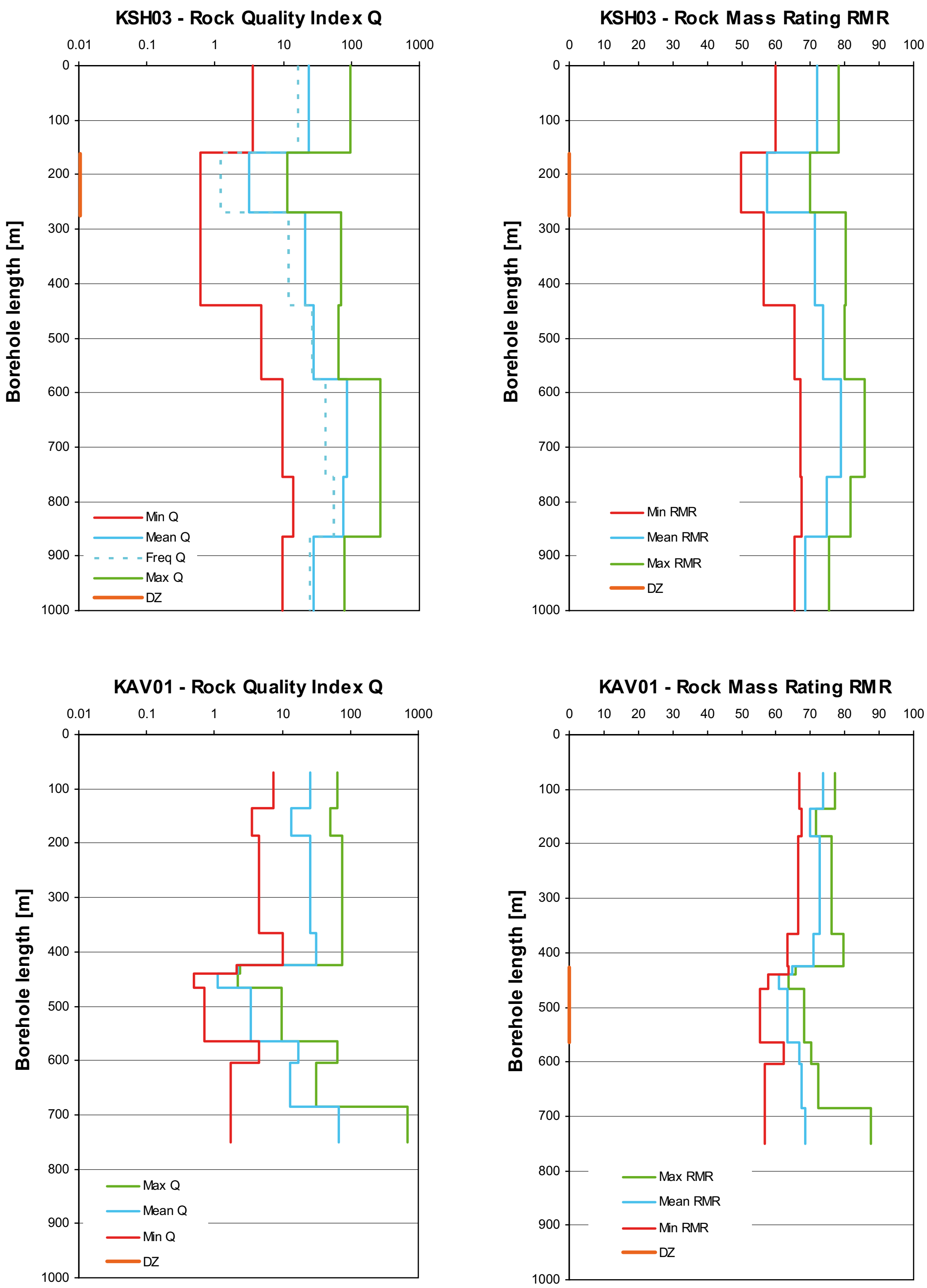

Figure 2-5. *Simpevarp Area: Variation of the Q and RMR with borehole length. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

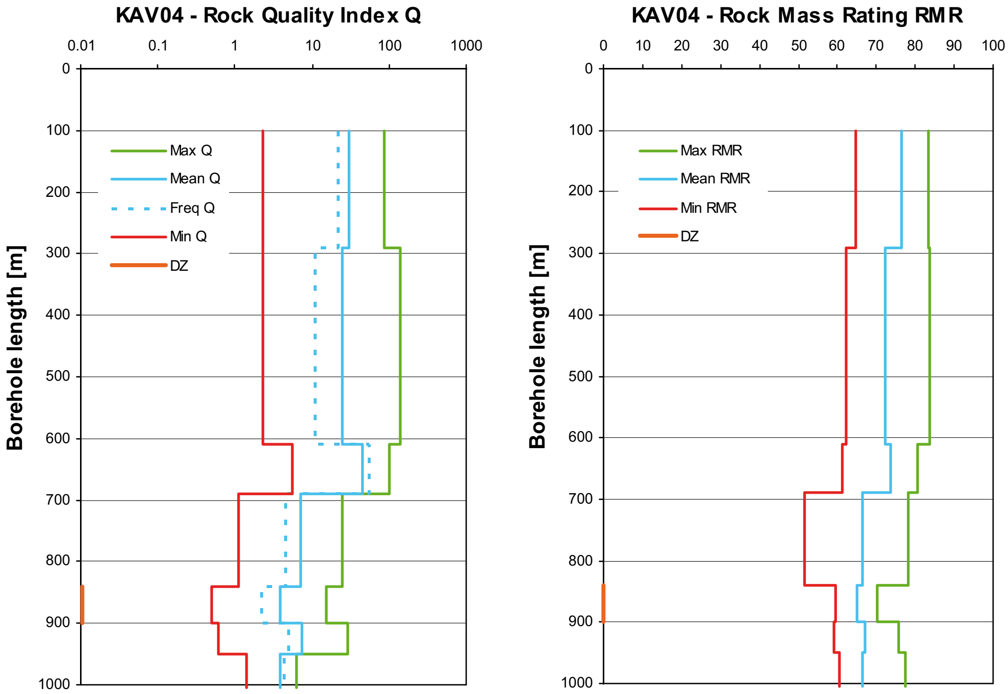

Figure 2-6. *Simpevarp Area: Variation of the Q and RMR with borehole lenght. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

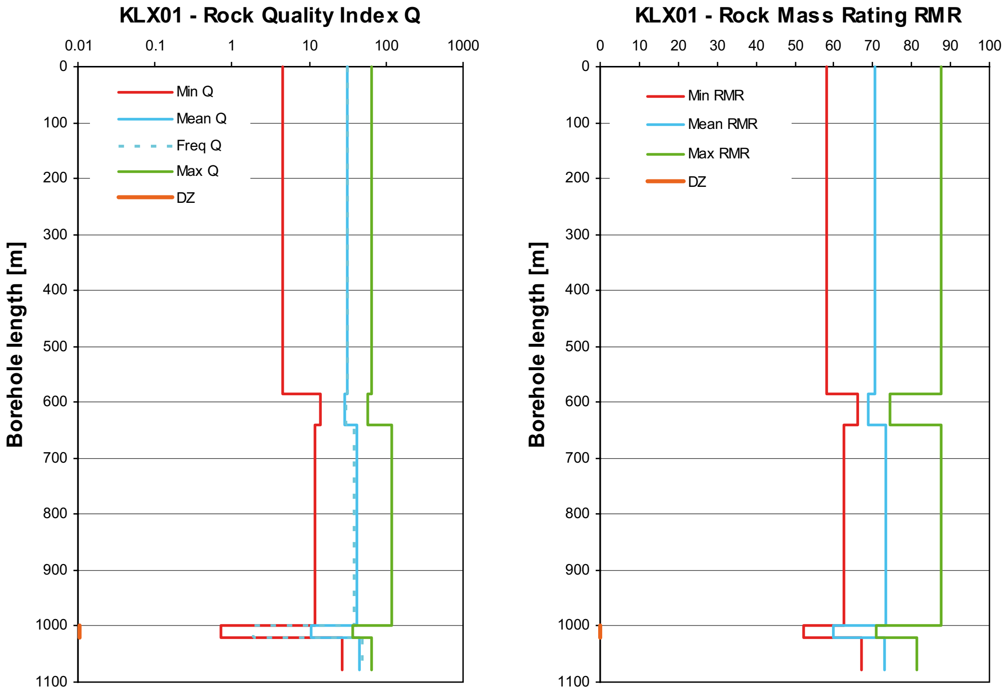

Figure 2-7. *Laxemar Area: Variation of the Q and RMR with borehole length. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

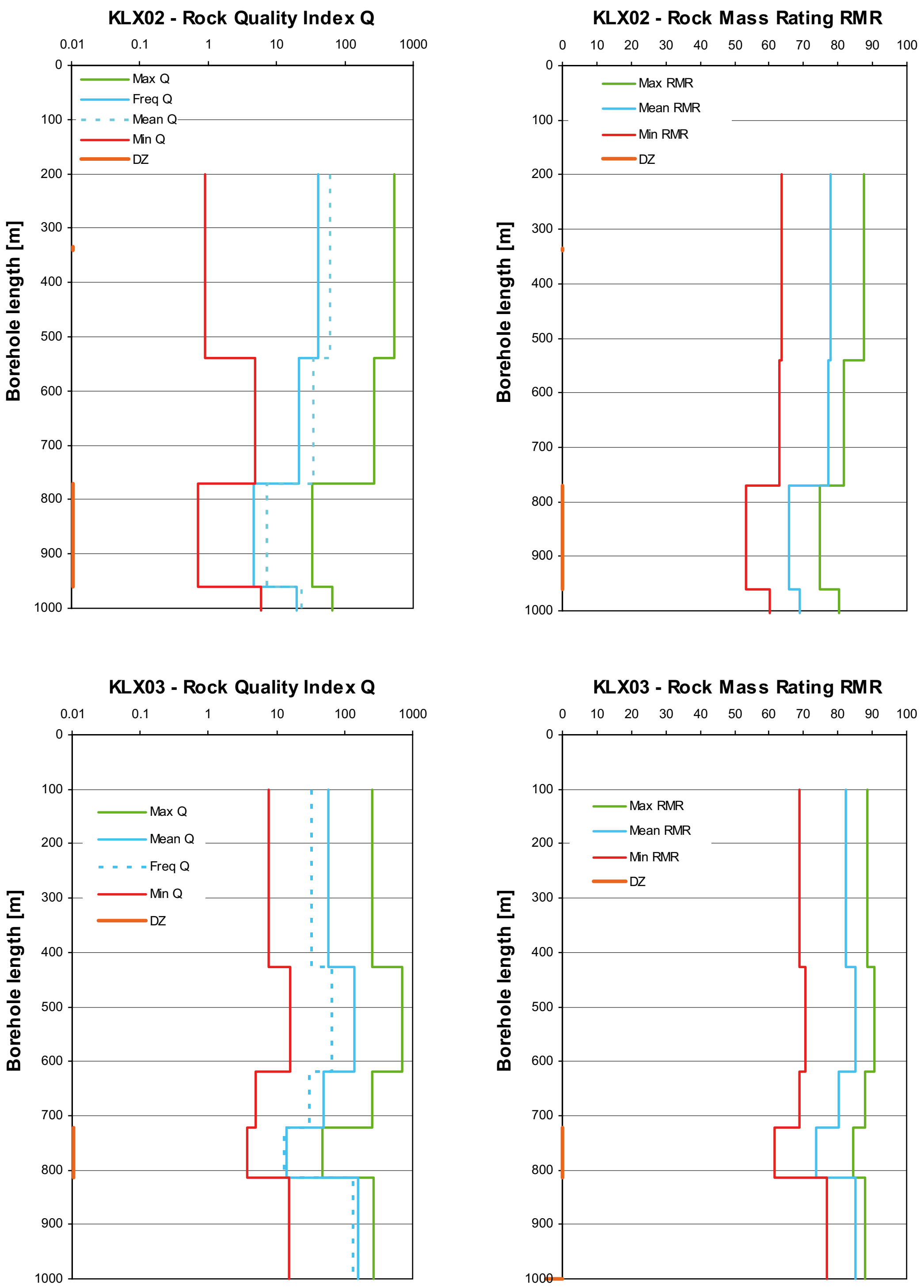

Figure 2-8. *Laxemar Area: Variation of the Q and RMR with borehole length. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

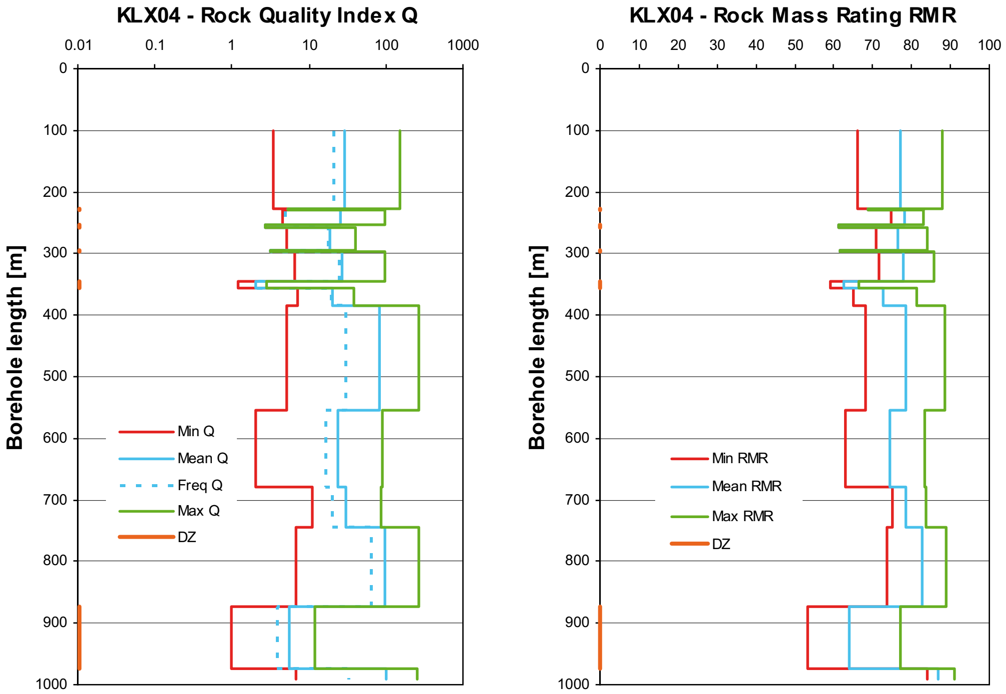

Figure 2-9. *Laxemar Area: Variation of the Q and RMR with borehole length. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

2.3 Rock Mechanics properties of the rock mass

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 induces a change of the rock stresses, thus, a change 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.

In this section, the mechanical properties derived from RMR and GSI are compared for all boreholes at Simpevarp and at Laxemar, respectively.

2.3.1 Average properties

Simpevarp Area

Figure 2-10 shows the comparison between the average deformation modulus of the competent rock and deformation zones for all the boreholes. Generally, the boreholes in Simpevarp and Ävrö (KSH01AB, KSH02, KSH03, KAV01 and KAV04) show a variation of deformation modulus between 20% and 40% for both the competent and fractured rock. The deformation zones in KSH03 present the lowest deformation modulus.

Figure 2-11 compares the uniaxial compressive strength of the rock mass estimated by RMR/GSI and the Hoek & Brown's Criterion of the competent and fractured rock. In terms of strength, the boreholes in Simpevarp and Ävrö are rather consistent. As expected, the lowest uniaxial compressive strength is attributed to the deformation zones in KSH03A.

Figure 2-12 shows the average apparent friction angle for the competent and fractured rock, respectively. The friction angle for a confinement pressure between 10 and 30 MPa varies between 39° and 45° for the competent rock, and between 37° and 42° for the deformation zones. The highest friction angles are estimated for the competent rock and the deformation zones in borehole KSH01AB. This can be explained by the fact that the intact rock in KSH01AB is dominated by Ävrö granite and monzodiorite (Rock Domain C, SKB code 501044 and 501036), which have a rather high friction angle (59.5°). The friction angle is lowest for KSH02 both for competent and fractured rock. In fact, the dominant rock type in this borehole is fine-grained dioritoid (Rock Domain B, SKB code 501030), 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.

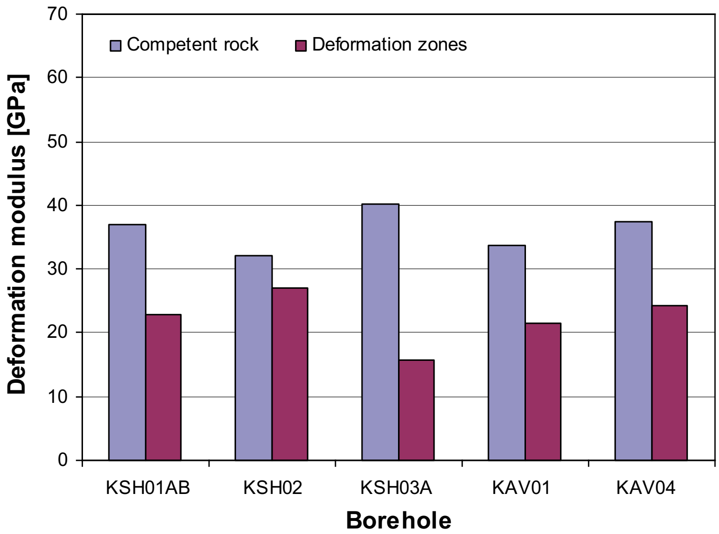

Figure 2-10. *Simpevarp Area: Mean deformation modulus of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.*

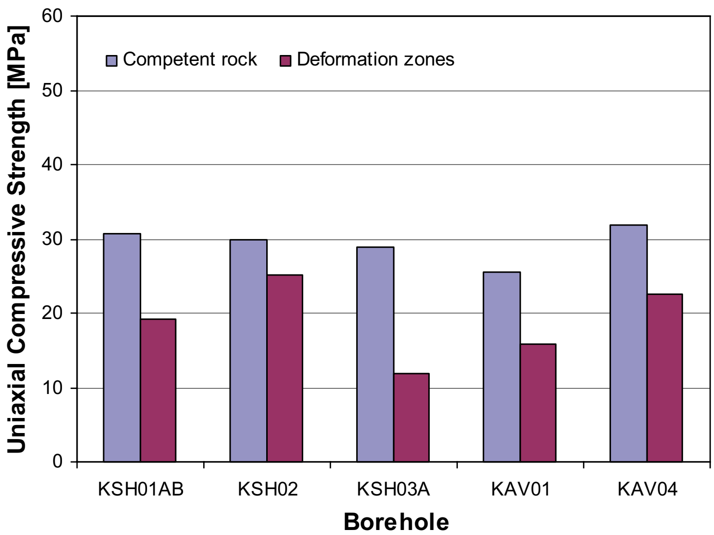

Figure 2-11. *Simpevarp Area: Mean uniaxial compressive strength of the rock mass according to Hoek and Brown's Criterion for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.*

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 2-13). The lowest cohesion is estimated for the deformation zones in KSH03A (14.5 MPa).

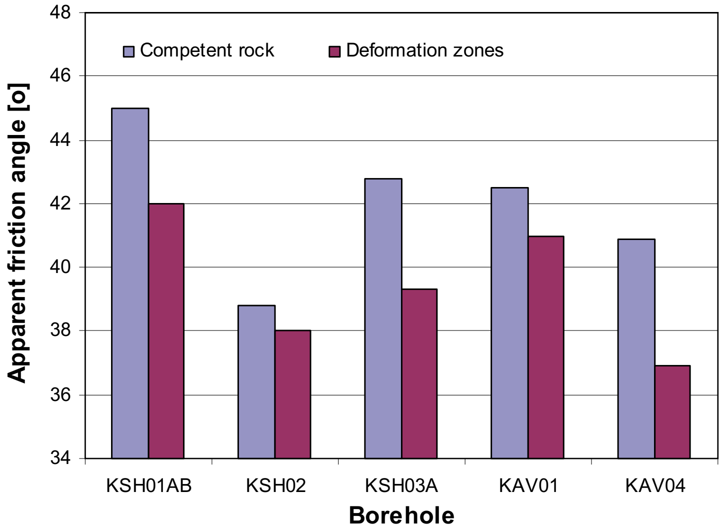

Figure 2-12. *Simpevarp Area: Mean apparent friction angle of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.*

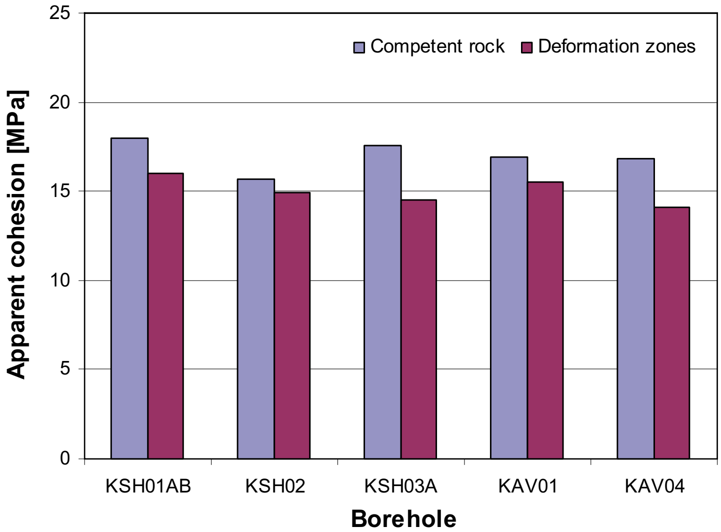

Figure 2-13. *Simpevarp Area: Mean apparent cohesion of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.*

Laxemar Area

Figure 2-14 shows the comparison between the average deformation modulus of the competent rock and deformation zones for borehole KLX01, KLX02, KLX03 and KLX04. The rock mass at Laxemar is less homogeneous than that at Simpevarp. However, the competent rock at Laxemar has a higher deformation modulus than at Simpevarp, ranging between 38 and 65 GPa. The deformation zones in all boreholes except KLX03 present very similar parameters to the deformation zones at Simpevarp. KLX01 exhibits the lowest average deformation modulus of all the boreholes at Laxemar. The deformation modulus of this borehole does not differ from the values reported at Simpevarp.

Figure 2-15 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. The same comments as for Figure 2-10 apply here.

Figure 2-16 shows the average apparent friction angle for the competent and fractured rock. For that concerning the friction angle and cohesion, the cohesion and friction angle are rather homogenous at Laxemar, differently than for the deformation modulus and uniaxial compressive strength. The friction angle for a confinement pressure between 10 and 30 MPa varies between 42° and 45° for the competent rock and between 38° and 43° for the deformation zones. The deformation zones in KLX03 seem to have higher strength than the deformation zones in the other boreholes at Laxemar.

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 2-17). The lowest cohesion is estimated for the deformation zone in KLX04 (14.9 MPa).

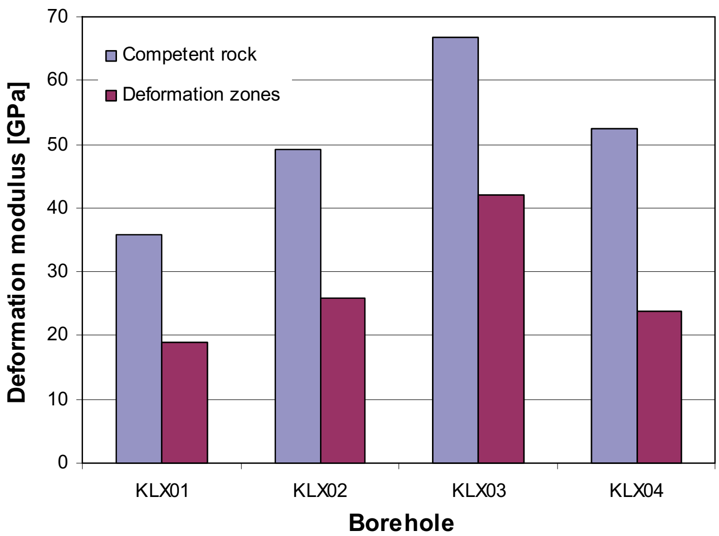

Figure 2-14. *Laxemar Area: Mean deformation modulus of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.*

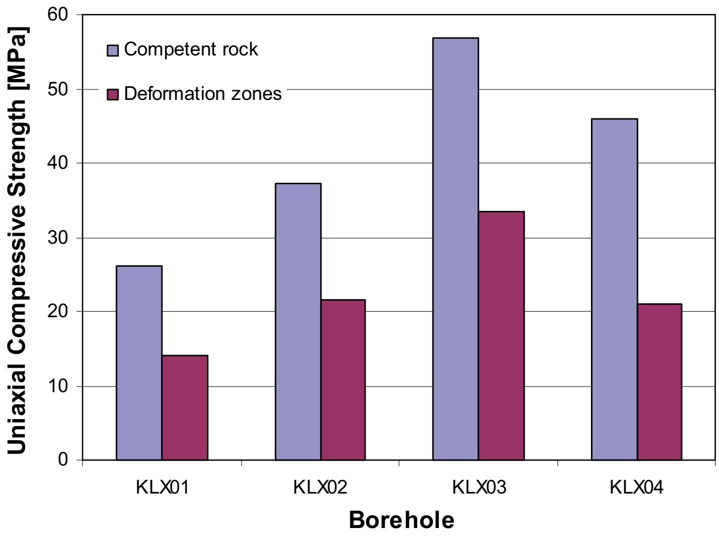

Figure 2-15. Laxemar Area: Mean uniaxial compressive strength of the rock mass according to Hoek and Brown's Criterion for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively.

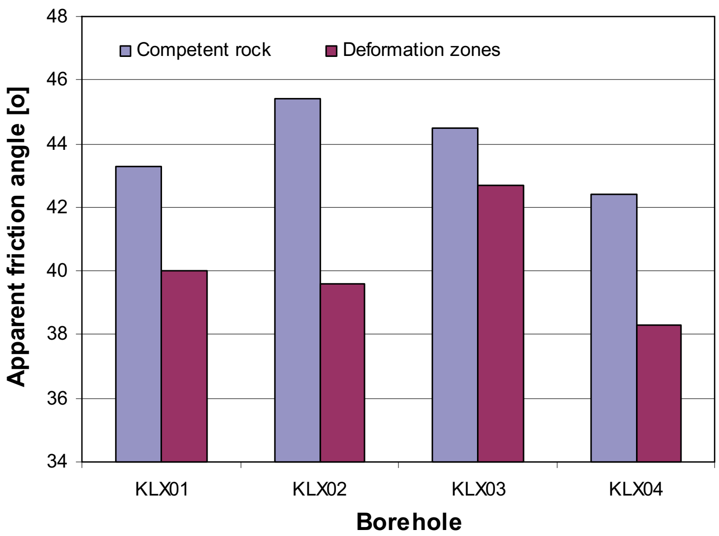

Figure 2-16. Laxemar Area: Mean apparent friction angle of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.

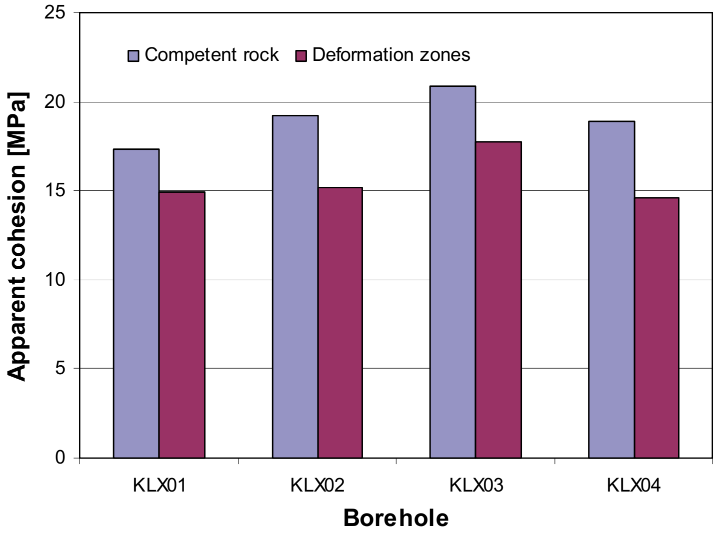

Figure 2-17. *Laxemar Area: Mean apparent cohesion of the rock mass for the analysed boreholes. The average values for competent rock and deformation zones are shown, respectively. The confinement stress is between 10 and 30 MPa.*

2.3.2 Variation along the boreholes

The graphs in the following sections 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.

Simpevarp Area

When analysing the variation of the parameters along the boreholes, a weak increase with depth can be observed for KSH01AB, KSH02 and KSH03A. For borehole KAV01 and KAV04, on the other hand, the mechanical properties of the rock mass even seem to decrease with depth because of the presence of deep deformation zones. These deformation zones extend between 60 and 180 m along the boreholes.

Figure 2-18 through Figure 2-22 show the variation of the equivalent deformation modulus, uniaxial compressive strength (according to the Hoek & Brown's Criterion), apparent cohesion and friction angle (according to the Coulomb's Criterion) of the rock mass along borehole KSH01AB, KSH02, KSH03, KAV01 and KAV04, for each homogenous rock unit.

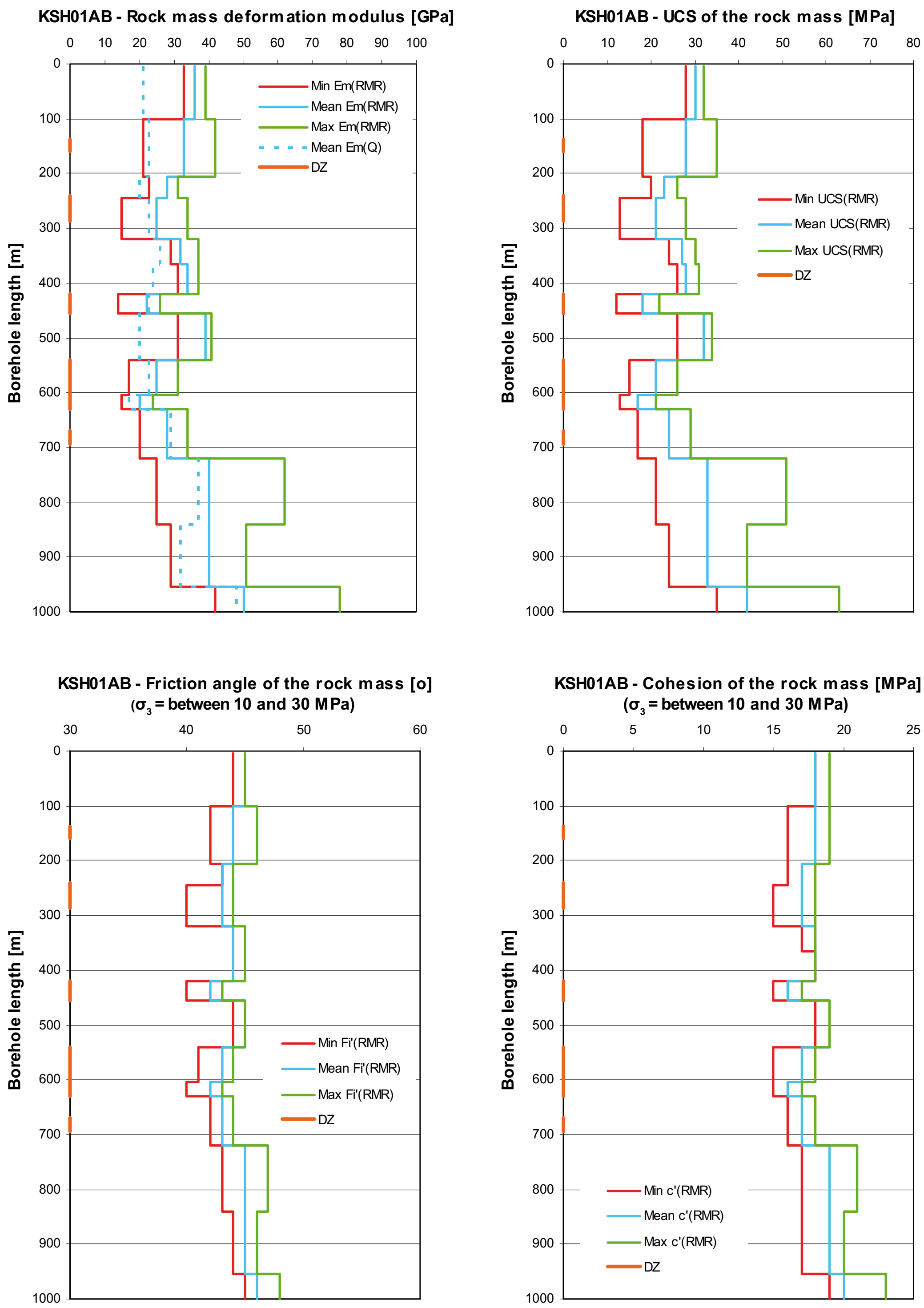

Figure 2-18. *KSH01AB: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

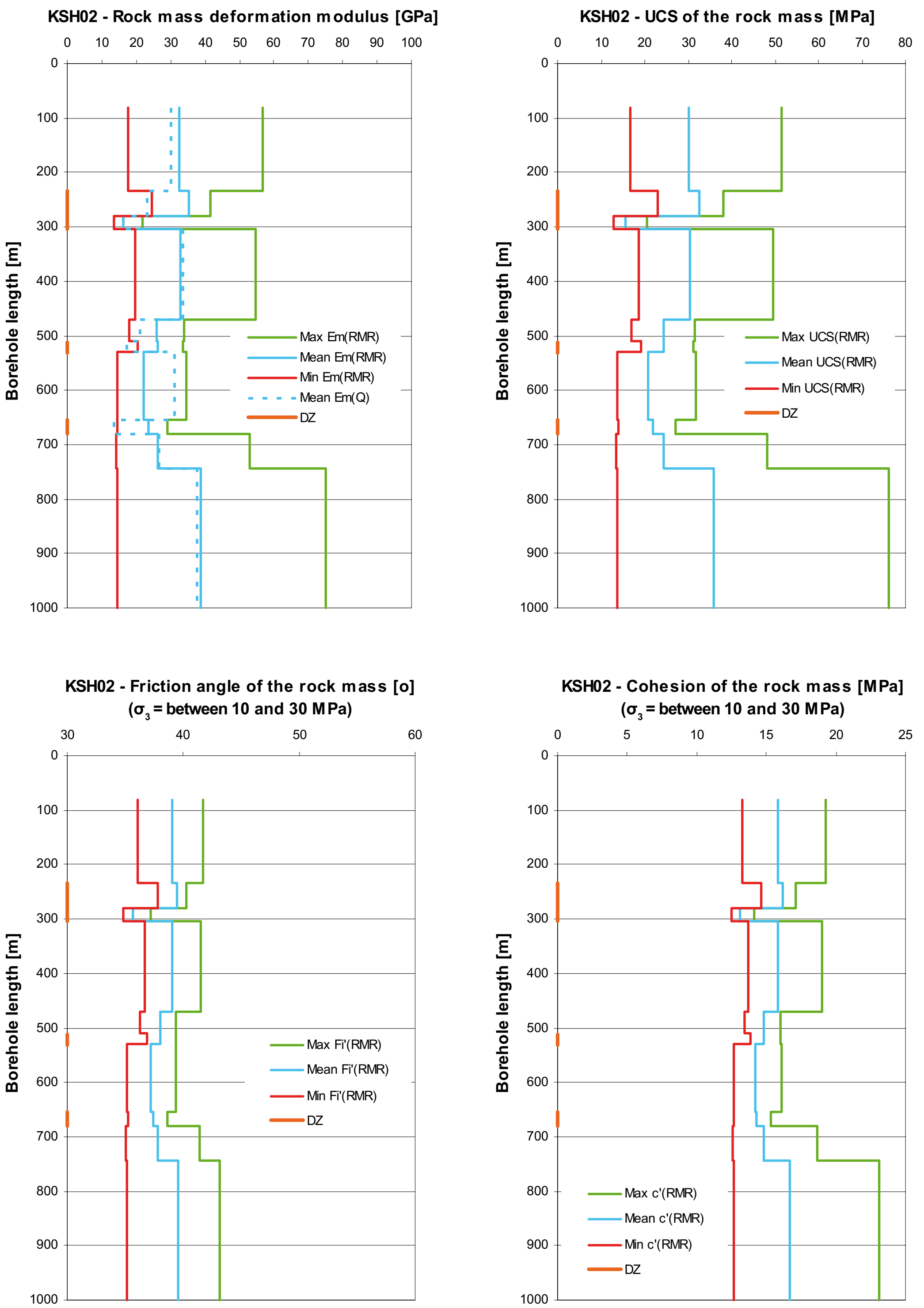

Figure 2-19. *KSH02: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

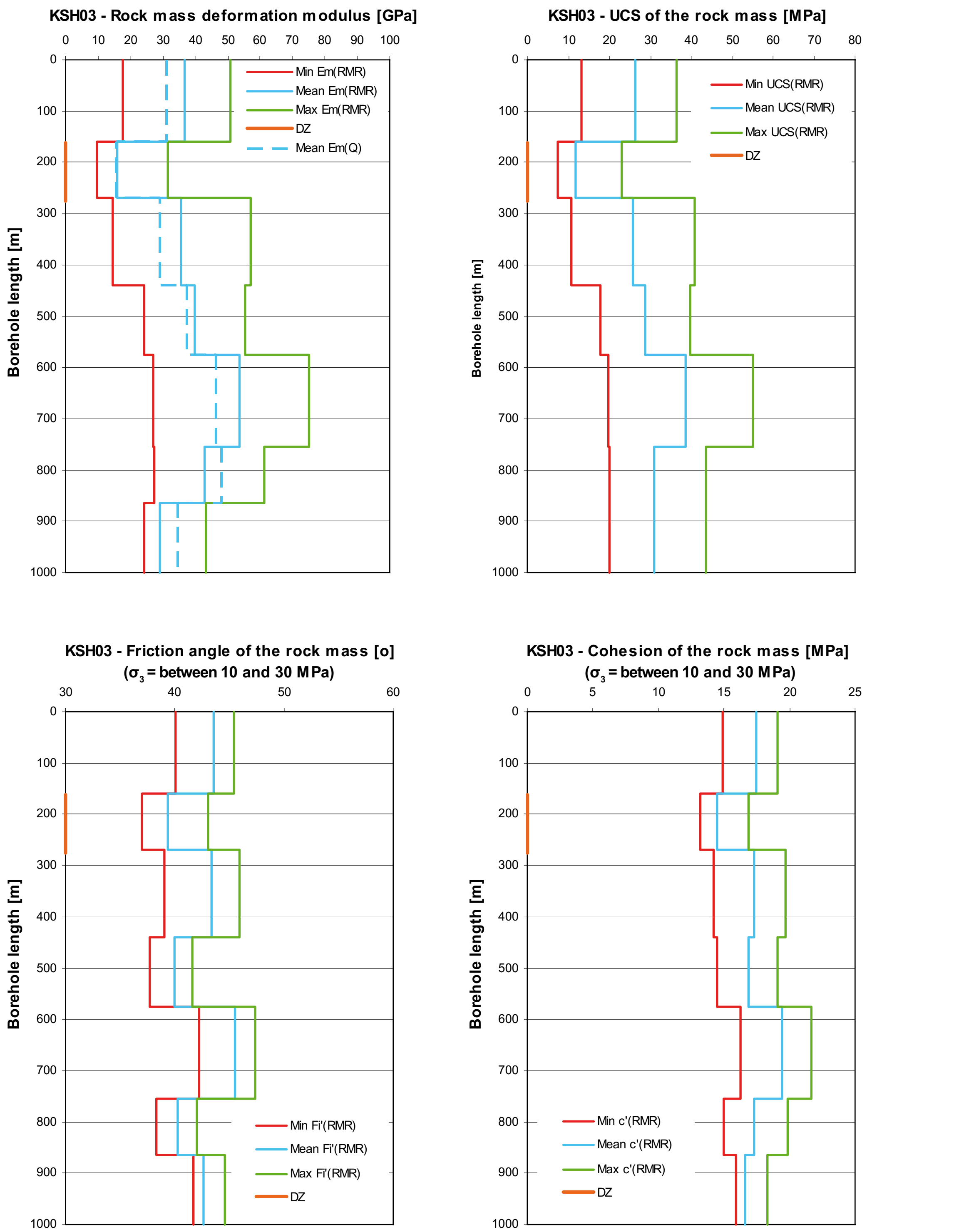

Figure 2-20. *KSH03A: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

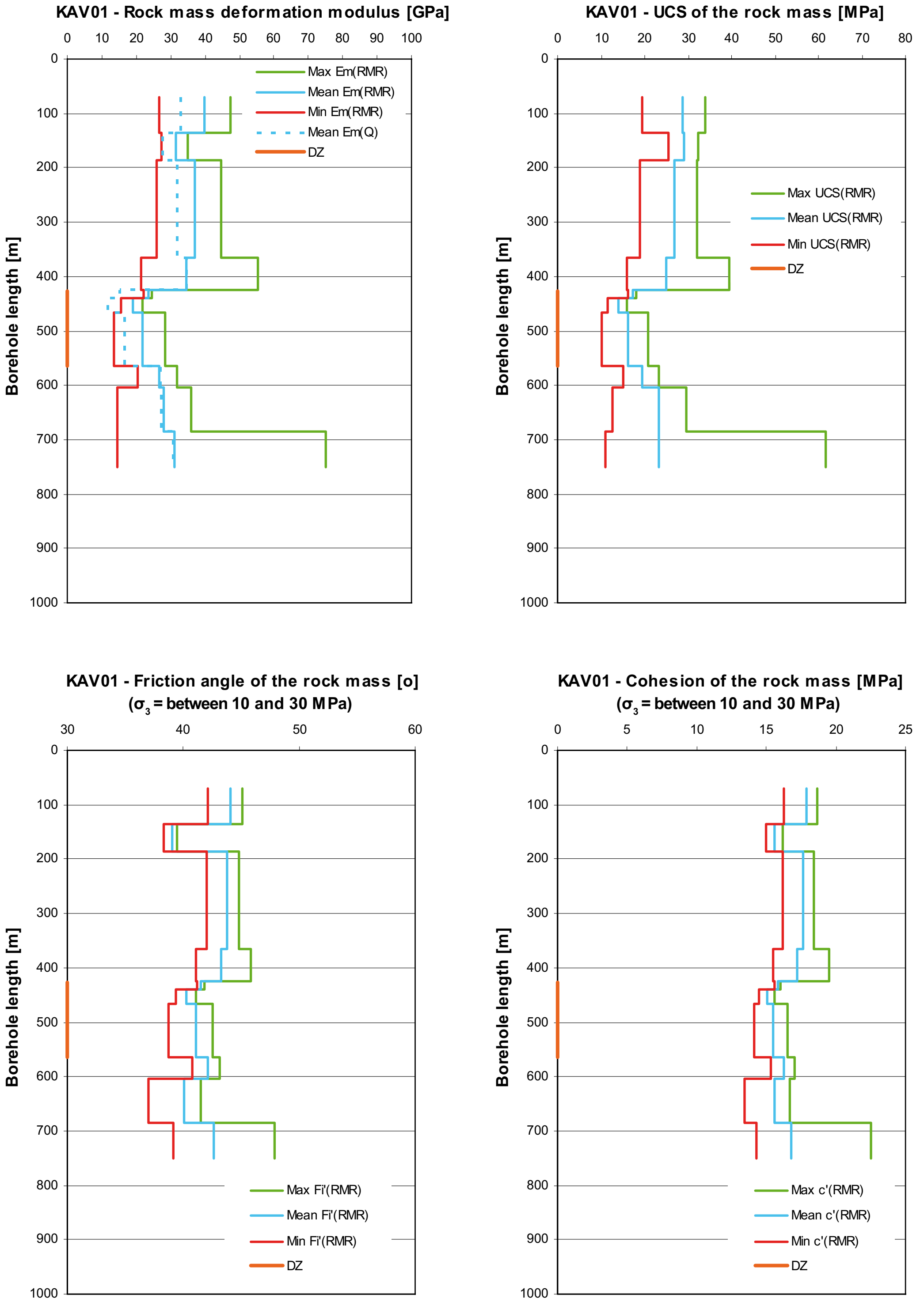

Figure 2-21. *KAV01: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

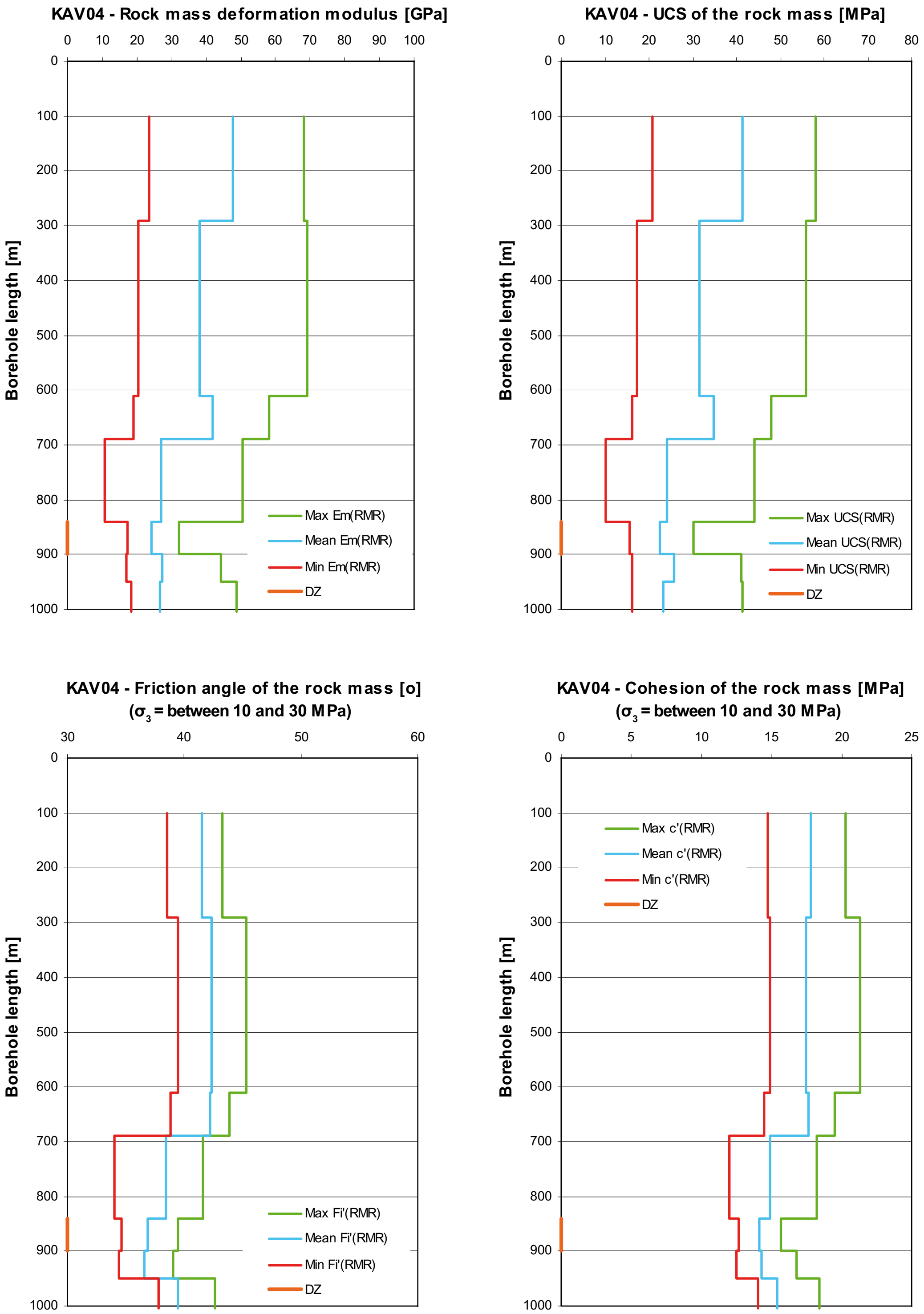

Figure 2-22. *KAV04: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

Laxemar Area

The boreholes in Laxemar, which are KLX01, KLX02, KLX03 and KLX04, show rather throughout homogeneous properties and do not show any marked variation with depth. On the other hand, all the boreholes are intercepted by deformation zones at depth, which are often preceded and followed by transition zones of higher fracture frequency.

Figure 2-23 through Figure 2-26 show the variation of the equivalent deformation modulus, uniaxial compressive strength (according to the Hoek & Brown's Criterion), apparent cohesion and friction angle (according to the Coulomb's Criterion) of the rock mass along the boreholes, for each homogenous rock unit.

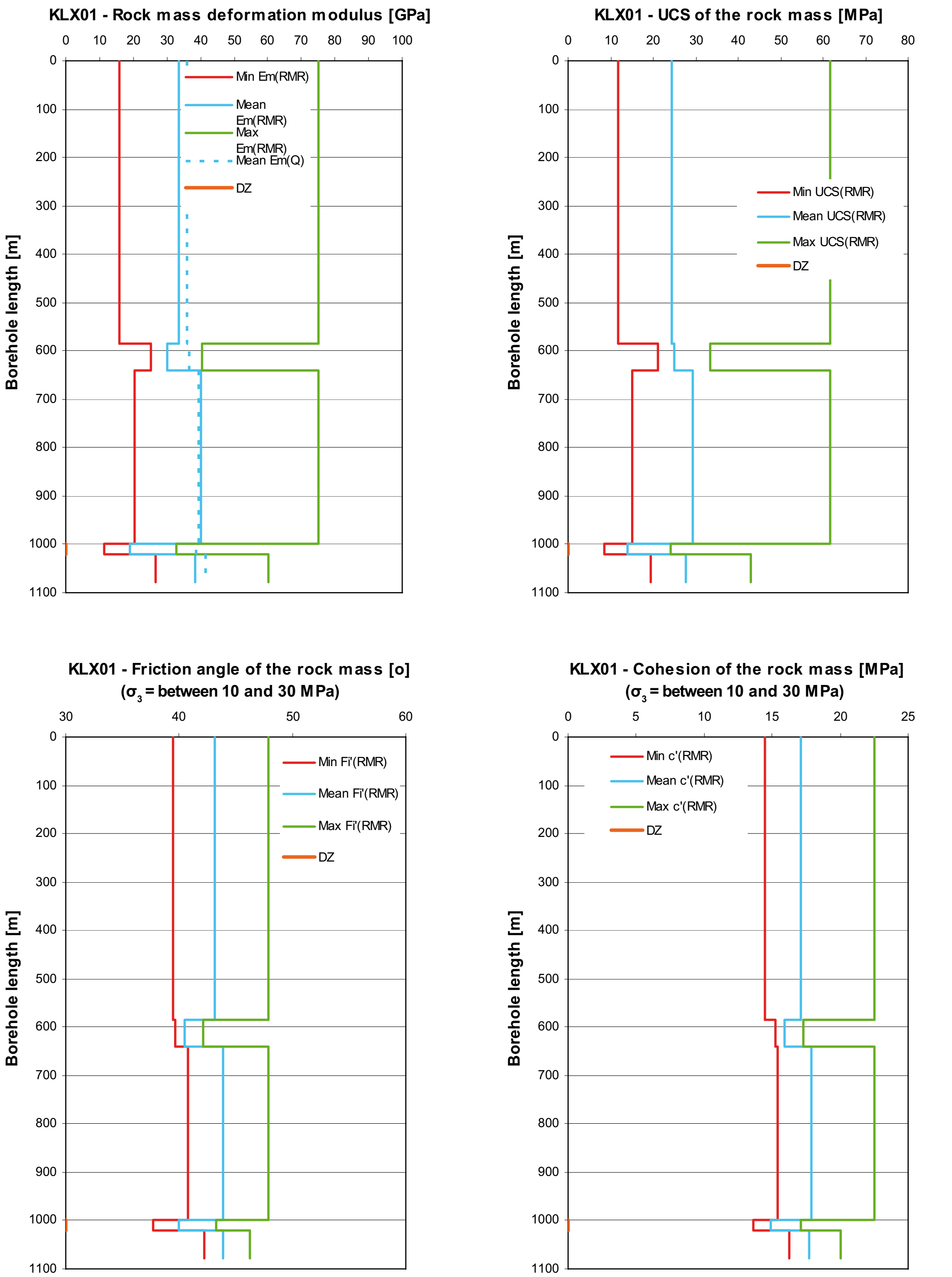

Figure 2-23. *KLX01: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

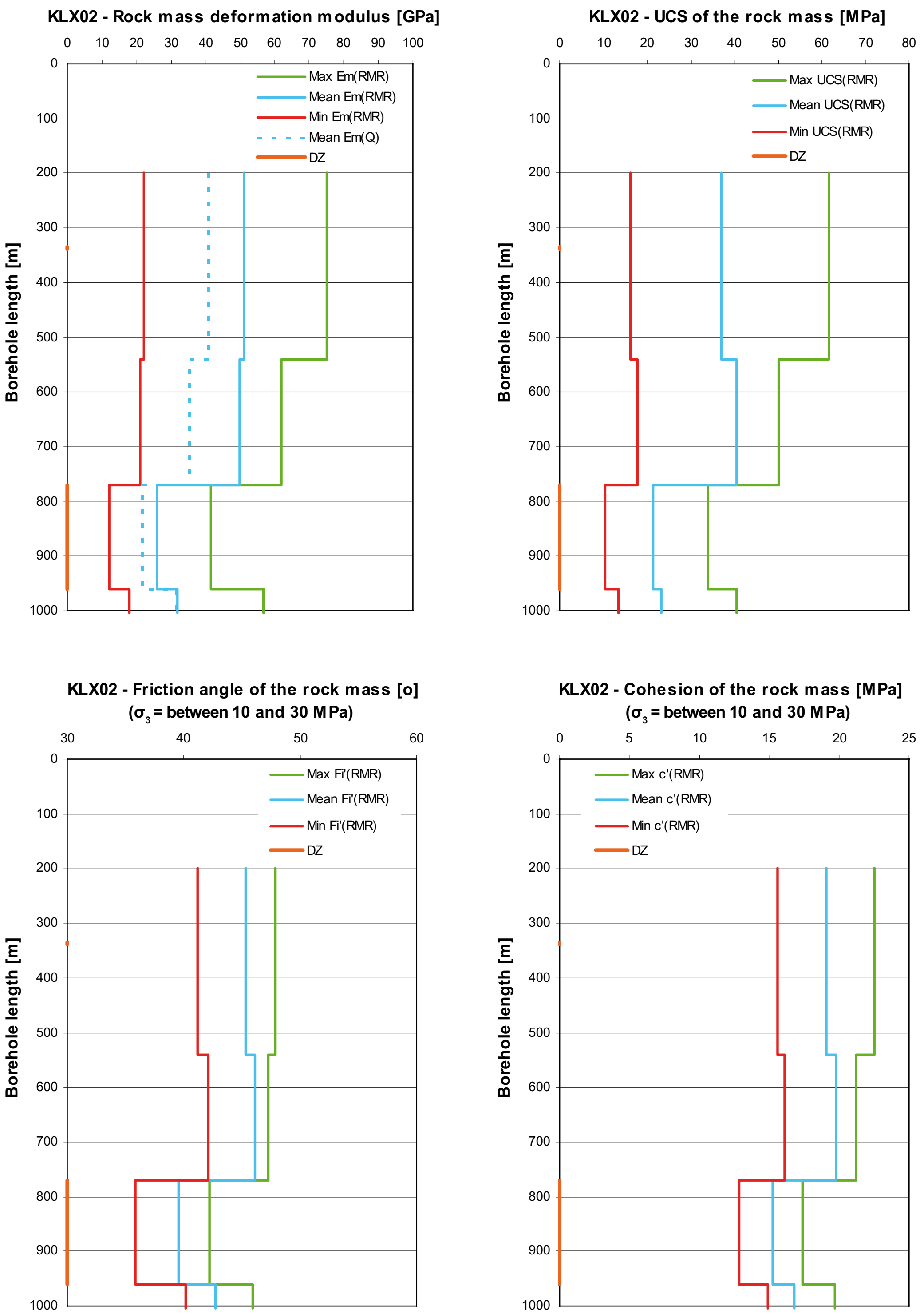

Figure 2-24. *KLX02: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

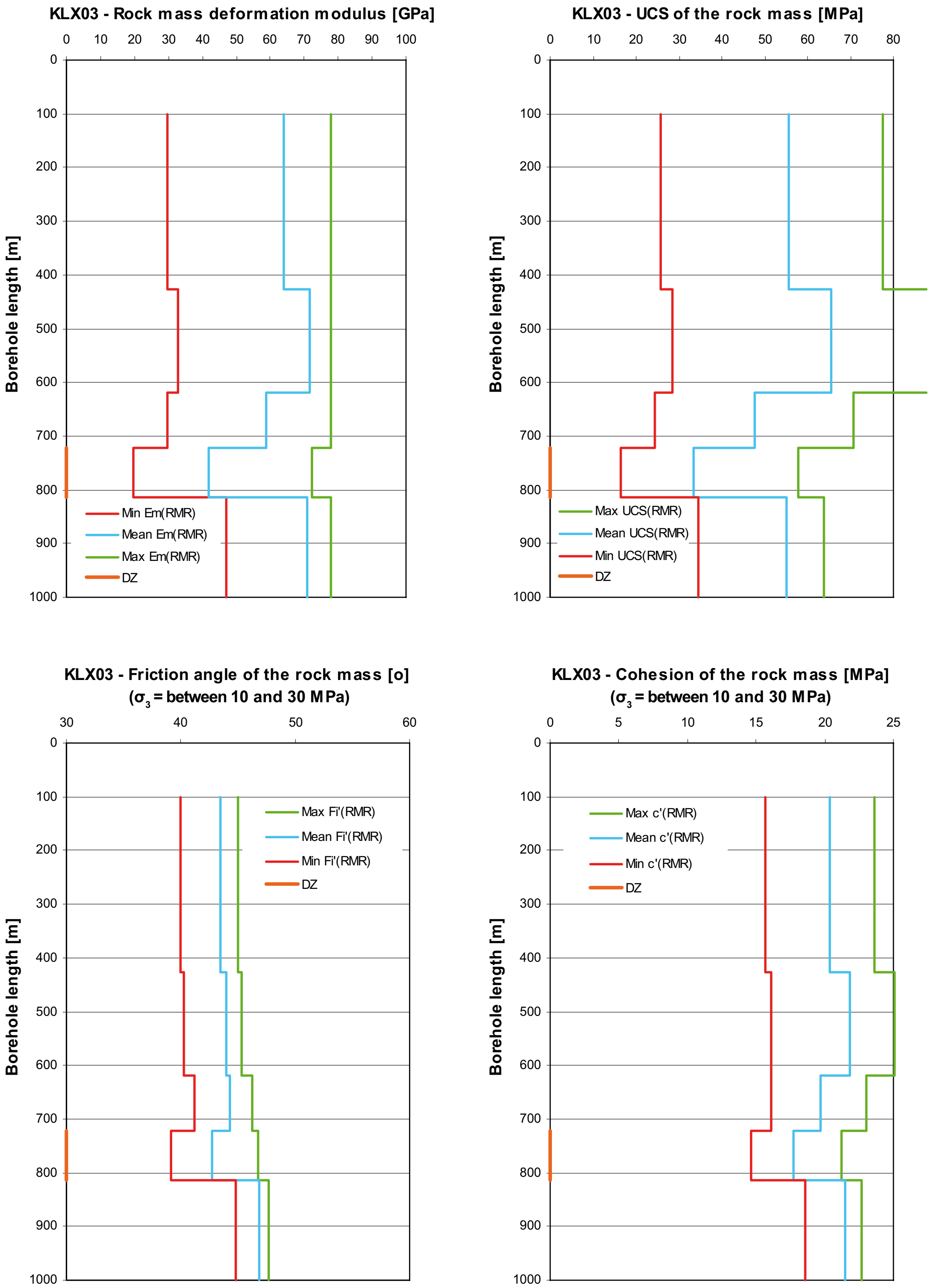

Figure 2-25. *KLX03: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

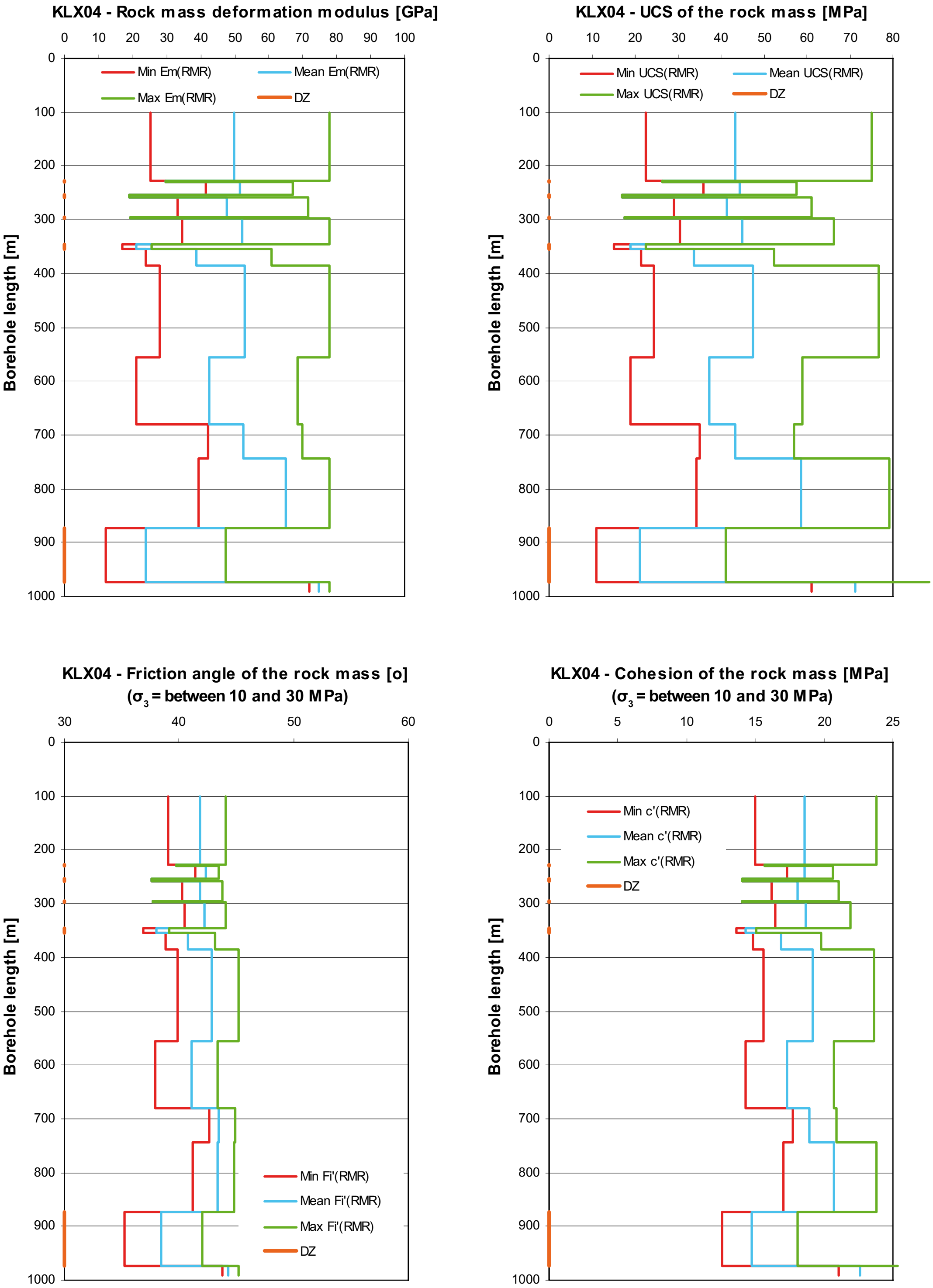

Figure 2-26. *KLX04: Variation of the deformation modulus, uniaxial compressive strength, friction angle and cohesion of the rock mass with depth, respectively. The minimum, mean and maximum values are shown for each rock unit in the geological "single-hole interpretation".*

3 Uncertainties

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 of the input data; ii) opinion of different operators performing the characterisation of 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 itself. For Q and RMR, the range of the possible minimum and maximum values 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 the variation of other mechanical properties (e.g. of the laboratory results).

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 $\Delta_{conf\ mean}$ of parameter P 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. The number n is also the number of values on which the mean can be calculated (on average) for each rock domain/deformation zone.

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 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 3-1. Here, the obtained confidence interval of the mean u– and u+ rigidly translate when the uncertainty of the mean value of the parameter are considered.

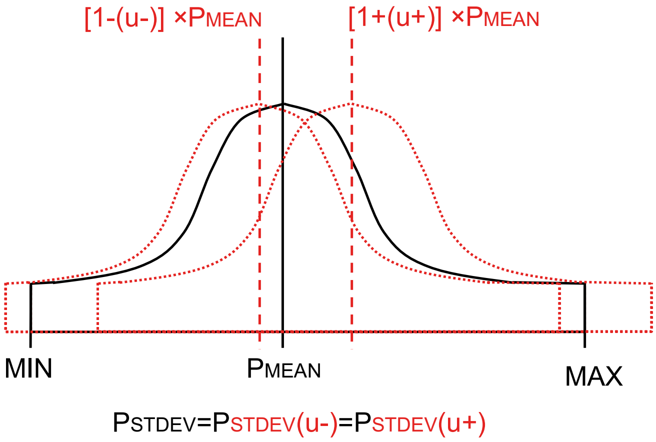

Figure 3-1. *Description of the statistical distribution and uncertainty of the Rock Mechanics parameters determined by means of the Empirical Approach.*

4 Rock Domains

In the following sections, summary tables with the Q and RMR values, and the derived properties of the rock mass are provided as for the rock mass assumed as an equivalent continuum inside the Rock Domains. 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 presented. The mechanical properties are summarised separately for all the boreholes on the Simpevarp Peninsula and Ävrö Island, and for the boreholes in the Laxemar Area.

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

4.1 Geological Model

The Rock Domains identified in the Regional and Local Model Volume of the Laxemar SDM version 1.2 are shown in Figure 2-1 /Wahlgren et al. 2005/. The analysed boreholes intercept six Rock Domain types in the Local Model, in particular (Table 2-1):

- RSMA in Ävrö granite are the most extensive,
- RSMB in fine-grained dioritoid are located exclusively at Simpevarp,
- RSMC composed by a mixture of Ävrö granite and quartz monzodiorite also appear only at Simpevarp,
- RSMD quartz monzonite to monzodiorite are typical of the southern Laxemar Area,
- RSMBA are a mixture of the rock types in the Rock Domains A and B and are included in the Rock Domains RSMM,
- RSMM are a narrow rock volume containing a large fraction of diorite and gabbro and is located on the southern Laxemar Area.

The geological "single-hole interpretation" of the borehole data identified the presence of a certain volume of rock mass (i.e. length along the boreholes) that potentially could be classed as deformation zones. This portion of the rock mass is referred to as "fractured rock" in the following sections. Not all this volume of rock was assigned to the Deterministic Deformation Zones described in Section 5.1. Thus, some potentially fractured rock volumes might be included in the Rock Domains according to Table 4-1. These volumes may range between 0% and 13% of the Rock Domain and are occupied by minor deformation zones, weaker rock volumes and swarms of fractures. The percentages in Table 4-1 are obtained from the borehole information, thus a certain bias due to the preferential vertical orientation of the boreholes cannot be avoided. Considering that the average inclination of the Deterministic Deformation zones intercepting the boreholes is about 70°, these percentages could be reduced to one half. This assumes that the fractured rock and minor deformation zones have the same orientation as the Deterministic Deformation Zones. However, this determination is only based on geological considerations and does not take into account the strength and deformability of the rock mass. A Rock Mechanics evaluation will be carried out in the following sections about "minor deformation zones" inside the Rock Domains.

Table 4-1. Percentage in length of competent and fractured rock belonging to the Rock Domains according to the single-hole interpretation. The rock mass in the Deformation Zone Model is excluded.

Rock Domain	% length of the boreholes	
	Competent rock	Fractured rock
RSMA Simpevarp	100%	0%
RSMB Simpevarp	87%	13%
RSMC Simpevarp	93%	7%
RSMA Laxemar	99%	1%
RSMBA Laxemar	96%	4%
RSMD Laxemar	92%	8%
RSMM Laxemar	89%	11%

4.2 Minor deformation zones in the Rock Domains

The figures in Table 4-1 refer to results of the geological single-hole interpretation of the boreholes. The fractured rock is estimated based on the geological indicators (e.g. ductile and/or brittle deformations, frequency of the sealed fractures, oxidization, foliation, weathering, migmatisation) for potential deformation zones in the Deformation Zone Model.

Besides the deterministic deformation zones, the single-hole interpretation also includes fractured rock that not necessarily can be classified as deformation zones from a Rock Mechanics point of view. The analysis of the Deterministic Deformation Zones provides thresholds of Q and RMR that characterize the zones. Equation (5) provides the "signature" of the zones to which all rock volumes with Q and/or RMR lower than certain values (respectively 4 and 60) are assigned. By applying Equation (5) to Q and RMR obtained for the nine boreholes included in this empirical characterisation exercise, Figure 4-1 and Figure 4-2 are obtained. Equation (5) seems to identify the core of the deterministic deformation zones intercepted by the boreholes. Furthermore, a series of minor features are also highlighted by Equation (5) that usually do not extend longer than 5–10 m along the boreholes. According to Section 5.3, these sections of borehole can allocate minor deformation zones about 200 m or longer.

In Table 4-2, the same results shown in Figure 4-1 and Figure 4-2 are also summarised in numbers. This table lists the percentage in length of the minor deformation zones within each Rock Domain, where the Deterministic Deformation Zones are excluded. The results provided by the Q and RMR system do not completely coincide with each other but show the same trend. An estimation of the extension of the minor deformation zones in the Rock Domains could be considered ranging between the lower and upper values obtained in Table 4-2.

Table 4-2 can also be compared with the results of the single-hole interpretation in Table 4-1. The relative differences between the Rock Domains are almost the same in the two tables, where the Rock Domains at Simpevarp show larger percentage of fractured rock than the Rock Domains at Laxemar. However, the results for the Rock Domains at Simpevarp are very close to each other differently than for the results for the Rock Domains at Laxemar. This is probably due to the fact that the Simpevarp Area has, at this stage of the modelling, reached a higher level of completion than the Laxemar Area. Thus, it can be expected that as soon as new borehole information from Laxemar will be collected, the amount of "fractured rock" in Laxemar's Rock Domains would probably diminish on consequence of the identification of new deterministic deformation zones. In fact, a larger amount of information might sometimes lead to the recognition of geological features that could not be identified before. In other words, the level of detail of the Site Descriptive Model increases together with the amount of available new information.

Even the percentages in Table 4-2 could be reduced by half considering the fact the deformation zones are often rather steep and have long intersections with the boreholes, as already commented on in Section 4.1 and 5.2.

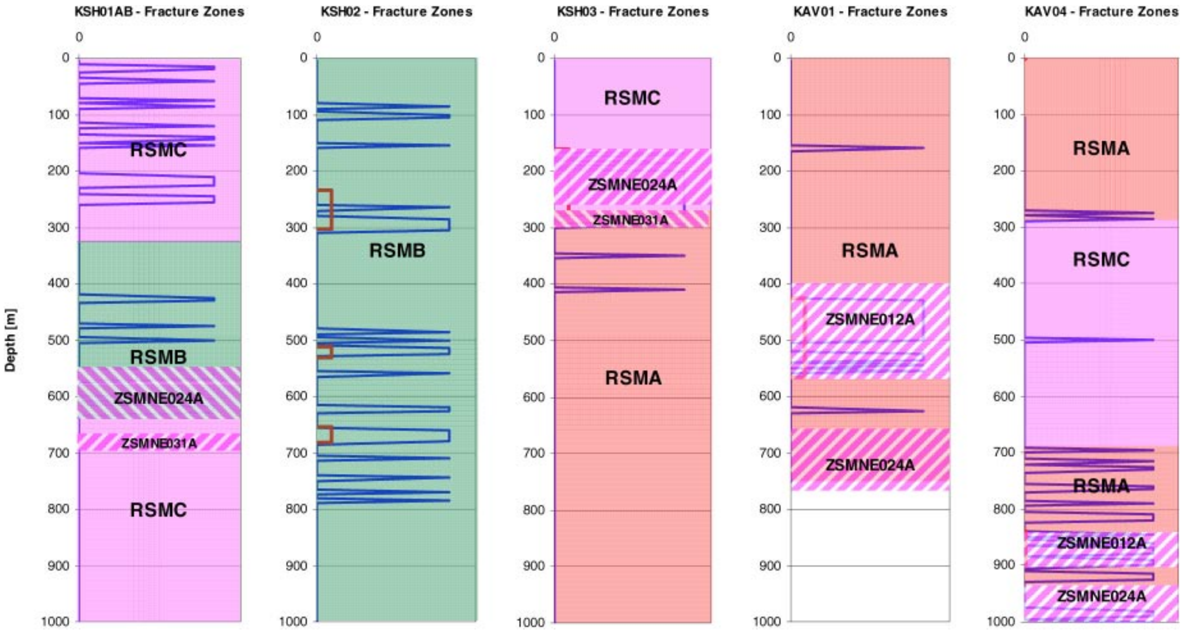

Figure 4-1. *Boreholes in the Simpevarp Subarea (Laxemar Model version 1.2): deterministic and minor deformation zones identified by means of Equation (5) (blue line) and by the Deformation Zone Model (raster areas). The Rock Domains with theirs names are are marked with different colours. The fractured zones indicated by the geological single-hole interpretation are also shown in orange colour.*

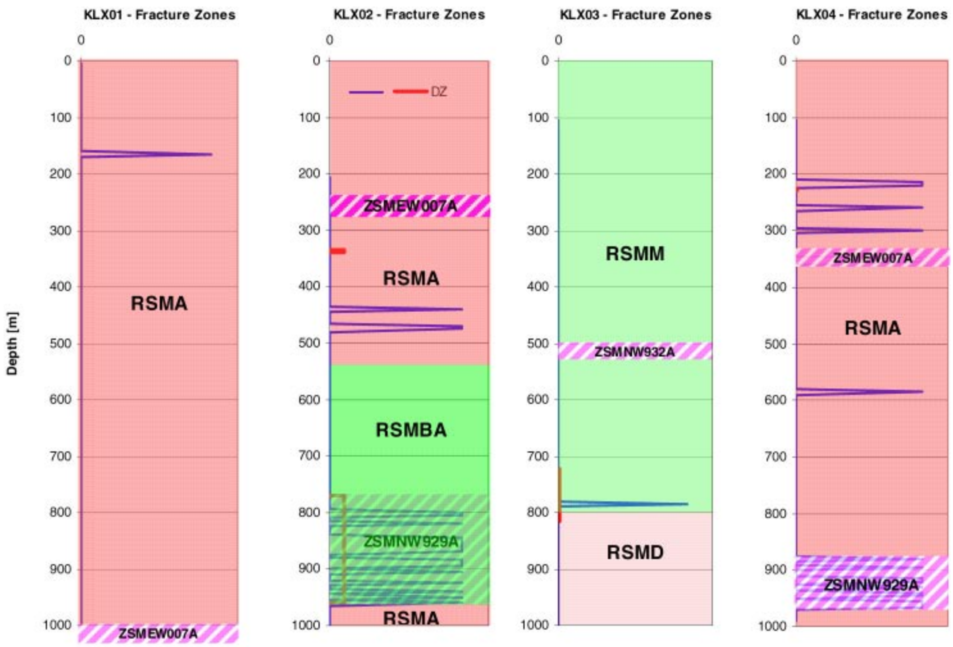

Figure 4-2. *Boreholes in the Laxemar Subarea (Laxemar SDM version 1.2): deterministic and minor deformation zones identified by means of Equation (5) (blue line) and by the Deformation Zone Model (raster area). The Rock Domains with theirs names are marked with different colours. The fractured zones indicated by the geological single-hole interpretation are also shown in orange colour.*

Table 4-2. Percentage in length of minor deformation zones identified by Equation (5) in the Rock Domains of the Laxemar SDM version 1.2. The Deterministic Deformation Zones are excluded.

Rock Domain	Minor deformation zones – % in length of the boreholes	
	Based on Q values	Based on RMR values
RSMA Simpevarp	7%	1%
RSMB Simpevarp	11%	7%
RSMC Simpevarp	8%	1%
RSMA Laxemar	2%	0%
RSMBA Laxemar	0%	0%
RSMD Laxemar	0%	0%
RSMM Laxemar	1%	0%

4.3 Rock Quality Index (Q)

Table 4-3 shows that the average rock mass quality according to the Q-system is in the class "good rock" for all Rock Domains. However, the Rock Domains at Laxemar seem to have slightly higher quality than the Rock Domains at Simpevarp. The fractured rock in the Domains has poorer quality ("fair rock") than the competent rock.

The uncertainty of the determination of the mean value of Q is summarised in Table 4-4 for the competent and fractured in the Rock Domains. 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 –4% while the upper boundary is about +15%. The uncertainty on the quality of the fractured rock is much larger due to the larger variability of the geological parameters and the smaller available data set.

Table 4-3. Q values for the competent and fractured rock mass in the Rock Domains in the Laxemar SDM version 1.2.

Q [–]	Competent rock			Fractured rock		
Rock Domain	Min	Mean [most freq.]	Max	Min	Mean [most freq.]	Max
RSMA Simpevarp	0.6	34.3 [22.0]	264	–	–	–
RSMB Simpevarp	1.5	22.6 [12.9]	352	0.5	4.90 [3.1]	20.4
RSMC Simpevarp	2.3	26.6 [12.1]	352	0.9	6.0 [4.7]	22.4
RSMA Laxemar	0.9	44.7 [30.5]	528	2.7	3.7 [3.1]	5.4
RSMBA Laxemar	4.9	34.1 [21.2]	264	–	–	–
RSMD Laxemar	15.5	155.5 [132.0]	264	14.2	31.4 [32.7]	47.4
RSMM Laxemar	5.0	81.8 [34.1]	704	3.7	10.7 [9.4]	19.4

The values within brackets are the most frequent Q.

Table 4-4. Uncertainty of the mean Q for the competent and fractured (stochastic and/or deterministic deformation zones) rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean Q value itself.

Uncertainty of the mean as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain	Min	Max	Min	Max
RSMA Simpevarp	–3%	+11%	–	–
RSMB Simpevarp	–4%	+15%	–15%	+83%
RSMC Simpevarp	–3%	+15%	–15%	+60%
RSMA Laxemar	–3%	+15%	–53%	+191%
RSMBA Laxemar	–7%	+24%	–	–
RSMD Laxemar	–3%	+1%	–45%	+111%
RSMM Laxemar	–2%	+2%	–21%	+87%

* The Q system spans over several order of magnitude.

4.4 Rock Mass Rating (RMR)

RMR shows that the rock quality in Rock Domain RSMA does not vary much between the Simpevarp and the Laxemar Site. The other Rock Domains in Laxemar have better quality than RSMA. The same pattern can also be observed for the properties of the fractured rock in the Rock Domains. The uncertainty on the determination of RMR for the competent rock is very low (about ± 2%), while the uncertainty for the fractured rock is much higher (about ± 10%). 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".

Table 4-5. RMR values of the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

RMR [–]	Competent rock			Fractured rock		
Rock Domain	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA Simpevarp	51.4	72.6/5.6	85.7	–	–	–
RSMB Simpevarp	56.0	69.8/5.7	87.2	55.4	65.5/5.8	74.7
RSMC Simpevarp	59.9	72.4/4.7	85.6	57.5	64.5/3.2	70.0
RSMA Laxemar	58.0	74.8/6.4	90.9	61.2	63.9/4.4	69.0
RSMBA Laxemar	63.1	77.3/5.0	81.7	–	–	–
RSMD Laxemar	76.9	85.0/3.3	87.9	78.5	80.8/2.9	84.1
RSMM Laxemar	69.9	82.8/4.8	90.8	61.7	72.4/6.5	84.4

Table 4-6. Uncertainty of the mean RMR for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean RMR value itself.

Uncertainty of the mean RMR as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain	**Min**	**Max**	**Min**	**Max**
RSMA Simpevarp	–1%	+1%	–	–
RSMB Simpevarp	–2%	+1%	–5%	+5%
RSMC Simpevarp	–1%	+1%	–6%	+6%
RSMA Laxemar	–1%	+1%	–23%	+17%
RSMBA Laxemar	–3%	+1%	–	–
RSMD Laxemar	–2%	+0%	–14%	+3%
RSMM Laxemar	–2%	+0%	–6%	+4%

4.5 Deformation modulus of the rock mass

The equivalent deformation modulus of the rock mass determined by the RMR empirical method applies for low confinement stress (between 1 and 2 MPa). In Table 4-7, the minimum, maximum, mean deformation modulus and its standard deviation are summarised for the competent and fractured rock mass in the Rock Domains. 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 75–78 GPa. The mean deformation modulus of the competent rock for Rock Domain RSMD and RSMM at Laxemar is highest (about 66–71 GPa). Lower values are observed for the Rock Domains at Simpevarp and Ävrö (around 33–39 GPa). The lowest mean deformation modulus at Laxemar occurs in Rock Domain RSMA, which is, however, about 11% larger than for the same Rock Domain at Simpevarp. RSMBA has deformation modulus slightly higher than RSMA at Laxemar. The fractured rock inside the Rock Domains RSMA, RSMB and RSMC has an average deformation modulus between 23 and 26 GPa, which is between 18% and 47% lower than the deformation modulus for the competent rock. This difference is largest for RSMA at Laxemar.

Table 4-8 contains the uncertainty determination for the mean deformation modulus. For the competent rock, the uncertainty on the average values does not vary more than ± 4%. For the fractured rock, instead, the uncertainty varies from Rock Domain to Rock Domain, and is on average ± 35% of the mean value of the deformation modulus.

Table 4-7. Predicted deformation modulus E_m values of the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2 (low confinement).

E_m [GPa]	Competent rock			Fractured rock		
Rock Domain	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA Simpevarp	10.8	38.6/12.6	75.0*	–	–	–
RSMB Simpevarp	14.1	32.8/11.1	75.0*	13.6	25.7/8.3	41.4
RSMC Simpevarp	17.7	37.7/10.6	75.0*	15.4	23.5/4.2	31.6
RSMA Laxemar	15.9	43.9/15.7	78.0*	19.1	22.8/6.1	29.9
RSMBA Laxemar	21.2	49.9/12.2	61.9	–	–	–
RSMD Laxemar	47.0	70.9/9.0	78.0*	51.6	59.3/10.3	71.0
RSMM Laxemar	29.6	65.6/13.2	78.0*	19.6	38.8/15.3	72.3

* The maximum deformation modulus is assumed to coincide with the Young's modulus of the intact rock matrix that ranges between 75 and 78 GPa, depending on the dominant rock type.

Table 4-8. Uncertainty of the mean deformation modulus E_m of the rock mass for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean E_m value itself.

Uncertainty of the mean E_m as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain	Min	Max	Min	Max
RSMA Simpevarp	–3%	+5%	–	–
RSMB Simpevarp	–4%	+8%	–12%	+29%
RSMC Simpevarp	–4%	+5%	–14%	+33%
RSMA Laxemar	–3%	+4%	–44%	+115%
RSMBA Laxemar	–9%	+7%	–	–
RSMD Laxemar	–9%	+3%	–39%	+17%
RSMM Laxemar	–5%	+2%	–16%	+27%

Table 4-9. Predicted Poisson's ratio ν_m values of the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

ν_m [–]	Competent rock			Fractured rock		
Rock Domain	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA Simpevarp	0.03	0.12/0.04	0.24	–	–	–
RSMB Simpevarp	0.04	0.10/0.03	0.23	0.04	0.08/0.03	0.13
RSMC Simpevarp	0.06	0.12/0.03	0.25	0.05	0.08/0.01	0.10
RSMA Laxemar	0.05	0.13/0.04	0.24	0.05	0.06/0.02	0.08
RSMBA Laxemar	0.07	0.16/0.04	0.20	–	–	–
RSMD Laxemar	0.16	0.24/0.03	0.27	0.18	0.20/0.04	0.24
RSMM Laxemar	0.08	0.19/0.04	0.26	0.07	0.13/0.05	0.24

4.6 Poisson's ratio of the rock mass

The Poisson's ration of the competent and fractured rock is listed in Table 4-9. The mean Poisson's ratio varies, for the competent rock, between 0.10 and 0.24, and, for the fractured rock, around 0.10, respectively.

The uncertainties of the mean Poisson's ratio ν_m for the Rock Domains are similar to the uncertainties calculated for the rock mass deformation modulus E_m due to the way ν_m is calculated (see Table 4-8). In fact, the Poisson's ratio is directly obtained from the deformation modulus of the rock mass together with the Young's modulus and Poisson's ratio of the intact rock.

4.7 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 from RMR through GSI. The uniaxial compressive strength, which corresponds to a convex strength criterion, is independent on the confinement. This parameter does not coincide with the "apparent" compressive strength that can be obtained from the Coulomb's Strength Criterion (Section 4.8).

The competent rock in the three Rock Domains at Simpevarp has very similar uniaxial compressive strength, around 31 MPa (Table 4-10). RSMA at Laxemar seems to exhibit a higher value of about 34 MPa than its counterpart in Simpevarp. The Rock Domains RSMBA, RSMD and RSMM present higher uniaxial compressive strength of the order of 41–58 MPa. The fractured rock inside the Rock Domains have a uniaxial compressive strength ranging between 20 and 32 MPa, with the exception of RSMD that has a higher strength.

In Table 4-11, 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. For the competent rock, the uncertainty can be summarised as about ± 7% of the mean value. As usual, the uncertainty on the strength of the fractured rock mass is higher.

Table 4-10. Predicted uniaxial compressive strength of the rock mass $UCS_{H\&B}$ according to the Hoek and Brown's Criterion for the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

$UCS_{H\&B}$ [MPa]*	Competent rock			Fractured rock		
Rock Domain	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA Simpevarp	10.0	31.0/10.3	58.1	–	–	–
RSMB Simpevarp	13.5	29.9/10.2	76.1	12.1	23.5/7.8	38.0
RSMC Simpevarp	13.1	30.8/8.5	63.0	13.2	19.8/3.4	26.4
RSMA Laxemar	11.8	34.7/14.8	88.6	17.1	20.2/5.2	26.3
RSMBA Laxemar	17.8	40.6/9.6	50.1	–	–	–
RSMD Laxemar	34.6	55.0/9.5	63.7	37.8	43.2/7.3	51.5
RSMM Laxemar	24.5	57.5/14.1	87.8	16.4	31.6/12.0	57.9

* Equivalent unconfined strength.

Table 4-11. Uncertainty of the mean uniaxial compressive strength of the rock mass $UCS_{H\&B}$ determined according to the Hoek and Brown's Criterion for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean $UCS_{H\&B}$ value itself.

Uncertainty of the mean $UCS_{H\&B}$*as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain	Min	Max	Min	Max
RSMA Simpevarp	–4%	+7%	–	–
RSMB Simpevarp	–5%	+12%	–14%	+42%
RSMC Simpevarp	–5%	+7%	–18%	+37%
RSMA Laxemar	–3%	+5%	–47%	+149%
RSMBA Laxemar	–11%	+8%	–	–
RSMD Laxemar	–10%	+6%	–43%	+35%
RSMM Laxemar	–6%	+6%	–19%	+42%

* Equivalent unconfined strength.

4.8 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 confinement stresses between 10 and 30 MPa is performed to obtain the simpler parameters of the linear Coulomb's Strength Criterion (e.g apparent cohesion, friction angle, and uniaxial compressive strength). Another set of parameters is obtained if the range of stress 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 22 MPa, thus the variation are only about 40% from the minimum to the maximum value (Table 4-12). Analogously, the range of variation of the cohesion of the fractured rock is between 15 and 20 MPa.

The uncertainties of the apparent cohesion are summarised in Table 4-13. As for other parameters, the uncertainty of the mean cohesion of the competent rock (around 2.5%) is about five times the uncertainty of the mean cohesion of the fractured rock (around 13%). The uncertainty intervals are often rather symmetrical. The uncertainty for the fractured rock in RSMB and RSMC at Simpevarp and RSMA at Laxemar is slightly larger due to the fact that the minor zones in these domains are smaller and more numerous.

Table 4-12. Predicted cohesion c' of the rock mass according to the Mohr-Coulomb Criterion for the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

c' [MPa]*	Competent rock			Fractured rock		
Rock Domain	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA Simpevarp	12.0	17.2/1.7	21.7	–	–	–
RSMB Simpevarp	12.6	16.2/2.0	23.1	12.5	15.2/1.4	17.1
RSMC Simpevarp	14.5	17.9/1.4	22.8	15.0	16.4/0.7	17.7
RSMA Laxemar	14.3	18.1/2.0	25.3	14.0	14.6/1.0	15.7
RSMBA Laxemar	16.1	19.8/1.4	21.2	–	–	–
RSMD Laxemar	18.6	21.5/1.3	22.7	19.1	19.9/1.0	21.0
RSMM Laxemar	15.7	20.7/2.0	25.1	14.6	17.2/1.9	21.2

* Linear envelope with confinement between 10 and 30 MPa.

Table 4-13. Uncertainty of the mean cohesion of the rock mass c' for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. 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		Fractured rock	
Rock Domain	Min	Max	Min	Max
RSMA Simpevarp	–2%	+2%	–	–
RSMB Simpevarp	–3%	+3%	–7%	+10%
RSMC Simpevarp	–2%	+2%	–8%	+8%
RSMA Laxemar	–1%	+1%	–21%	+33%
RSMBA Laxemar	–5%	+2%	–	–
RSMD Laxemar	–4%	+2%	–17%	+10%
RSMM Laxemar	–3%	+2%	–8%	+10%

In Table 4-14, the apparent friction angle of the rock mass for confinement stresses between 10 and 30 MPa is reported. The mean value of the friction angle of the competent rock ranges between 42° and 47°, except Rock Domain RSMB in fine-grained dioritoid that has only 40°. This rock type matrix has lower friction angle (around 53°) than the other rock types (around 60°). On average, the friction angle of the fractured rock varies between 38° and 42°, except for Rock Domain RSMD where it reaches 46°.

Table 4-15 shows that the uncertainty of the friction angle is rather low. This means that the mean friction angle of the competent rock is estimated within an interval of about ± 1%. For the fractured rock this value becomes about 7%. 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.

By means of the apparent cohesion and friction angle, the apparent uniaxial compressive strength of the rock mass for confinement stress between 10 and 30 MPa can be determined (Table 4-16). 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 is between 70 MPa and 110 MPa. For the fractured rock, the range of apparent uniaxial compressive strength is between 64 MPa and 98 MPa.

The uncertainties of the mean apparent uniaxial compressive strength are very similar to those for the equivalent uniaxial compressive strength in Section 4.7 (Table 4-17).

Table 4-14. Predicted friction angle of the rock mass φ' according to the Mohr-Coulomb Criterion for the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

φ' [°]*	Competent rock			Fractured rock		
Rock Domain	Min	Mean/ St Dev	Max	Min	Mean/ St Dev	Max
RSMA Simpevarp	34.0	42.0/2.6	47.4	–	–	–
RSMB Simpevarp	35.0	39.9/2.7	45.3	34.8	38.9/2.4	43.0
RSMC Simpevarp	38.8	43.7/1.7	48.2	40.3	42.4/0.9	44.0
RSMA Laxemar	37.9	43.3/1.8	47.9	37.6	38.4/1.3	39.8
RSMBA Laxemar	42.1	46.1/1.4	47.3	–	–	–
RSMD Laxemar	44.8	46.9/0.8	47.7	45.2	45.8/0.8	46.7
RSMM Laxemar	40.0	43.8/1.2	46.2	39.1	42.2/1.8	45.4

* Linear envelope with confinement between 10 and 30 MPa.

Table 4-15. Uncertainty of the mean friction angle of the rock mass φ' for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean φ' value itself.

Uncertainty of the mean φ' as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain	Min	Max	Min	Max
RSMA Simpevarp	–1%	+1%	–	–
RSMB Simpevarp	–2%	+1%	–5%	+4%
RSMC Simpevarp	–1%	+1%	–6%	+3%
RSMA Laxemar	–1%	+1%	–16%	+11%
RSMBA Laxemar	–4%	+1%	–	–
RSMD Laxemar	–2%	+1%	–10%	+3%
RSMM Laxemar	–1%	+1%	–5%	+3%

Table 4-16. Predicted apparent uniaxial compressive strength UCS_m of the rock mass according to the Coulomb's Criterion for the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

Apparent UCS_{M-C}* (Mohr-Coulomb)	Competent rock			Fractured rock		
Rock Domain	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA Simpevarp	45.2	77.6/12.0	111.0	–	–	–
RSMB Simpevarp	48.6	69.8/12.6	106.9	48.0	63.9/9.0	77.5
RSMC Simpevarp	60.6	84.2/9.6	119.5	65.0	74.7/4.7	83.2
RSMA Laxemar	58.3	84.4/12.4	122.6	56.8	60.4/5.8	67.1
RSMBA Laxemar	72.6	98.7/10.2	108.4	–	–	–
RSMD Laxemar	89.6	109.1/8.8	117.1	92.9	98.2/7.0	106.1
RSMM Laxemar	67.5	97.4/11.9	122.2	61.4	78.2/12.0	103.2

* Linear envelope with confinement between 10 and 30 MPa.

Table 4-17. Uncertainty of the mean UCS_m of the rock mass according to the Mohr-Coulomb Criterion for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the 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		Fractured rock	
Rock Domain	**Min**	**Max**	**Min**	**Max**
RSMA Simpevarp	–2%	+3%	–	–
RSMB Simpevarp	–4%	+5%	–9%	+16%
RSMC Simpevarp	–3%	+3%	–12%	+13%
RSMA Laxemar	–2%	+2%	–29%	+50%
RSMBA Laxemar	–8%	+4%	–	–
RSMD Laxemar	–5%	+3%	–24%	+14%
RSMM Laxemar	–4%	+3%	–11%	+15%

4.9 Tensile strength of the rock mass

The equivalent tensile strength of the rock mass is determined from the Hoek & Brown's Strength Criterion determined from RMR and 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 (see Table 4-18). The differences between Rock Domain RSMB01 and the other two Rock Domains depend on the Hoek & Brown's parameter mi for the intact rock that is around 14 for the fine-grained dioritoid in RSMB01, and about 31 for the quartz monzonite to monzodiorite in the other two Rock Domains, respectively.

The uncertainties of the mean tensile strength (Table 4-19) are very close to those of the equivalent uniaxial compressive strength in Section 4.7 because they are determined in a very similar way.

Table 4-18. Predicted tensile strength TS_m of the rock mass according to the Hoek and Brown's Criterion for the competent and fractured rock mass in the Rock Domains for the Laxemar SDM version 1.2.

TS_m [MPa]	Competent rock			Fractured rock		
Rock Domain	**Min**	**Mean/ St Dev**	**Max**	**Min**	**Mean/ St Dev**	**Max**
RSMA Simpevarp	0.14	0.80/0.48	2.24	–	–	–
RSMB Simpevarp	0.33	1.02/0.49	3.45	0.31	0.74/0.31	1.34
RSMC Simpevarp	0.18	0.63/0.29	1.66	0.17	0.30/0.07	0.44
RSMA Laxemar	0.15	0.87/0.66	3.65	0.39	0.5/0.18	0.70
RSMBA Laxemar	0.25	0.79/0.24	1.03	–	–	–
RSMD Laxemar	0.68	1.28/0.29	1.55	0.76	0.92/0.21	1.16
RSMM Laxemar	0.52	1.97/0.68	3.57	0.30	0.76/0.40	1.68

Table 4-19. Uncertainty of the mean TS_m of the rock mass for the competent and fractured rock mass in the Rock Domains of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean TS_m value itself.

Uncertainty of the mean TS_m as % of the mean value itself	Competent rock		Fractured rock	
Rock Domain/ Deformation Zone	**Min**	**Max**	**Min**	**Max**
RSMA Simpevarp	–4%	+9%	–	–
RSMB Simpevarp	–5%	+11%	–13%	+42%
RSMC Simpevarp	–5%	+9%	–19%	+47%
RSMA Laxemar	–3%	+7%	–50%	+235%
RSMBA Laxemar	–12%	+10%	–	–
RSMD Laxemar	–11%	+9%	–49%	+51%
RSMM Laxemar	–7%	+7%	–21%	+68%

5 Deformation Zones

In the following sections, summary tables of the Q index, RMR rating, and the derived properties of the rock mass are provided as for an equivalent continuum medium. In particular, for each Deformation Zone, 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. The mechanical properties are also summarised for all the boreholes at the Simpevarp and Ävrö Site, and at the Laxemar Site.

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

5.1 Deformation Zone Model

The Deterministic Deformation Zones described in Section 1.1.2 intercept the boreholes according to the summary given in Table 5-1. Seven zones were identified in the boreholes: ZSMNE024A, ZSMNE031A, ZSMNE012A, ZSMNE004A, ZSMEW007A, ZSMNW929A and ZSMNW932A. No geological description was available for ZSMNE004A. Some of the geometrical and geological properties of the seven zones are given in Table 5-2. Moreover, a plot of the orientation of the deterministic deformation zones is presented graphically in Figure 5-1. The average inclination of these deformation zones is about 72°. This information will be used in next section for the estimation of the thickness of minor deformation zones.

Table 5-1. Deterministic deformation zones in the boreholes.

Borehole	Characterised length	Deformation Zones	Details	Total % in length
KSH01AB	900 m	ZSMNE024A ZSMNE031A	91 m 6 m	11%
KSH02	981 m	–	–	–
KSH03	901 m	ZSMNE024A ZSMNE031A	113 m 5 m	13%
KAV01	757 m	ZSMNE012A (EW7–NE4) ZSMNE024A	180 m 97 m*	37%
KAV04	904 m	ZSMNE004A ZSMNE012A ZSMNE024A	– 60 m 64 m*	14%
KLX01	1,078 m	ZSMEW007A	20 m	2%
KLX02	806 m	ZSMEW007A ZSMNW929A	10 m 190 m	25%
KLX03	899 m	ZSMNW932A	(prel. Info.)	–
KLX04	893 m	ZSMEW007A ZSMNW929A	9 m 100 m	12%

* This sections were not identified by the geological "single-hole interpretation".

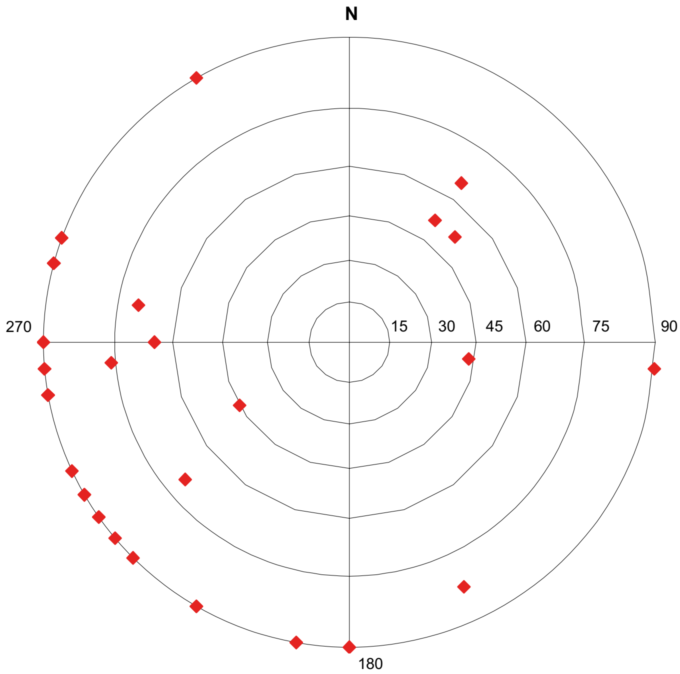

Figure 5-1. *Poleplot showing the orientation of the deterministic deformation zones identified for Laxemar SDM 1.2.*

Table 5-2. Properties of the Deterministic Deformation Zones intercepted by the boreholes and considered for rock mechanics purposes.

Deformation Zones	Length	Thickness	Strike/dip	Type of deformation	Comments
ZSMEW007A	3,300 ± 200 m	50 m [20–60 m]	278/43	Brittle	Water bearing. High confidence.
ZSMNW932A	2,800 ± 200 m	0 m [0–20 m]	120/90	No evidence from the field	Based on preliminary results on new borehole. High confidence.
ZSMNW929A	1,900 ± 100 m	50 m [20–50 m]	113/79	Brittle	Open fractures. High confidence.
ZSMNE012A (EW7-NE4)	5,500 ± 200 m	120 m [60–120 m]	060/45	Ductile/Brittle	Clay. 80 m tunnel intersection with support need. High confidence.
ZSMNE024A	11,600 m [10 km – >15 km]	80 ± 20 m	225/52	Ductile/Brittle	Significant failure of a tunnel roof wedge. High confidence.
ZSMNE031A	4,400 m [4 km – >15 km]	15 m [2–20 m]	215/52	Brittle	High confidence.

5.2 Relation between thickness and length

The thickness of the Deterministic Deformation Zones in Table 5-2 represents their width included the transition zone, i.e. the thickness of the volume of rock experiencing a higher fracture frequency than the rest of the rock mass (higher frequency than 4 fractures/m) and the core of the deformation zone where the fracture frequency is larger than 9 fractures/m /Munier and Hökmark 2004/. The plot of the length versus the thickness of the deterministic deformation zones in Laxemar SDM 1.2 is shown in Figure 5-2. In this figure, a rather linear relation between thickness and length can be observed. This is in agreement with earlier studies by /Vermilye 1996, Vermilye and Scholtz 1998, Cowie and Shipton 1998/ reported by /Munier and Hökmark 2004/. These authors proposed a linear relation with a proportionality constant of the order of 10^{-2}. The equation of the fitting line in Figure 5-2 is:

$$t = 0.0094\,L \text{ [m]} \quad (3)$$

where t is the thickness and L the length of the zones. The constant obtained here is very close to the value reported in the literature.

The importance of this relation is clear when treating the shorter deformation zones that intersect the boreholes. By extrapolating the relation between thickness and length to fracture, cross and minor deformation zones, an estimation of their thickness can be obtained. However, a correction should be applied due to the fact that seldom the minor deformation zones cross the boreholes at a right angle.

In Section 5.1, an orientation analysis of the orientation of the deterministic deformation zones indicates that these zones intercept the borehole axes with small angles. Assuming that also the minor deformation zones intercept the boreholes at small angles, the apparent thickness of the zones has to be corrected as follows:

$$t = t'\sin\alpha \quad (4)$$

where t is the actual thickness, t' is the apparent thickness (the length along the borehole) and α is the angle between the zone average plane and the borehole axis.

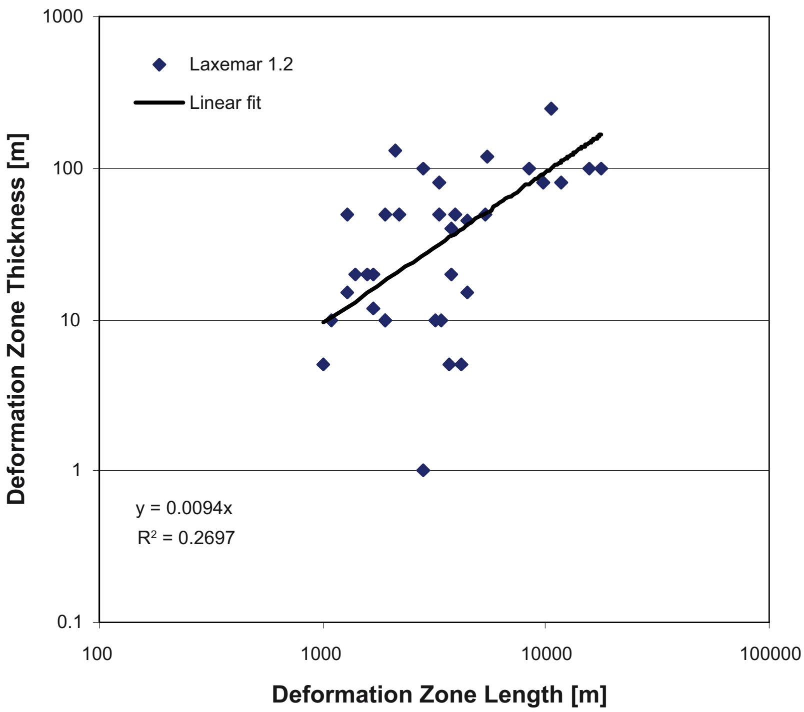

Figure 5-2. *Plot of the length versus thickness of the Deterministic Deformation Zones identified for Laxemar SDM 1.2.*

5.3 Thickness and length of the minor deformation zones

The empirical characterisation of the rock mass in this report is performed on 5 m long sections of borehole. Thus, the smallest zone that unequivocally can be identify by the empirical methods has an apparent thickness t' of 5 m. On the other hand, most of the analysed boreholes are pseudo-vertical. If the minor deformation zones have an orientation similar to the deterministic deformation zones in Section 5.1, then the average angle between the zone planes and the borehole orientation should be around 70°. Consequently, the actual thickness of the smallest minor deformation zone that can be calculated according to Equation (4) results to be 1.7 m.

By applying Equation (3), the values of length given the thickness can be obtained as in Table 5-3. Considering that the minimum actual thickness that can be observed by the empirical methods applied along the boreholes is about 1.7 m, it means that minor zones of about 180 m can be identified. Such determination would satisfy the requirements for the location of the deposition holes in a repository facility contained in the Design Premises /SKB 2004/. The Design Premises prescribe that deposition holes should be placed at least 2 m from "stochastically" determined fractures of radius between 100 and 200 m. If the "fractures" are assumed to be circular, then a permissible distance applies to "fractures" or minor deformation zones longer than twice the minimum radius, and thus longer than 200 m.

A consequence of the assumptions in this section is that even single fractures might have a certain thickness (see Table 5-3) and this could be assimilated to the thickness of the volume of rock in which the fracture can be encountered due to its waviness and roughness or due to its aperture.

5.4 Rock Mechanics signature of the deformation zones

The Deterministic Deformation Zones are characterised by one or several "cores" often with deformed, altered, migmatised and highly fractured rock mass, sometimes with the presence of clay, and a "transition zone" less affected by these phenomena but that differs from the rest of the rock mass. The transition zone constitutes a natural buffer zone between the rock mass outside the deformation zone and the zone core. The thickness of the deterministic zones accounts for both the core and transition zone.

The empirical characterisation of the boreholes in this report can localise the presence of fractured rock mass that persist along at least 5 m of borehole length, thus, down to minor deformation zones of at least 200 m length (100 m radius). The key point is thus to determine the suitable values of Q and RMR that would identify, or confirm, the presence of minor or deterministic deformation zones.

The simplest way to achieve the identification of the deformation zones by means of the Q and RMR values is to check the borehole sections where these assume the lowest values. According to the Q and RMR system, the limit between the rock mass classes described as "fair rock" and "poor rock" are at a Q value of 4 an RMR value of 40. Considering that the scale of rock quality according to RMR spans from very good crystalline rocks to almost soil-like degradation rocks, the limit between "fair" and "poor" rock does not coincide with that of the Q system, which

Table 5-3. Relation between length and thickness for the minor deformation zones estimated based on Equation (3).

Length	Thickness
100 m	0.9 m
200 m	1.9 m
1,000 m	9.4 m

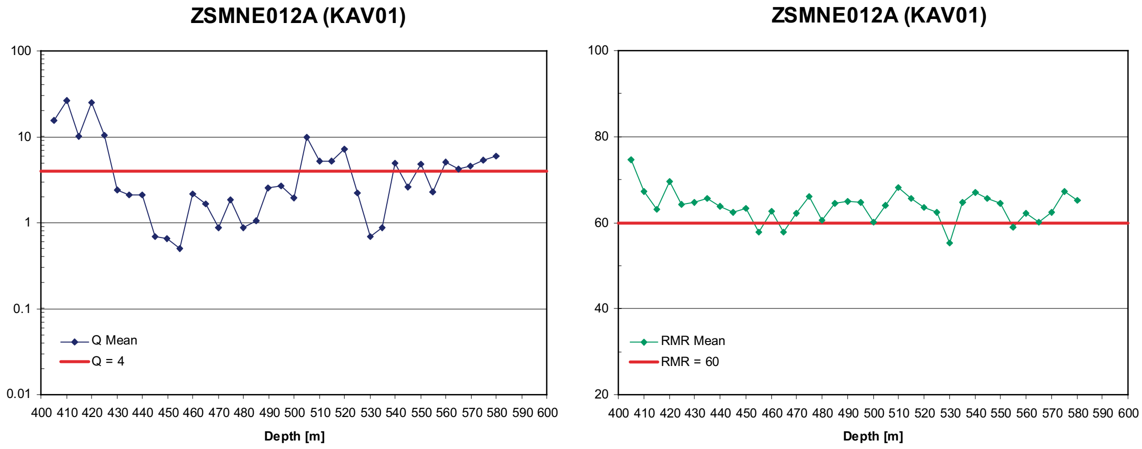

Figure 5-3. *Zone ZSMNE012A in borehole KAV01: mean observed Q (left) and RMR (right) and application of Equation (5).*

was designed particularly for better rock classes. Thus, the value of RMR characterising the deformation zones can be assumed to be 60. The occurrence of either a Q value smaller than 4 or a RMR value smaller than 60 is considered as the "signature" identifying the minor or deterministic deformation zones.

Deformation zone signature: $Q < 4$ and/or $RMR < 60$ (5)

As explained before, this technique will be able to locate the "core" rock volume of the deformation zones. The transition zone should be determined by studying the conditions of the rock mass around the core of the zone.

In Section 4.2, Equation (5) is applied to the rock along the boreholes. Figure 4-1 and Figure 4-2 show that the results agree well with the Deformation Zone Model, considering the limitation that Equation (5) would only recognize the "core" of the large and/or deterministic zones.

5.5 Rock Quality Index (Q)

The average Q value in the Deterministic Deformation Zones ranges between the classes of "fair" and "good rock" (Table 5-4). However, the minimum calculated values that refers to the "core" rock mass volume of the deformation zones, is always, with two exceptions, around 0.5, which means in "very poor rock". It can also be noticed that the most frequent values of Q are systematically lower than the average Q values, and are all except one in the same classes as the average but toward the lower ranges.

The uncertainty of the determination of the mean value of Q is summarised Table 5-5. The uncertainty of the mean Q for deformation zones is rather asymmetric: the lower boundary is between –8% and 33%, while the upper boundary is up to +144%. These large values can be explained by the fact that, due to the heterogeneities, Q often spans over several order of magnitude within the same rock mass because of its logarithmic nature.

Table 5-4. Q values of the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	Q [–]		
	Min	Mean [most freq.]	Max
ZSMEW007A	0.7	15.7 [2.5]	65.1
ZSMNW932A	–	32.9	–
ZSMNW929A	0.7	6.7 [4.7]	33.2
ZSMNE012A	0.5	4.8 [2.6]	26.3
ZSMNE024A	0.6	16.4 [4.8]	704.0
ZSMNE031A	5.7	8.2 [8.8]	10.0

* The values within brackets are the most frequent Q.

Table 5-5. Uncertainty of the mean Q for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as percentage of the mean Q value itself.

Deformation Zone	Uncertainty of the mean Q as % of the mean value itself*	
	Min	Max
ZSMEW007A	–28%	+300%
ZSMNW932A**	–	–
ZSMNW929A	–10%	+54%
ZSMNE012A	–10%	+49%
ZSMNE024A	–8%	+51%
ZSMNE031A	–33%	+144%

* The Q system spans over several order of magnitude.
** There is just one value available.

5.6 Rock Mass Rating (RMR)

The rock quality can also be quantified by RMR (Table 5-6). For the different Deterministic Deformation Zones, the average RMR is very consistent and about 65 ("fair rock"). The minimum values are also in the range of "fair rock". This might indicate a slight mismatch between the classes of Q and those of RMR.

The uncertainty evaluated for RMR is in general smaller than that for Q (Table 5-7). The mean value of RMR is expected to vary within an interval no larger than ± 10%.

Table 5-6. RMR values of the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	RMR [–]		
	Min	Mean/ St Dev	Max
ZSMEW007A	52.1	64.0/9.0	80.1
ZSMNW932A	–	85.3	–
ZSMNW929A	53.3	65.1/5.9	77.1
ZSMNE012A	55.2	64.1/3.7	74.6
ZSMNE024A	49.7	63.2/6.6	87.7
ZSMNE031A	61.9	65.5/5.7	72.1

Table 5-7. Uncertainty of the mean RMR for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as percentage of the mean RMR value itself.

Deformation Zone	Uncertainty of the mean RMR as % of the mean value itself	
	Min	Max
ZSMEW007A	–9%	+10%
ZSMNW932A*	–	–
ZSMNW929A	–3%	+3%
ZSMNE012A	–3%	+3%
ZSMNE024A	–3%	+3%
ZSMNE031A	–12%	+10%

* There is just one value available.

5.7 Deformation modulus of the deformation zones

The equivalent deformation modulus of the rock mass determined by the empirical methods applies for low confinement stress (between 1 and 2 MPa). In Table 5-8, the minimum, maximum, mean deformation modulus and its standard deviation are summarised for Deterministic Deformation Zones. The Deterministic Deformation Zones have a minimum and average deformation modulus between 10 and 25 GPa.

The uncertainty of the determined modulus seems to vary between –8% and 16%, except for zone ZSMEW007A and ZSMNE031A (Table 5-9). For these two zones, the data available is rather sparse, thus the uncertainty high.

Table 5-8. Predicted deformation modulus E_m of the rock mass for the Deterministic Deformation Zones of the Laxemar SDM version 1.2 (low confinement).

Deformation Zone	E_m [GPa]		
	Min	Mean/ St Dev	Max
ZSMEW007A	11.3	25.3/14.6	56.5
ZSMNW932A	–	76.1	–
ZSMNW929A	12.1	25.2/8.3	47.5
ZSMNE012A	13.5	23.1/5.0	41.3
ZSMNE024A	9.8	22.9/9.8	75.0*
ZSMNE031A	19.9	25.3/8.9	35.6

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

Table 5-9. Uncertainty of the mean deformation modulus E_m of the rock mass of the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean E_m value itself.

Deformation Zone	Uncertainty of the mean E_m as % of the mean value itself	
	Min	Max
ZSMEW007A	–21%	+64%
ZSMNW932A*	–	–
ZSMNW929A	–8%	+17%
ZSMNE012A	–8%	+17%
ZSMNE024A	–7%	+16%
ZSMNE031A	–31%	+57%

* There is just one value available.

5.8 Poisson's ratio of the deformation zones

The Poisson's ration of the deformation zones is listed in Table 5-10. The estimated mean Poisson's ratio is around 0.08 with an uncertainty of the mean value that might range between –30% to +65% (the same values as in Table 5-9 apply).

5.9 Uniaxial compressive strength of the deformation zones

The equivalent uniaxial compressive strength of the rock mass is here obtained from the Hoek & Brown's Strength Criterion by means of the relation between RMR and GSI. The uniaxial compressive strength is predicted for zero confinement stress. In Section 5.10 the "apparent" compressive strength is presented, as it is obtained from the Coulomb's Strength Criterion. Based on the level of stress chosen to quantify the friction angle and cohesion, the apparent compressive strenght can vary.

Most of the deformation zones have a uniaxial compressive strength around 20 MPa, except ZSMNW932A that exhibits 65 MPa (Table 5-11). The uncertainty on these values is rather large due to the variability of the properties inside the deformation zones and the relatively small amount of data available. The uncertainty on the mean value can be estimated to be between –40% and +80% (Table 5-12).

Table 5-10. Predicted Poisson's ratio ν_m of the rock mass for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	ν_m [–]		
	Min	Mean/ St Dev	Max
ZSMEW007A	0.04	0.08/0.05	0.18
ZSMNW932A	–	0.22	–
ZSMNW929A	0.03	0.08/0.03	0.14
ZSMNE012A	0.04	0.07/0.02	0.13
ZSMNE024A	0.03	0.07/0.03	0.24
ZSMNE031A	0.06	0.08/0.03	0.12

Table 5-11. Predicted uniaxial compressive strength of the rock mass $UCS_{H\&B}$ according to the Hoek and Brown's Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	$UCS_{H\&B}$ [MPa]*		
	Min	Mean/ St Dev	Max
ZSMEW007A	8.5	19.3/10.2	40.3
ZSMNW932A	–	64.6**	–
ZSMNW929A	10.3	21.4/6.8	41.1
ZSMNE012A	10.1	18.1/4.5	30.1
ZSMNE024A	7.5	18.4/8.2	61.6
ZSMNE031A	16.9	20.0/5.0	25.8

* Equivalent strength for zero confinement pressure.
** There is just one value available.

Table 5-12. Uncertainty of the mean uniaxial compressive strength of the rock mass $UCS_{H\&B}$ determined according to the Hoek and Brown's Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean $UCS_{H\&B}$ value itself.

Deformation Zone	Uncertainty of the mean $UCS_{H\&B}$ as % of the mean value itself	
	Min	Max
ZSMEW007A	–25%	+83%
ZSMNW932A*	–	–
ZSMNW929A	–10%	+21%
ZSMNE012A	–10%	+25%
ZSMNE024A	–8%	+24%
ZSMNE031A	–41%	+69%

* There is just one value available.

5.10 Coulomb's Strength Criterion of the deformation zones

The parameters of 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 deformation zone. From this Criterion, a linear approximation for stresses between 10 and 30 MPa is performed to obtain the parameters of the simpler linear Coulomb's Strength Criterion (e.g apparent cohesion, friction angle and uniaxial compressive strength). This set of parameters changes if the range of stress is changed. This is why the parameters in this section are called "apparent".

The apparent cohesion of the deformation zones in Table 5-13 might vary on average between 15 MPa and 22 MPa. The uncertainty on this parameter is between –20% to +20% (Table 5-14).

Table 5-13. Predicted cohesion c' of the rock mass according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	c' [MPa]*		
	Min	Mean/ St Dev	Max
ZSMEW007A	13.6	15.6/2.1	19.6
ZSMNW932A	–	21.6	–
ZSMNW929A	12.6	15.0/1.3	18.1
ZSMNE012A	12.7	15.3/1.1	18.1
ZSMNE024A	13.2	15.5/1.5	22.5
ZSMNE031A	15.9	16.4/0.9	17.4

* Linear envelope between 10 and 30 MPa.

Table 5-14. Uncertainty of the mean cohesion of the rock mass c' for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean c' value itself.

Deformation Zone	Uncertainty of the mean c' as % of the mean value itself	
	Min	Max
ZSMEW007A	–11%	+16%
ZSMNW932A*	–	–
ZSMNW929A	–5%	+5%
ZSMNE012A	–4%	+5%
ZSMNE024A	–4%	+4%
ZSMNE031A	–18%	+16%

* There is just one value available.

In Table 5-15, the apparent friction angle of the rock mass in the deformation zones for stresses between 10 and 30 MPa is reported. The mean value of the friction angle is between 39° and 42°, except for ZSMNW932A that has 44°. Table 5-16 shows that the uncertainty of the friction angle is around ± 5%. 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.

Table 5-15. Predicted friction angle of the rock mass φ' according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	φ' [°]*		
	Min	Mean/ St Dev	Max
ZSMEW007A	36.9	40.5/3.0	45.9
ZSMNW932A	–	44.1	–
ZSMNW929A	35.2	39.2/1.8	42.2
ZSMNE012A	34.6	40.1/2.3	44.4
ZSMNE024A	35.4	40.6/2.3	47.9
ZSMNE031A	41.7	42.4/1.1	43.6

* Linear envelope between 10 and 30 MPa.

Table 5-16. Uncertainty of the mean friction angle of the rock mass φ’ for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean φ’ value itself.

Deformation Zone	Uncertainty of the mean φ’ as % of the mean value itself	
	Min	Max
ZSMEW007A	–8%	+6%
ZSMNW932A*	–	–
ZSMNW929A	–4%	+2%
ZSMNE012A	–3%	+2%
ZSMNE024A	–3%	+2%
ZSMNE031A	–13%	+7%

* There is just one value available.

By means of the apparent cohesion and friction angle for a stress confinement between 10 and 30 MPa, the apparent uniaxial compressive strength of the rock mass can be determined. This is done for the sake of comparison with the results that will be obtained by the Theoretical Approach /see SKB 2005/, which are expressed in terms of apparent uniaxial compressive strength of the rock mass. The apparent uniaxial compressive strength of the Deterministic Deformation Zones is shown in Table 5-17. On average, the apparent compressive strength of the deformation zones might vary between 60 MPa and 100 MPa. The uncertainty of the mean apparent uniaxial compressive strength is predominantly around ± 8% with a maximum of 26% (see Table 5-18), thus higher than both the uncertainty of the mean friction angle and cohesion.

Table 5-17. Predicted apparent uniaxial compressive strength $UCS_{m\ M\text{-}C}$ of the rock mass according to the Coulomb’s Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	Apparent $UCS_{m\ M\text{-}C}$* (Mohr-Coulomb)		
	Min	Mean/ St Dev	Max
ZSMEW007A	54.3	68.3/14.5	97.0
ZSMNW932A	–	102.2	–
ZSMNW929A	48.5	63.6/8.0	81.3
ZSMNE012A	48.3	66.0/7.6	85.9
ZSMNE024A	51.2	68.1/10.5	116.9
ZSMNE031A	70.8	74.5/5.9	81.4

* Linear envelope between 10 and 30 MPa.

Table 5-18. Uncertainty of the mean $UCS_{m\ M\text{-}C}$ of the rock mass according to the Mohr-Coulomb Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean $UCS_{m\ M\text{-}C}$ (Mohr-Coulomb) value itself.

Deformation Zone	Uncertainty of the mean $UCS_{m\ M\text{-}C}$ (Mohr-Coulomb) as % of the mean value itself	
	Min	Max
ZSMEW007A	–16%	+25%
ZSMNW932A*	–	–
ZSMNW929A	–6%	+8%
ZSMNE012A	–6%	+8%
ZSMNE024A	–5%	+7%
ZSMNE031A	–26%	+26%

* There is just one value available.

5.11 Tensile strength of the deformation zones

The equivalent tensile strength of the deformation zones is determined from the Hoek & Brown's Strength Criterion obtained by means of the relation between RMR and GSI. According to the Hoek & Brown's Criterion, the tensile strength of the deformation zones spans between 0.3 and 0.5 MPa, with the exception of ZSMNW932A that shows a higher value (Table 5-19). The uncertainty of the mean tensile strength is very close to that of the equivalent uniaxial compressive strength in Section 5.9 because it is determined in a very similar way (Table 5-20).

Table 5-19. Preliminarily predicted tensile strength TS_m of the rock mass according to the Hoek and Brown's Criterion for the Deterministic Deformation Zones of the Laxemar SDM version 1.2.

Deformation Zone	TS_m [MPa]		
	Min	Mean/ St Dev	Max
ZSMEW007A	0.10	0.35/0.24	0.80
ZSMNW932A	–	2.35	–
ZSMNW929A	0.18	0.50/0.22	1.28
ZSMNE012A	0.12	0.36/0.22	1.11
ZSMNE024A	0.08	0.42/0.28	1.43
ZSMNE031A	0.24	0.31/0.11	0.44

Table 5-20. Uncertainty of the mean TS_m of the rock mass for the Deterministic Deformation Zones of the Laxemar SDM version 1.2. The uncertainty of the mean is expressed as the percentage of the mean TS_m value itself.

Deformation Zone	Uncertainty of the mean TS_m as % of the mean value itself	
	Min	Max
ZSMEW007A	–26%	+129%
ZSMNW932A*	–	–
ZSMNW929A	–10%	+27%
ZSMNE012A	–10%	+35%
ZSMNE024A	–7%	+27%
ZSMNE031A	–42%	+84%

* There is just one value available.

6 Conclusions

This report contains the delivery of the rock mass characterisation by means of the Empirical Approach to the Laxemar Site Descriptive Model version 1.2. The data presented here will be "harmonized" (integrated and coordinated) with the results of the Theoretical Approach obtained based on the same geological information and will lead to the compilation of the Rock Mechanics Model for the Laxemar Site.

The analyses are based on the characterisation that was performed on the geomechanical information available from nine boreholes (KSH01AB, KSH02, KSH03, KAV01, KAV04, KLX01, KLX02, KLX03 and KLX04). The data used were included in the delivery from the Data-freeze on November 1st, 2004.

The Lithological Model (also called Rock Domain Model) provides the partitioning of the rock mass into Rock Domains according to geological criteria of homogeneity including rock types, weathering, age, etc. The nine boreholes constituting the base of the present Rock Mechanics characterisation intercept six of the Rock Domains contained in the Regional Model Volume for Laxemar SDM 1.2:

- RMSA in Ävrö granite,
- RMSB in fine-grained dioritoid,
- RMSC in a mixture of Ävrö granite and quartz monzodiorite,
- RSMD in quartz monzonite to monzodiorite,
- RSMBA in a mixture of Ävrö granite and fine-grained dioritoid,
- RSMM in diorite and gabbro.

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 already for the Simpevarp Site Descriptive Model version 1.2 that the two methods gave rather similar results /SKB 2005/. Thus, it was decided to determine the mechanical properties of the rock mass only based on the RMR values because a wider range of formulae is available to relate RMR values with the Hoek & Brown's and 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 from the Hoek & Brown's Criterion; 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 Coulomb's Criterion (from the cohesion and friction angle for stresses between 10 and 30 MPa).

The fractured rock in the Rock Domains of the Laxemar SDM version 1.2 represent, according to the geological "single-hole interpretations", 14% of the total borehole length. For the Simpevarp Area, the percentage of borehole length occupied by fractured rock amount to 15%. For the Laxemar Area this percentage is 13%. The fractured rock has then been in part attributed to the Deterministic Deformation Zones, and in part included in the Rock Domains.

According to the Deformation Zone Model, the Deterministic Deformation Zones in the Laxemar SDM version 1.2 represent, on average, 13% of the borehole length. For the Simpevarp Area, the percentage of borehole length occupied by Deterministic Deformation

Zones amount to 15%. Thus, on average, there should be between 1% and 3% of poor and fractured rock inside the Rock Domains. This difference might be explained by slightly less fracturing in Laxemar compared to Simpevarp.

Compared to the former version of the Simpevarp SDM version 1.2, the amount of "deformation zones" identified by the geological "single-hole interpretation" and not assigned to any Deterministic Deformation Zones has decreased. In fact, the fractured rock for Simpevarp SDM version 1.2 was about 15.5% of the whole borehole length, while for Laxemar SDM version 1.2 is only 3%. The decrease of the portion of borehole not assigned to any deterministic deformation zone can be explained by the fact that the resolution of the Deformation Zone Model has increased thanks to the contribution of new geological data. Some changes in the modelling methodology might also have affected the results. This part of the boreholes, so-called "stochastic deformation zones", is modelled by the Distinct Fracture Network Model for Laxemar SDM version 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 also studied separately in this report.

The comparison of deformation modulus of the Rock Domains for the Simpevarp and Laxemar Area shows interesting features. At Simpevarp, the deformation modulus of the Rock Domains RSMA, RSMB and RSMC seems to be very similar and ranging between 33 and 38 GPa. On the other hand, the Rock Domains at Laxemar exhibit values of the deformation modulus ranging from 44 GPa to 71 MPa. RSMD and RSMM seem to have the highest values (66–71 GPa), while RSMA the lowest (about 44 GPa). This mirrors also on the average properties of the rock in each borehole, where KLX03 (RSMD and RSMM) has the highest deformation modulus and KLX01 (RSMA) has the lowest, respectively.

The comparison of the deformation modulus in this report with the values estimated by the Simpevarp SDM version 1.2 /SKB 2005/ gives a measure of the reliability of this kind of modelling (Table 6-1). For Simpevarp, where the earlier evaluation was based on four boreholes, the agreement is very good. The new evaluation has considered one new borehole. It can be observed that the uncertainty range of the mean value of the deformation modulus tends to diminish. The estimation of the deformation modulus of RSMA at Laxemar in the Simpevarp SDM version 1.2 was not as good. This can be due to the fact that the estimation was based on just one borehole, while the new estimation is now based on results from three additional boreholes. However, the lower and upper uncertainty boundary for the two versions coincides.

The equivalent uniaxial compressive and tensile strength of the rock mass was determined based on RMR/GSI and the Hoek & Brown's Criterion. On average, it was found that all Rock Domains at Simpevarp have very close uniaxial compressive strength: around 30 MPa for the competent rock and around 20 MPa for the stochastic deformation zones. The estimated tensile strength, on the other hand, varies from Rock Domain to Rock Domain.

Cohesion and friction angle for stresses between 10 and 30 MPa are also very similar for the Rock Domains at Simpevarp. On average, for the competent rock the cohesion is 17 MPa, while the friction angle is 42° for the competent rock.

At Laxemar, the Rock Domains appear to have much larger variation of the properties when compared to each other. RSMD and RSMM seem to have the highest stiffness and strength: the average deformation modulus ranges between 66 and 71 GPa while the average uniaxial compressive strength ranges between 55 and 58 MPa. Even the friction angle and the cohesion are higher than for the other Rock Domains.

Table 6-1. Comparison between the deformation modulus of the rock mass in the Rock Domains given by the Simpevarp SDM version 1.2 /SKB 2005/ and the Laxemar SDM 1.2 (this report).

Rock Domain	Simpevarp SDM 1.2		Laxemar SDM 1.2	
	Mean/Stdv	Uncertainty range of the mean	Mean/Stdv	Uncertainty range of the mean
RSMA Simpevarp	38 GPa/ 12 GPa	36–41 GPa	38 GPa/ 13 GPa	37–40 GPa
RSMB Simpevarp	33 GPa/ 11GPa	31–36 GPa	33 GPa/ 11 GPa	32–36 GPa
RSMC Simpevarp	37 GPa/ 9 GPa	33–43 GPa	38 GPa/ 11 GPa	36–40 GPa
RSMA Laxemar	49 GPa/ 13 GPa	46–52 GPa	44 GPa/ 16 MPa	43–46 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 six boreholes, three of which are at Simpevarp and three at Laxemar. Table 6-1 shows that the rock mass at the Laxemar Site has better mechanical properties than that at the Simpevarp Site, although the rock type is the same.

Six Deterministic Deformation Zones were analysed by means of the empirical methods. In particular, data was available about ZSMNE024A, ZSMNE031A, ZSMNE012A, ZSMEW007A, ZSMNW929A and ZSMNW932A. All these zones have surprisingly similar rock mass quality and mechanical properties, except ZSMNW932A, where very little information is available. All the other zones, which length spans from 1,900 m to 11,600 m, present an average deformation modulus of about 24 GPa, cohesion of 16 MPa and friction angle of 41° (cohesion and friction angle apply for a confinement stress between 10 and 30 MPa). Thus, this set of parameters can be assumed for the characterisation of such kind of deformation zones.

All the Deterministic Deformation Zones of which borehole data are available seem to have homogeneous mechanical properties. This can be explained by the fact that the zones are subdivided into sections of 5 m of borehole and the properties that represent each section as an equivalent homogeneous rock mass are studied. This produces an averaging effect that smoothes the influence of the heterogeneities often associated to deformation zones on the resulting mechanical properties. Much more heterogeneous results would be obtained if borehole sections of 1 m length were studied. Considering the properties of the zones assumed to be homogeneous at the scale of 5 m, the average deformation modulus, uniaxial compressive strength, friction angle and cohesion can be calculated and result to be respectively about 24 GPa, 19 MPa, 41° and 16 MPa. Only ZSMNW932A shows different properties, but this might be explained by the limited amount of information on this zone.

It seems also reasonable that a set of mechanical properties should apply for the "minor deformation zones" occurring inside the Rock Domains (Figure 6-1). Although their properties vary from Rock Domain to Rock Domain, the scarcity of the data on which the estimation is made might suggest grouping them together. The average mechanical properties could then be assumed to be the same as for the Deterministic Deformation Zones.

In Table 6-2, a comparison of the deformation modulus of two Deterministic Deformation Zones reported in the former version of the SDM and the deformation modulus estimated in this report are compared. It can be noticed that, in both cases, the estimation made in the former version of the SDM does not match the new estimation. On the other hand, the upper range of possible mean values of the former SDM coincides with the lower range of possible mean values.

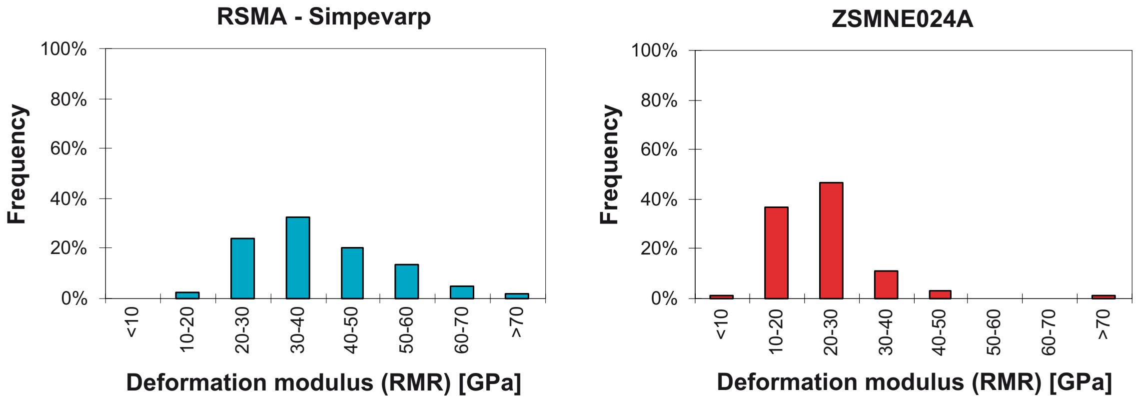

Figure 6-1. *Histogram of the deformation modulus calculated from RMR of the rock mass in Rock Domain RSMA (left) and Deterministic Deformation Zone ZSMNE024A (right).*

Table 6-2. Comparison between the deformation modulus of the rock mass in the Deterministic Deformation Zones given by the Simpevarp SDM version 1.2 /SKB 2005/ and the Laxemar SDM 1.2 (this report).

Deterministic Deformation Zone	Simpevarp SDM 1.2		Laxemar SDM 1.2	
	Mean/ St. dev.	Uncertainty range of the mean	Mean/ St. dev.	Uncertainty range of the mean
ZSMNE024A	16 GPa/ 5 GPa	14–22 GPa	23 GPa/ 10 GPa	22–27 GPa
ZSMEW007A	47 GPa	–	25 GPa/ 15 GPa	20–47 GPa

The results shown in Table 6-1 and Table 6-2 seem to indicate that:

a) When the standard deviation of the mechanical property (e.g. deformation modulus) does not significantly change, the estimation of the property is stable even considering new data. In this case the new uncertainty interval of the mean value of the parameter contains the mean value previously calculated.

b) When the standard deviation of the mechanical property (e.g. deformation modulus) changes significantly, the estimation of the property is not stable until enough new data are considered. In this case, the agreement between the two versions can be found only on one extreme of the uncertainty interval of the mean.

These conclusions somehow confirm the applicability of the technique for the evaluation of the uncertainties and also support the validity of the average values of the rock mass quality and mechanical properties.

In this study, a technique for recognition of the fractured rock sections in the boreholes based on the threshold values of Q equal to 4 and RMR equal to 60 was applied. By applying this technique, the length of borehole to be ascribed to these so called "minor deformation zones" could be calculated. It can be observed that this rock mechanics determination agrees well with the possible "deformation zones" identified by the geological "single-hole interpretation" of the boreholes at Simpevarp and Laxemar. For the nine boreholes, the average length of "minor zones" was quantified to be about 9%. Considering that most of the deformation zones occur at a rather steep angle, this percentage could be reduced to about half resulting in 4.5% of the rock mass volume. This value refers to "minor deformation zones" that in the borehole would extend at least for 5 m. This would correspond to a zone thickness of about 1.7 m, when a correction for orientation is applied. Assuming that the same length-thickness relation that applies for the Deterministic Deformation Zones (Section 5.2) also applies to the “minor deformation zones” inside the Rock Domains, thus a thickness of about 1.7 m would be related to a length of about 180 m. This length is very close to the minimum length of fractured zone that requires a “respect distance” according to the design premises presented in /SKB 2004/.

The empirically determined mechanical properties presented in this report will be merged with analogous results of numerical modelling of the mechanical behaviour of the rock mass based on the same geological input. This process is called “harmonization”. 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 Laxemar Candidate Site. To build a complete Rock Mechanics Model of the site, however, the knowledge of the boundary conditions in terms of rock mass stresses and water pressure is necessary. In fact, most of the mechanical properties of the rock mass included in this report are stress-dependent.

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Appendix

A1 Rock Domains

A1.1 Histograms for Rock Domain RSMA at Simpevarp

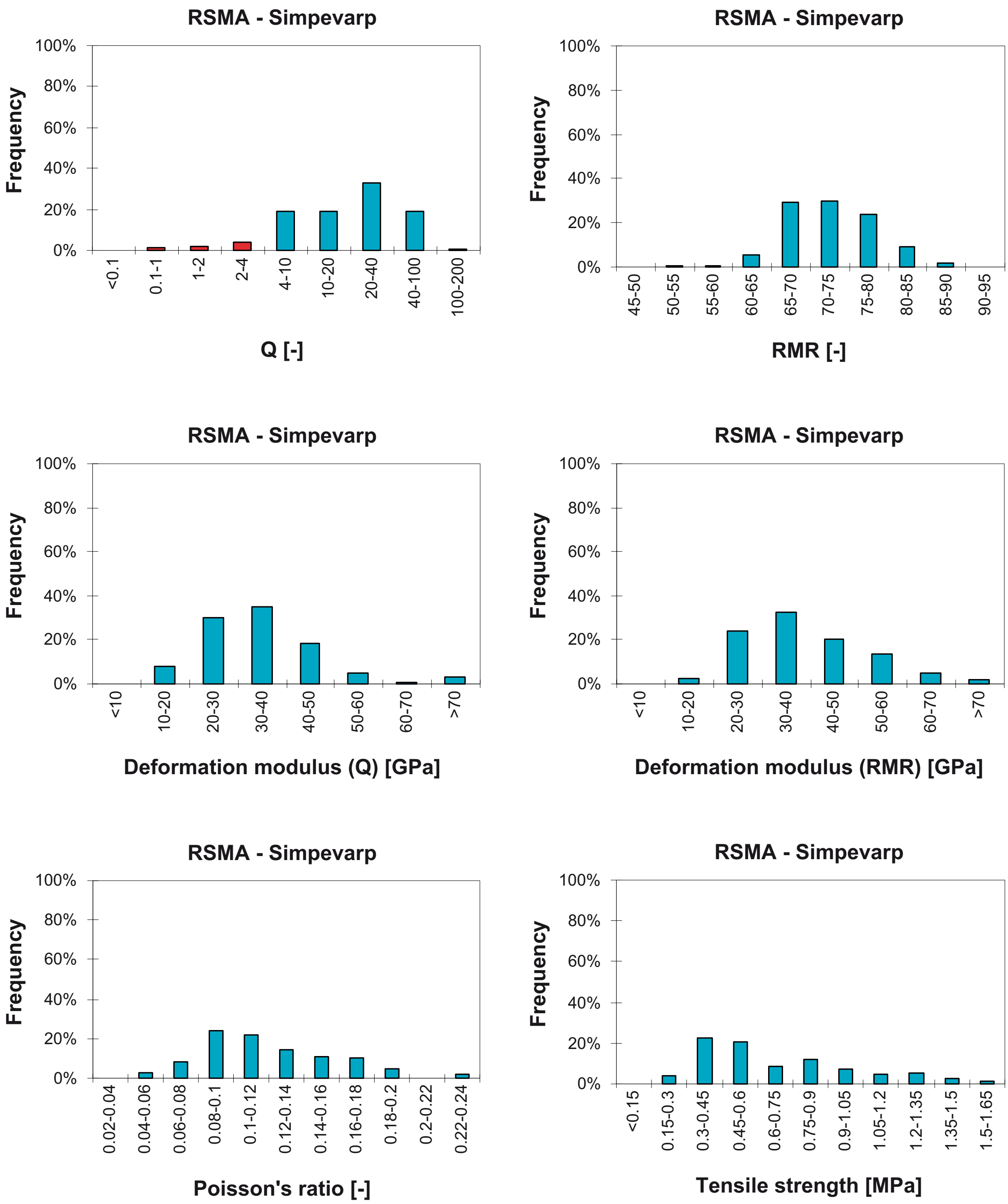

Figure A1-1. *Rock Domain RSMA at Simpevarp: Histograms showing the results of RMR and Q and derived mechanical properties.*

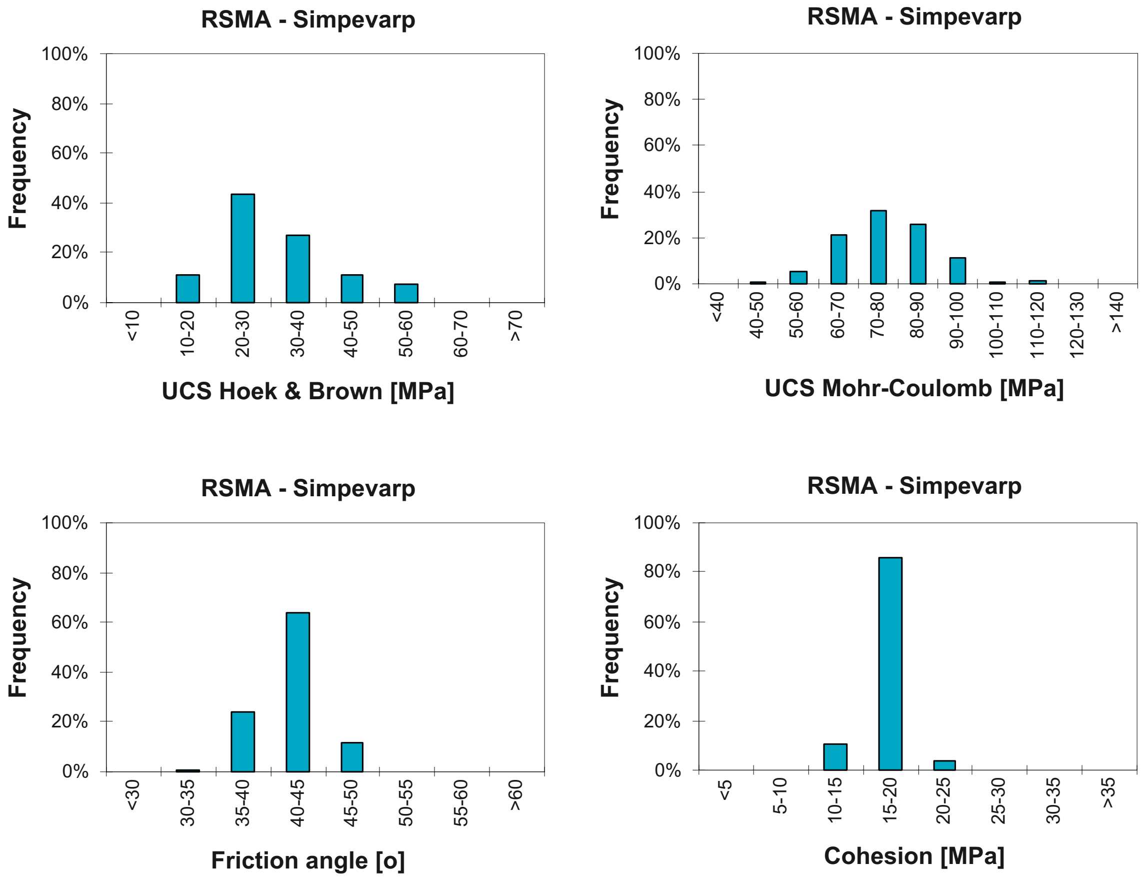

Figure A1-2. *Rock Domain RSMA at Simpevarp: Histograms showing the results of the derived mechanical properties.*

A1.2 Histograms for Rock Domain RSMA at Laxemar

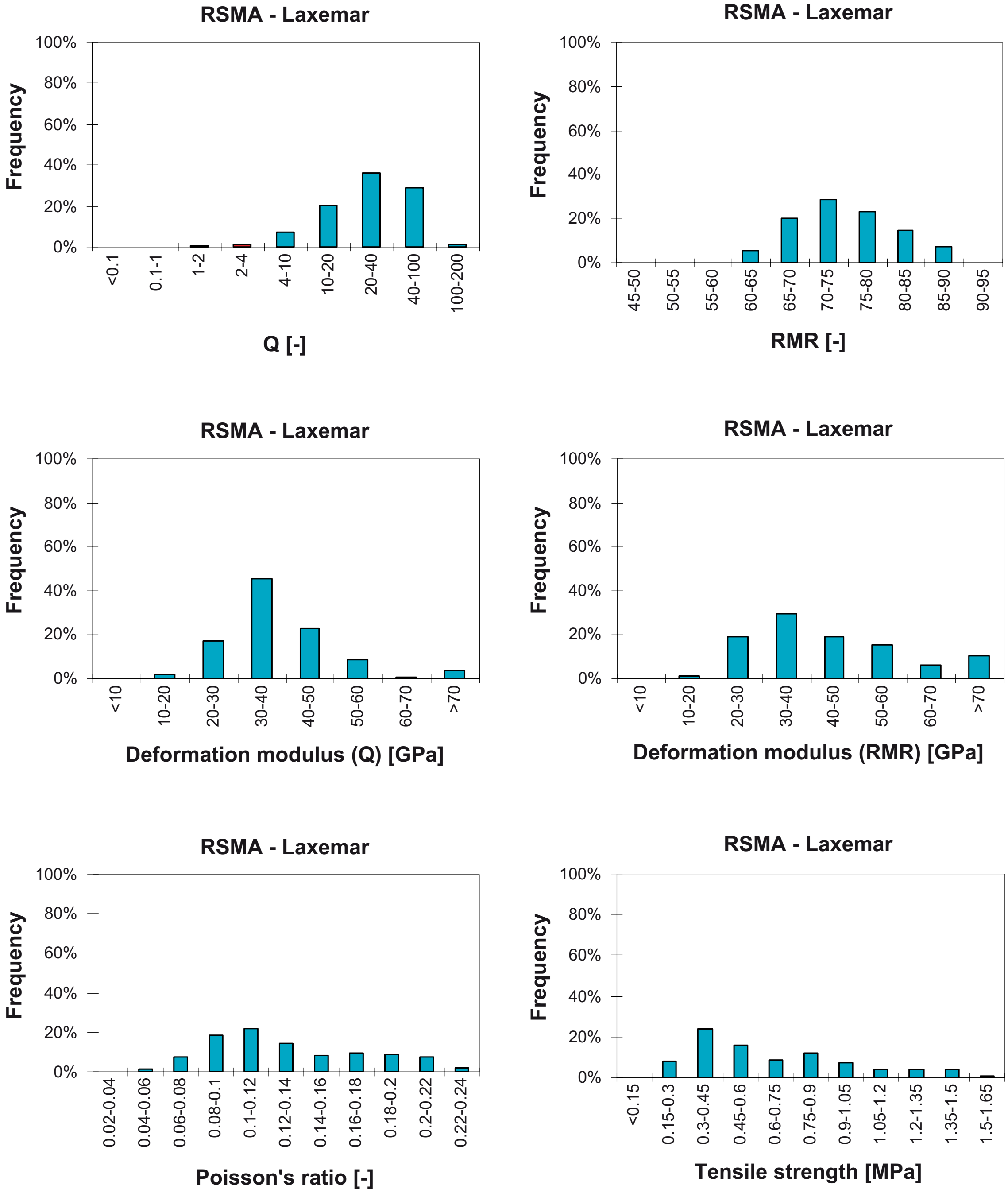

Figure A1-3. *Rock Domain RSMA at Laxemar: Histograms showing the results of RMR and Q and derived mechanical properties.*

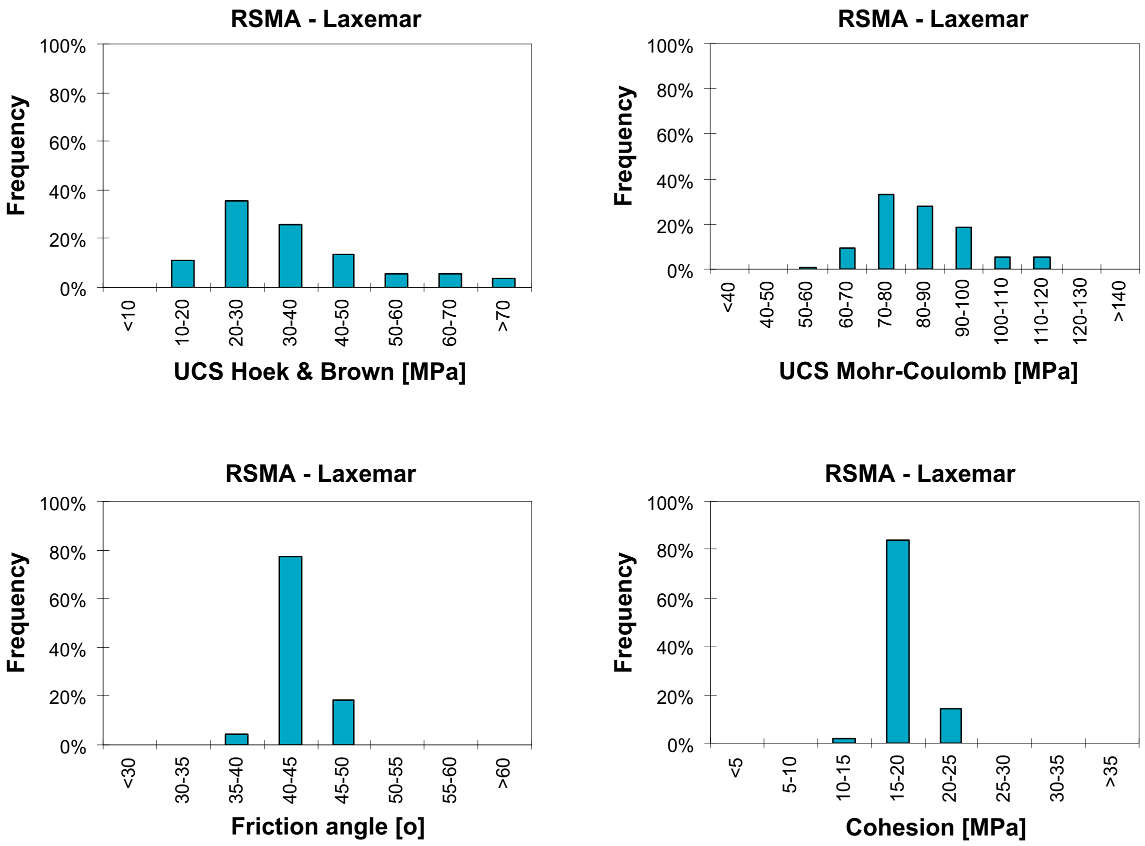

Figure A1-4. *Rock Domain RSMA at Laxemar: Histograms showing the results of derived mechanical properties.*

A1.3 Histograms for Rock Domain RSMB at Simpevarp

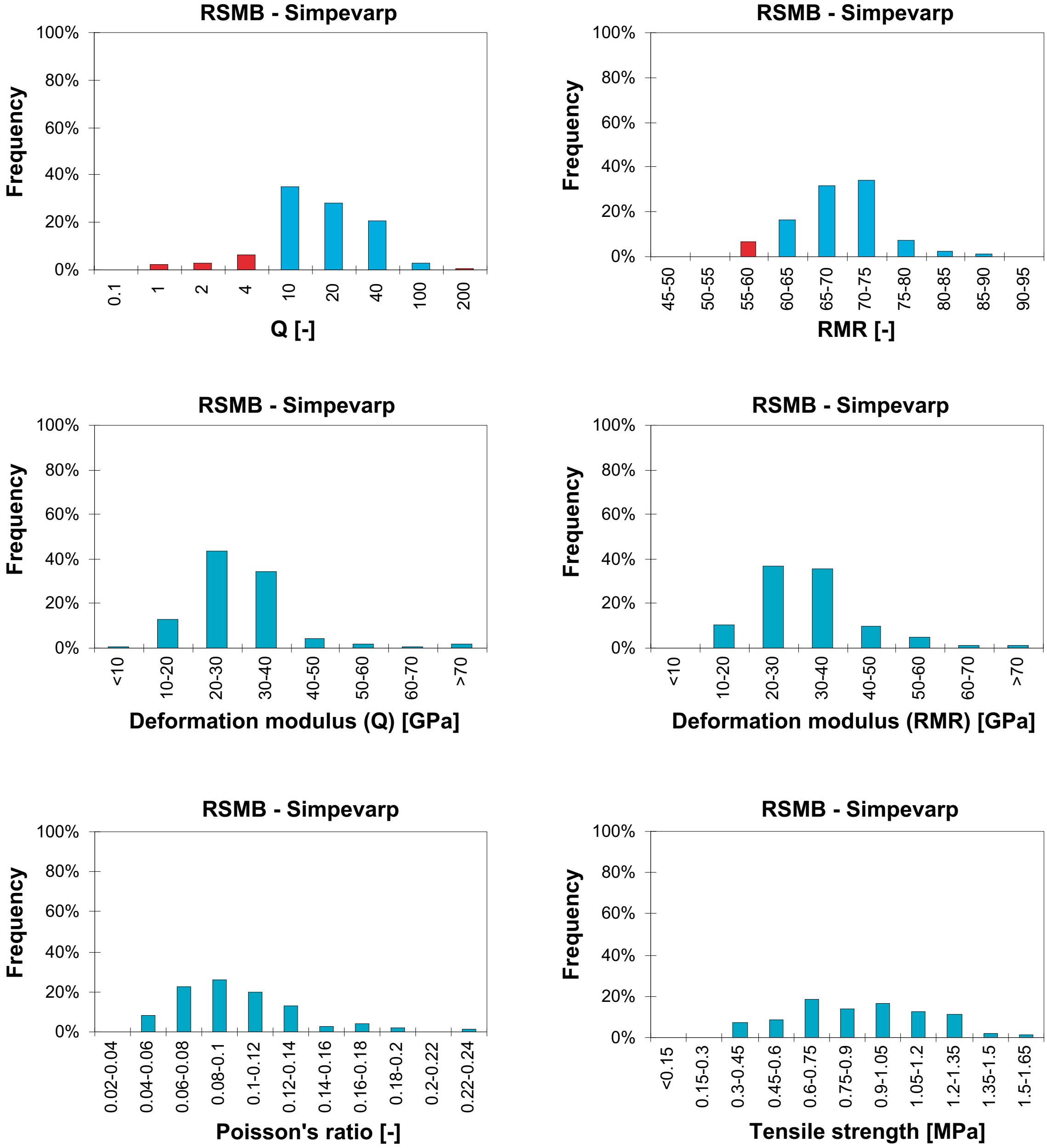

Figure A1-5. *Rock Domain RSMB at Simpevarp: Histograms showing the results of RMR and Q and derived mechanical properties.*

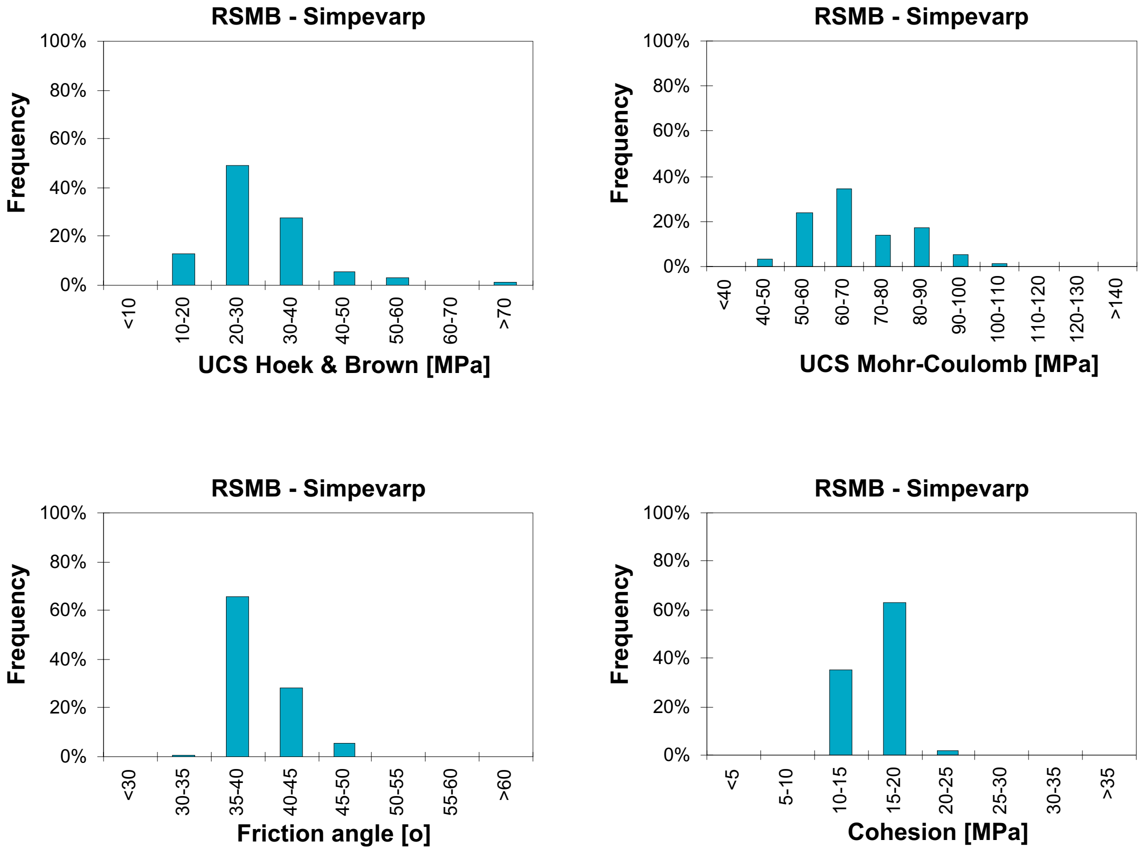

Figure A1-6. *Rock Domain RSMB at Simpevarp: Histograms showing the results of derived mechanical properties.*

A1.4 Histograms for Rock Domain RSMBA at Laxemar

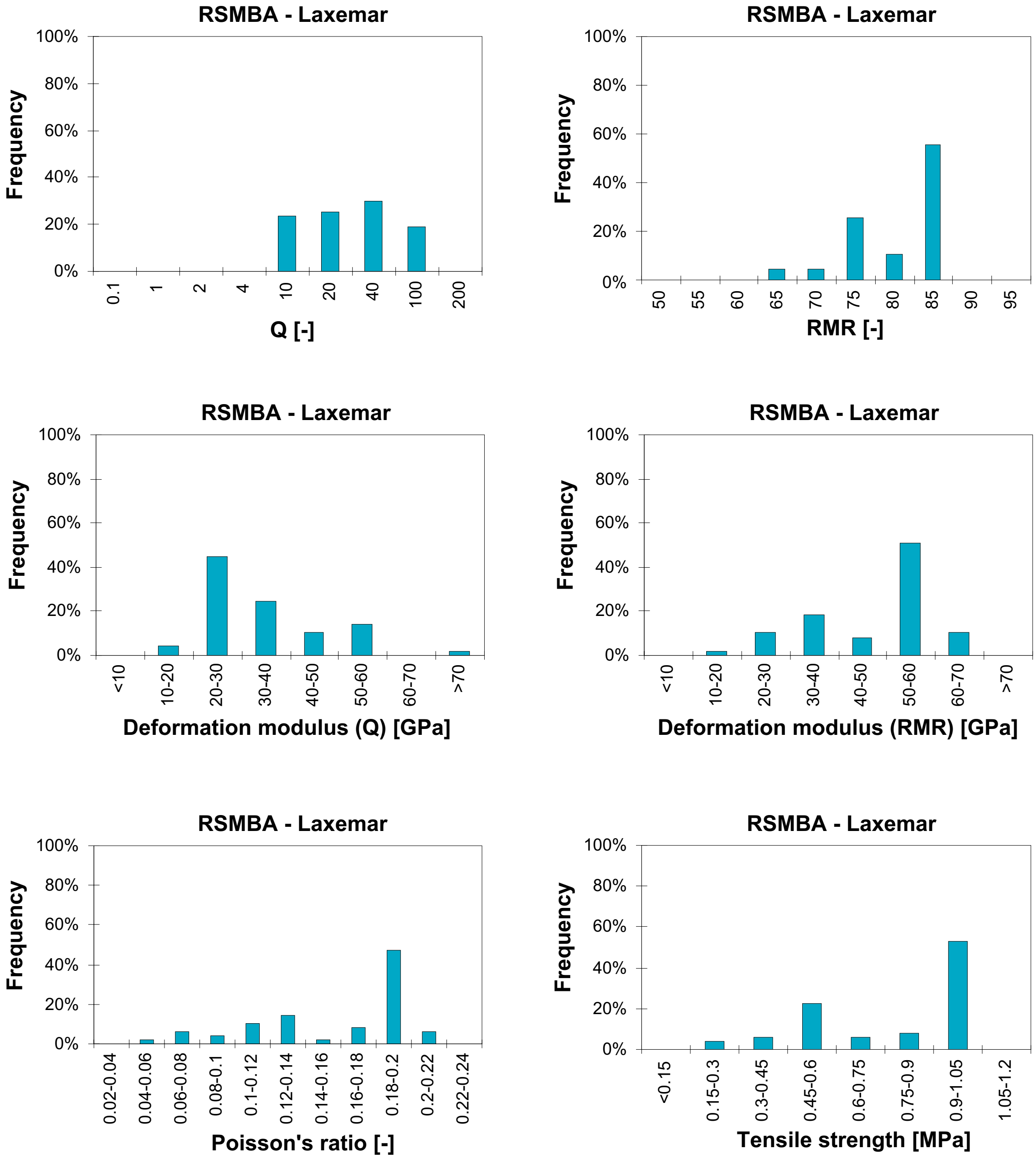

Figure A1-7. *Rock Domain RSMBA at Laxemar: Histograms showing the results of RMR and Q and derived mechanical properties.*

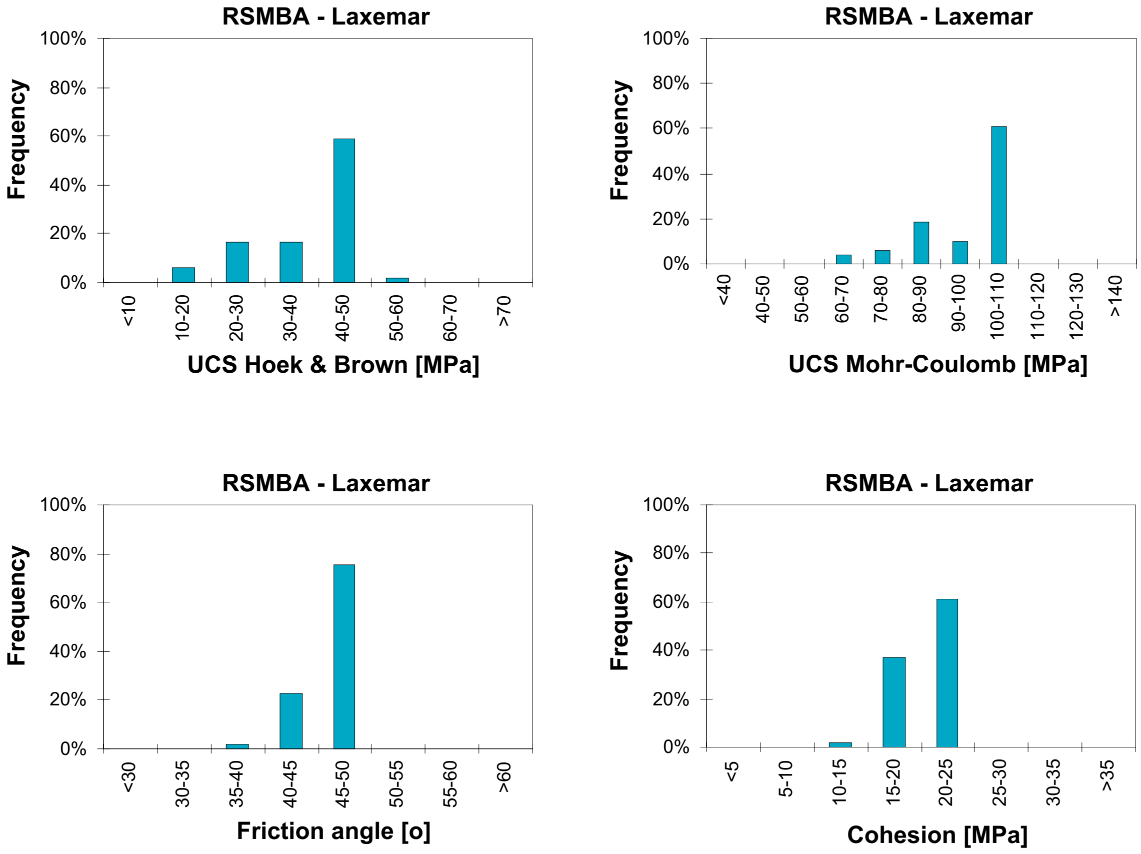

Figure A1-8. *Rock Domain RSMBA at Laxemar: Histograms showing the results of derived mechanical properties.*

A1.5 Histograms for Rock Domain RSMC at Simpevarp

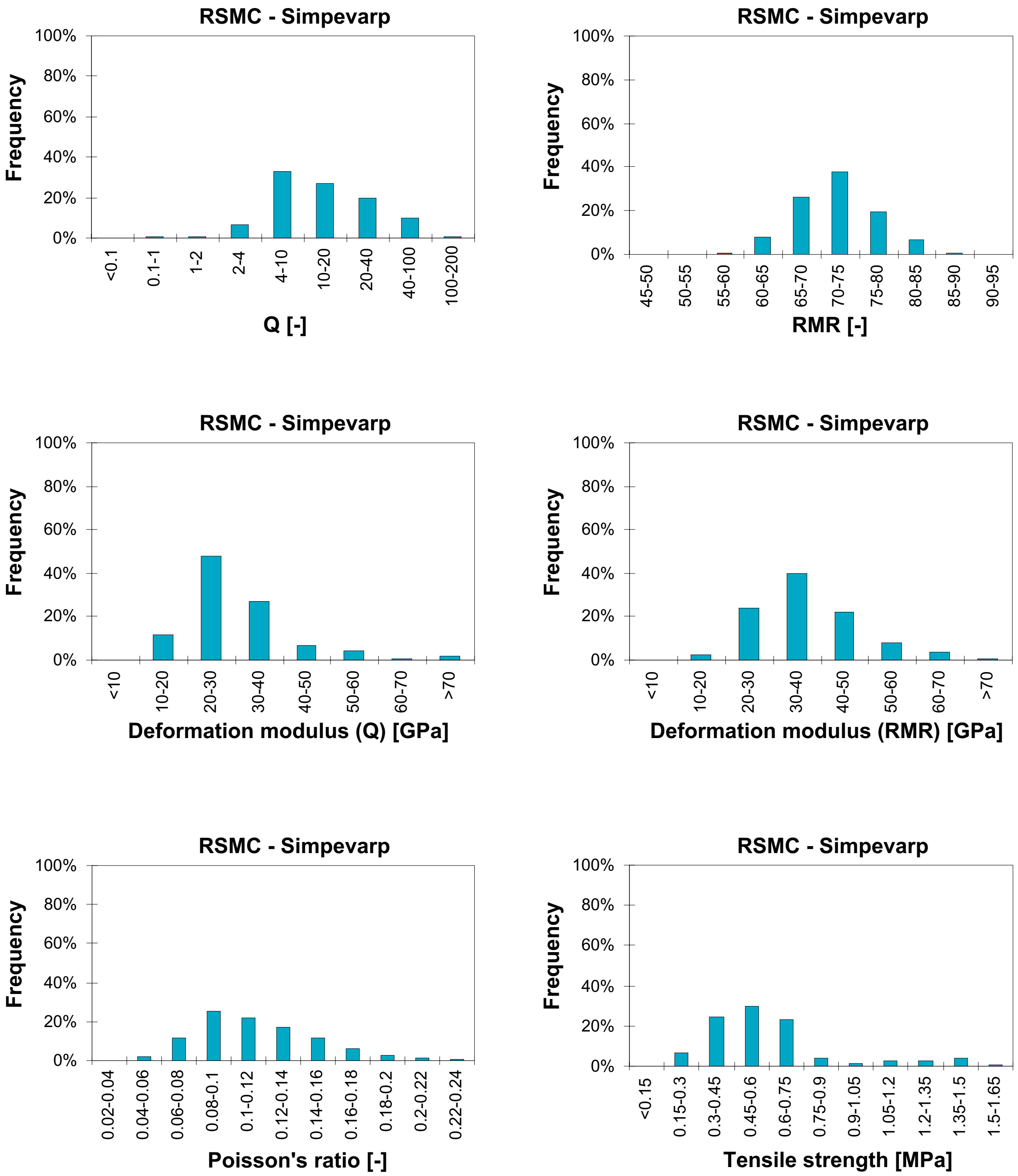

Figure A1-9. *Rock Domain RSMC at Simpevarp: Histograms showing the results of RMR and Q and derived mechanical properties.*

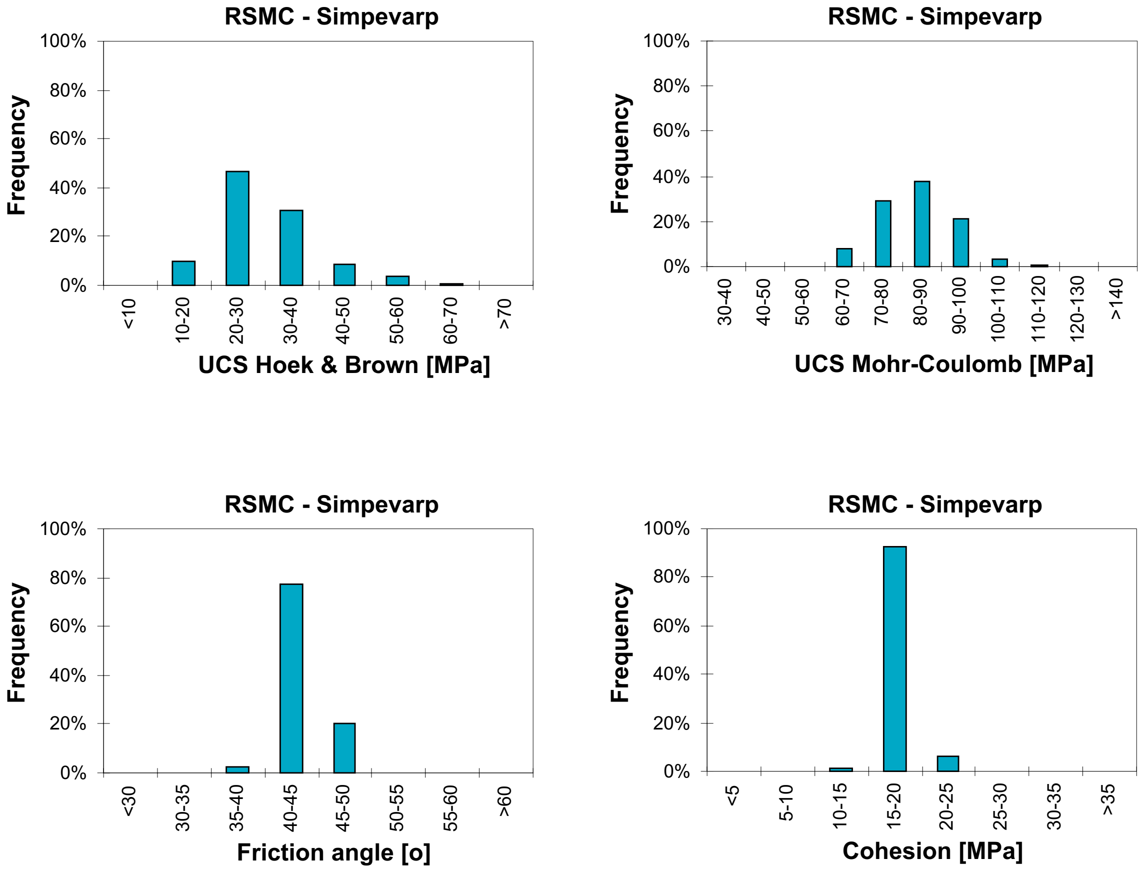

Figure A1-10. *Rock Domain RSMC at Simpevarp: Histograms showing the results of derived mechanical properties.*

A1.6 Histograms for Rock Domain RSMD at Laxemar

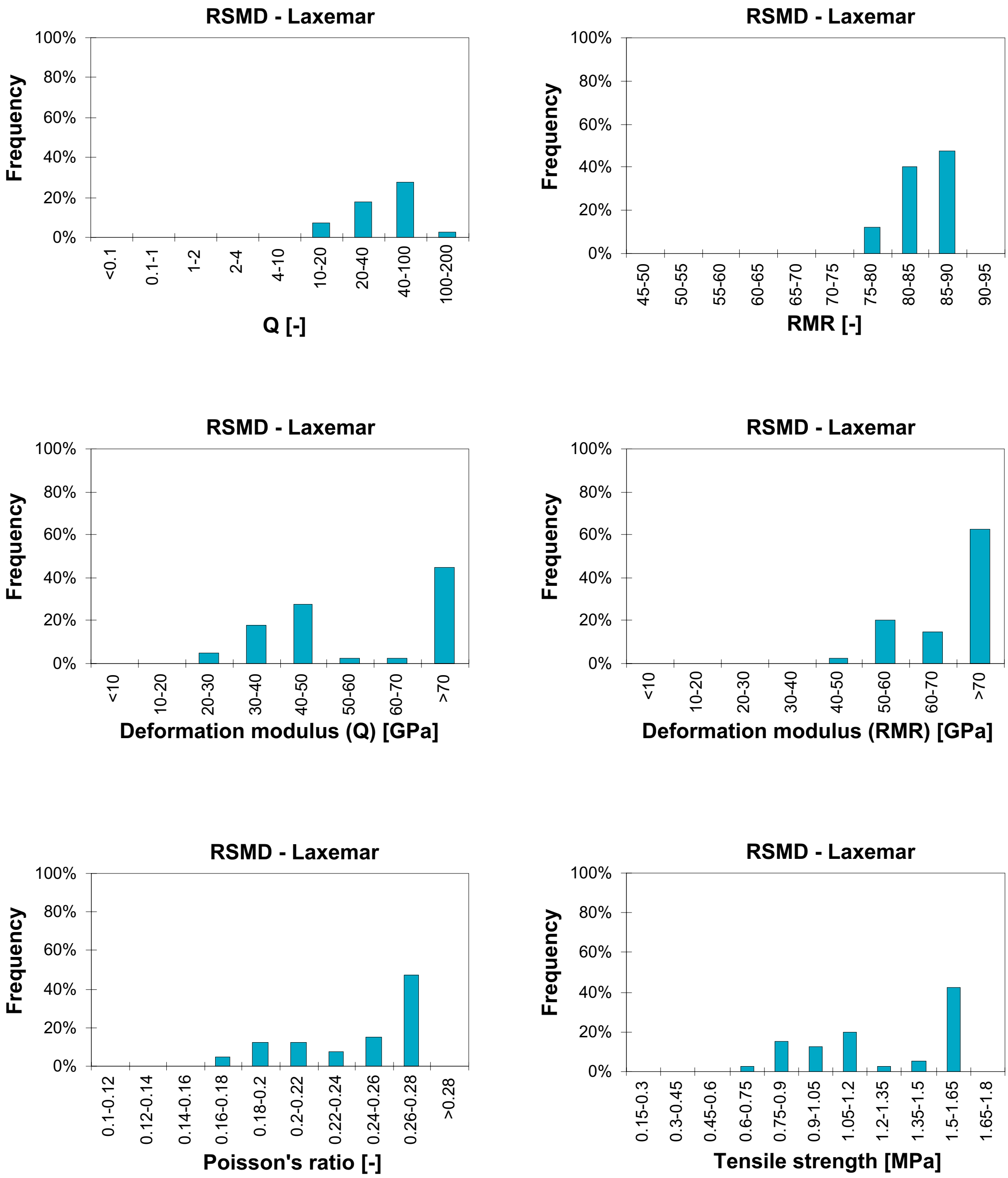

Figure A1-11. *Rock Domain RSMD at Laxemar: Histograms showing the results of RMR and Q and derived mechanical properties.*

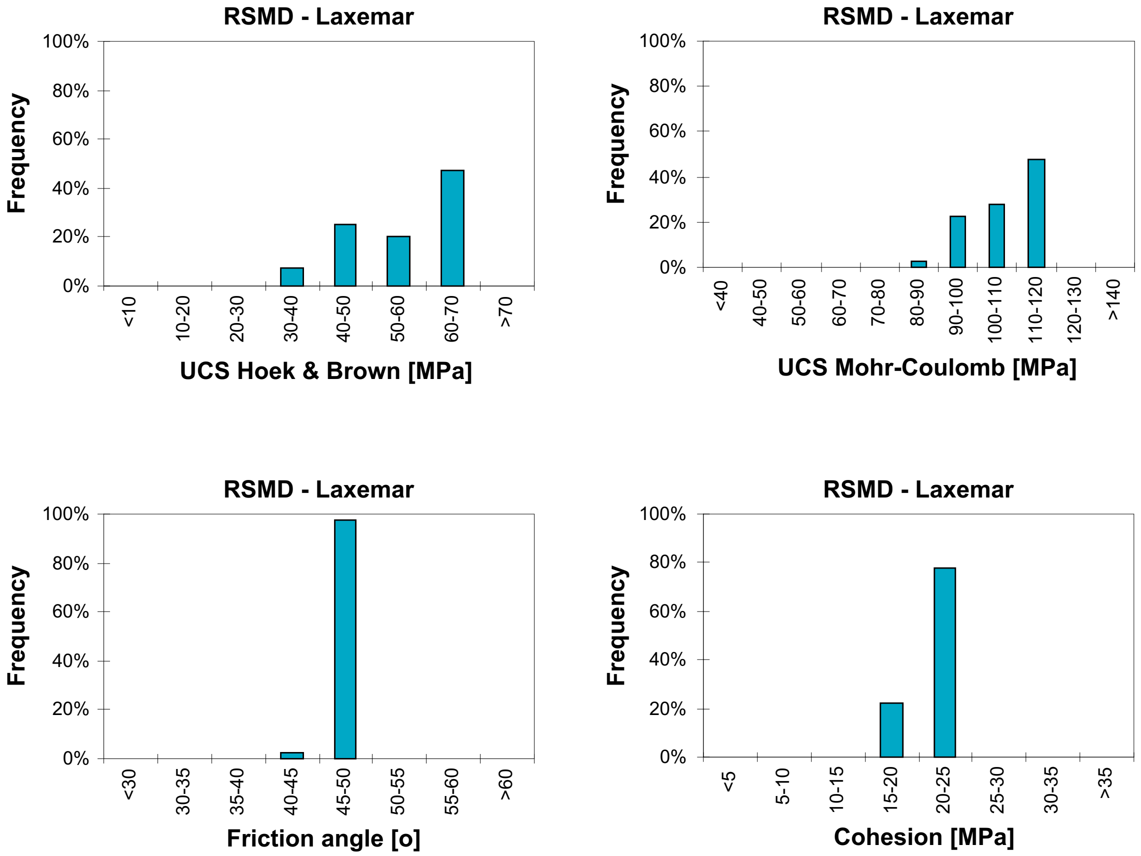

Figure A1-12. *Rock Domain RSMD at Laxemar: Histograms showing the results of derived mechanical properties.*

A1.7 Histograms for Rock Domain RSMM at Laxemar

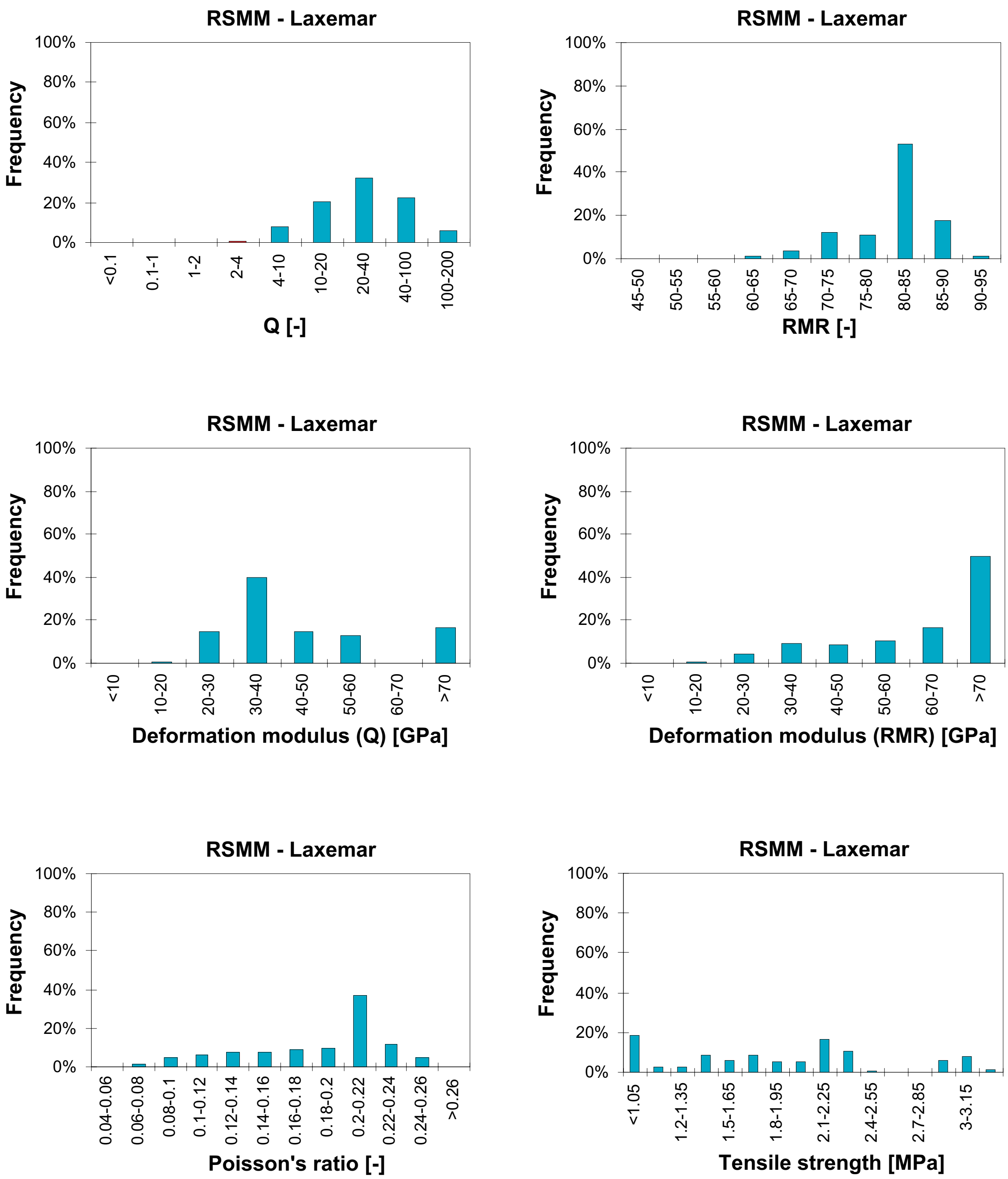

Figure A1-13. *Rock Domain RSMM at Laxemar: Histograms showing the results of RMR and Q and derived mechanical properties.*

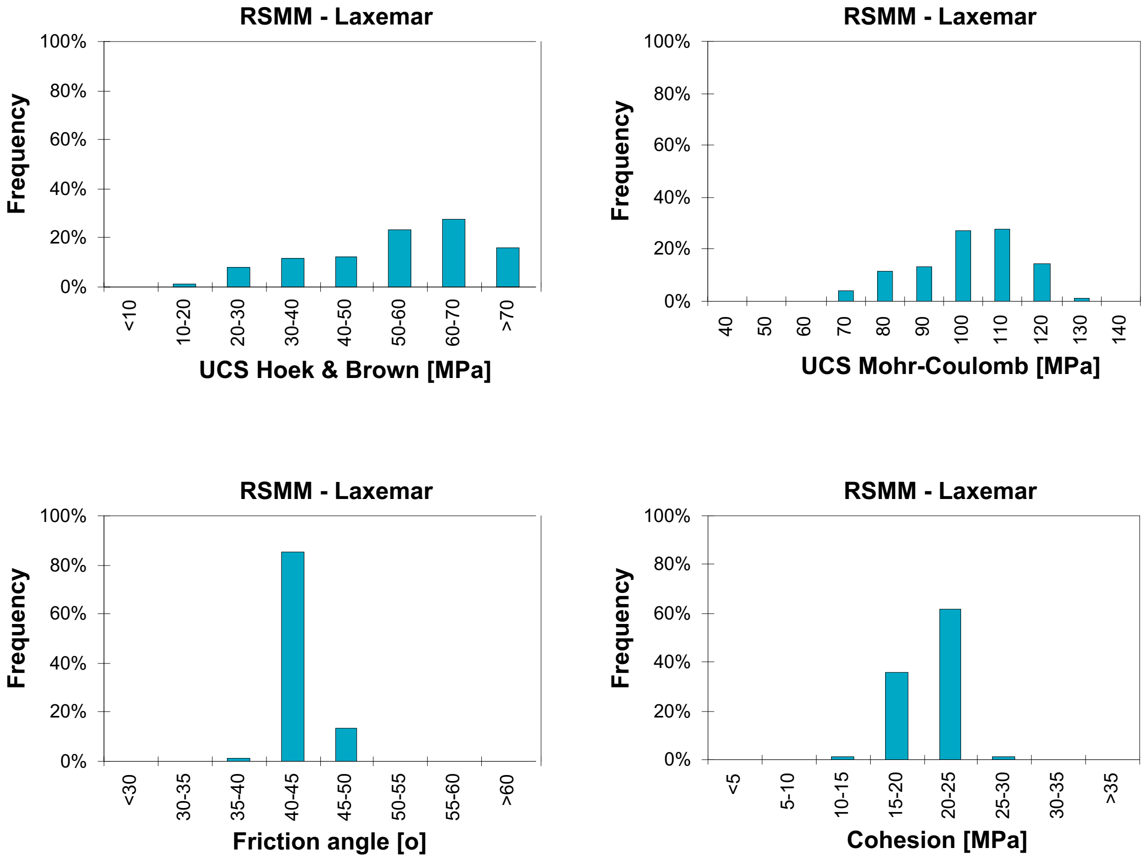

Figure A1-14. *Rock Domain RSMM at Laxemar: Histograms showing the results of derived mechanical properties.*

A2 Deterministic Deformation Zones

A2.1 Histograms for Zone ZSMEW007A

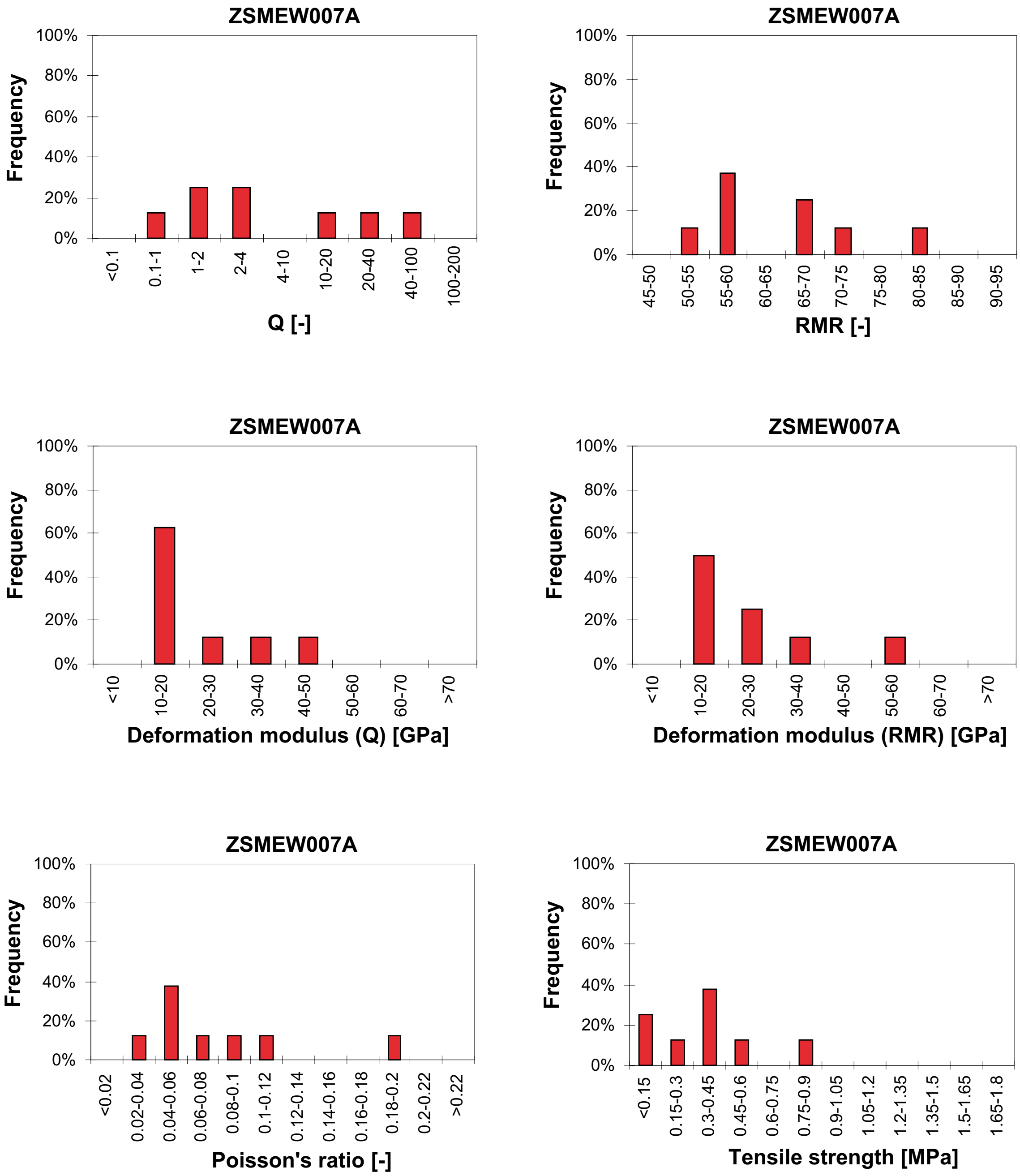

Figure A1-15. *Zone ZSMEW007A: Histograms showing the results of RMR and Q and derived mechanical properties.*

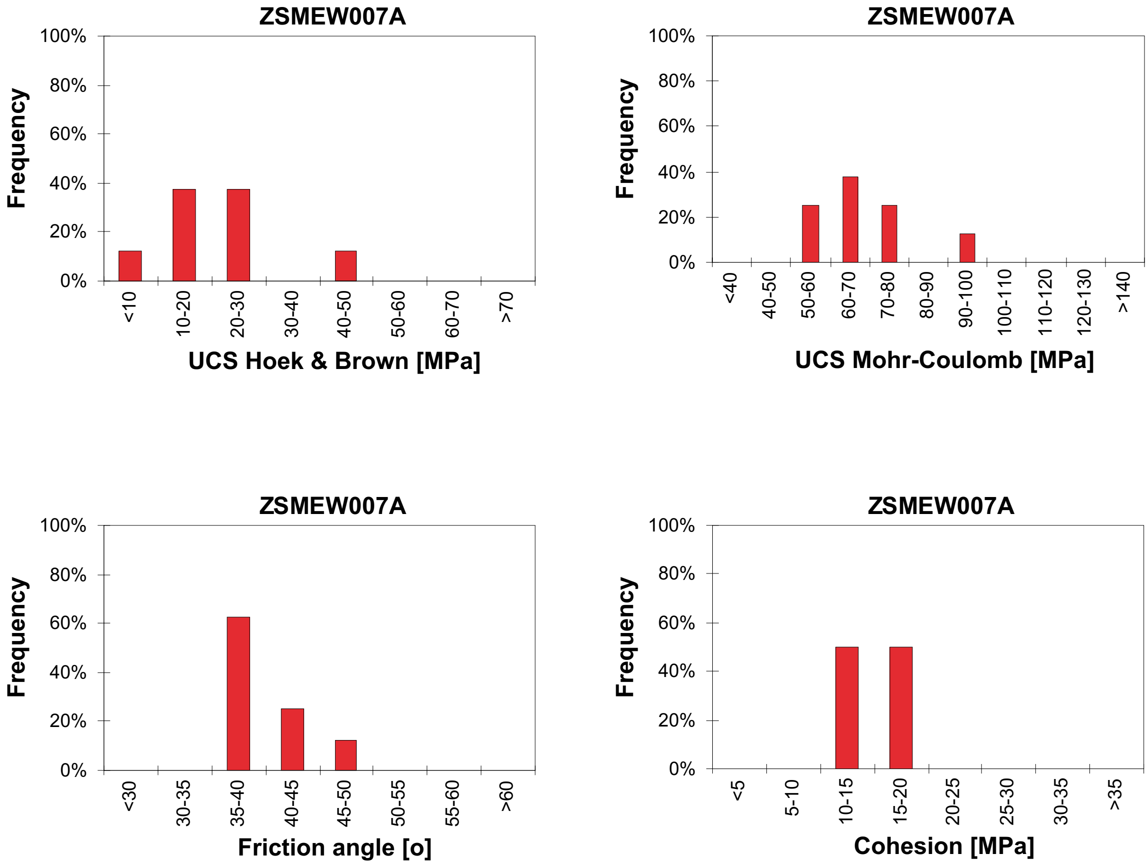

Figure A1-16. *Zone ZSMEW007A: Histograms showing the results of derived mechanical properties.*

A2.2 Histograms for Zone ZSMNW929A

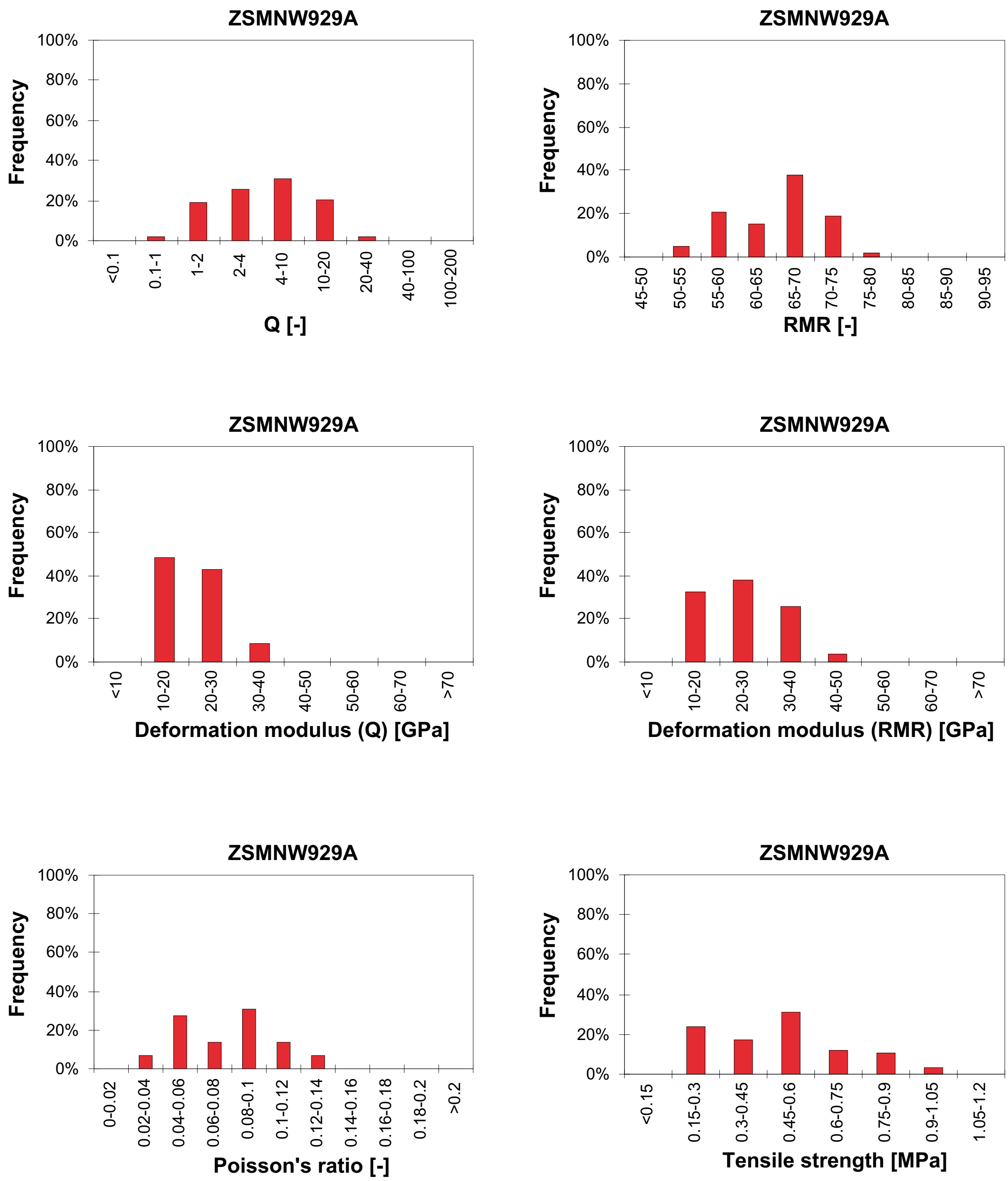

Figure A1-17. *Zone ZSMNW929A: Histograms showing the results of RMR and Q and derived mechanical properties.*

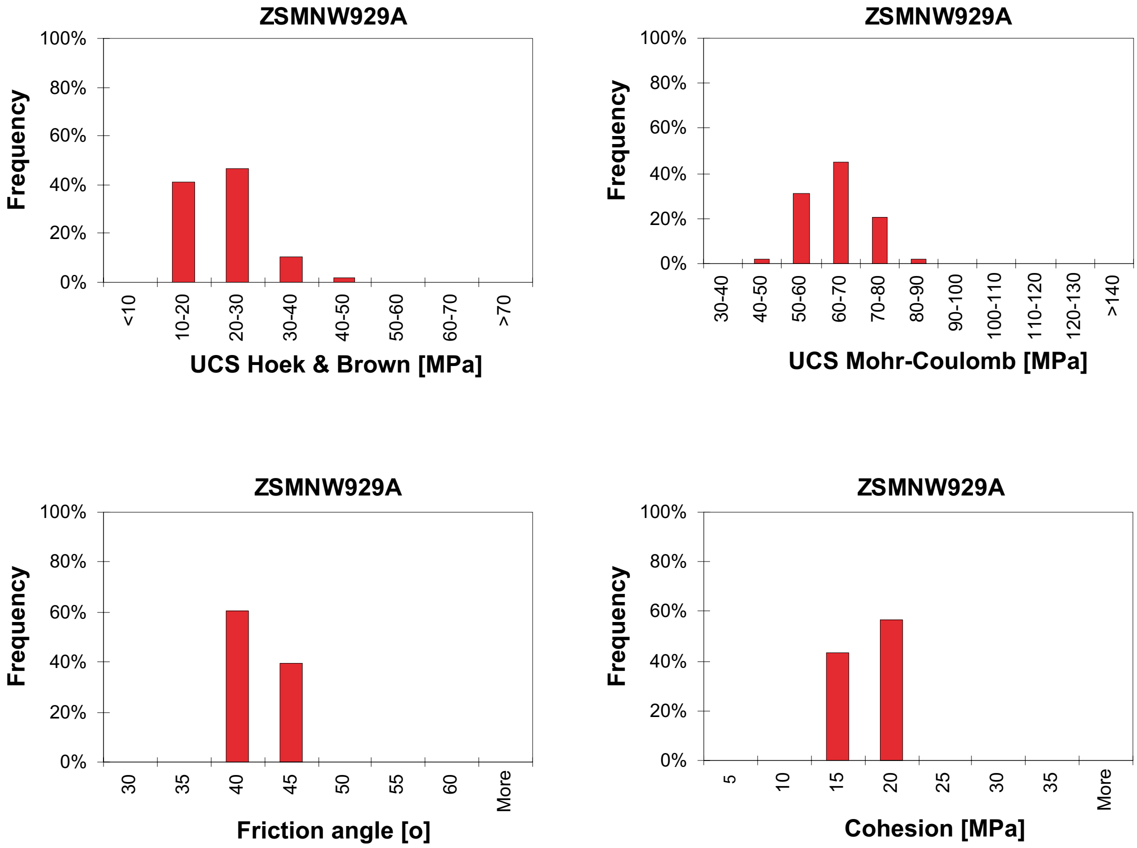

Figure A1-18. *Zone ZSMNW929A: Histograms showing the results of derived mechanical properties.*

A2.3 Histograms for Zone ZSMNE012A

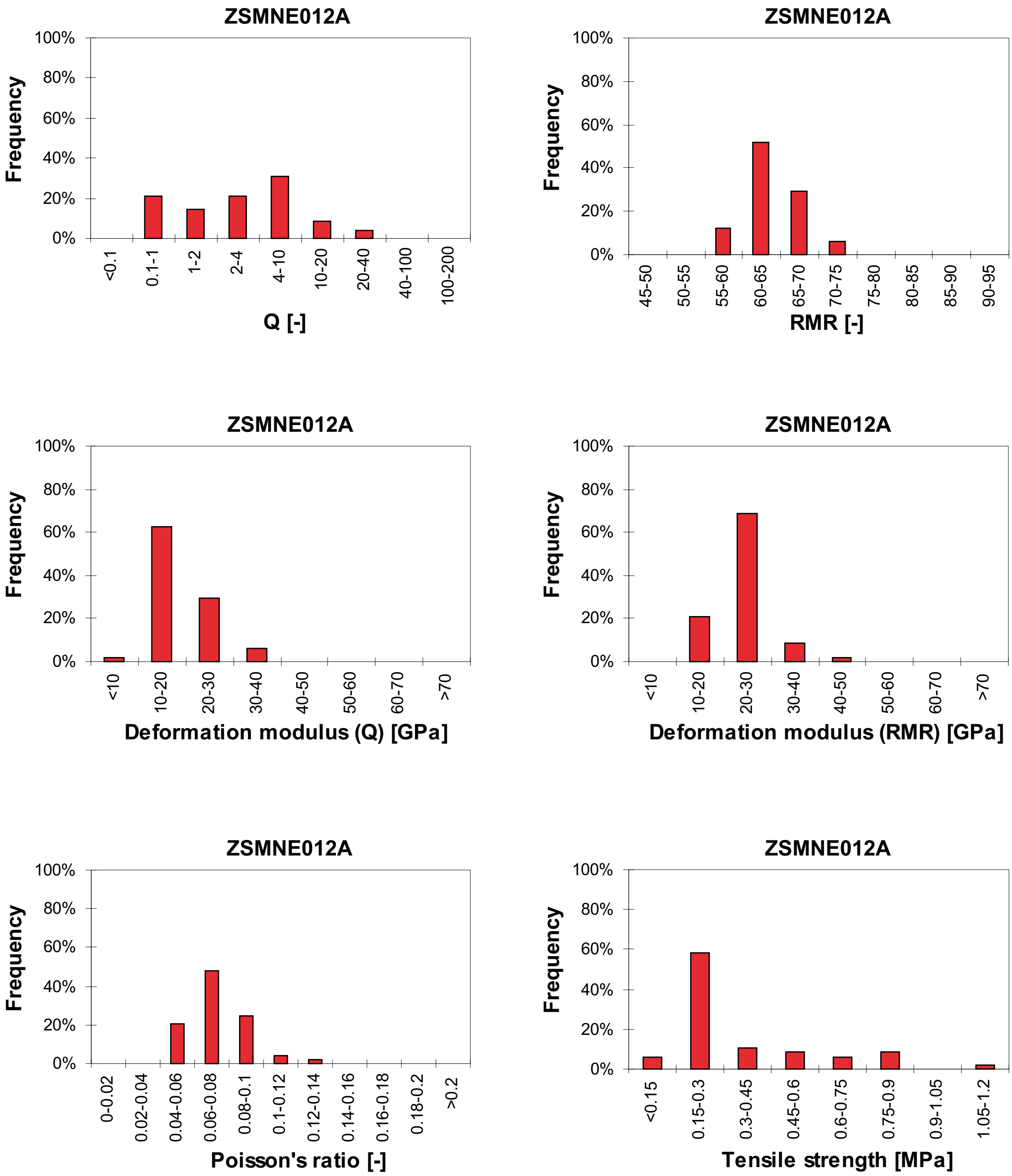

Figure A1-19. *Zone ZSMNE012A: Histograms showing the results of RMR and Q and derived mechanical properties.*

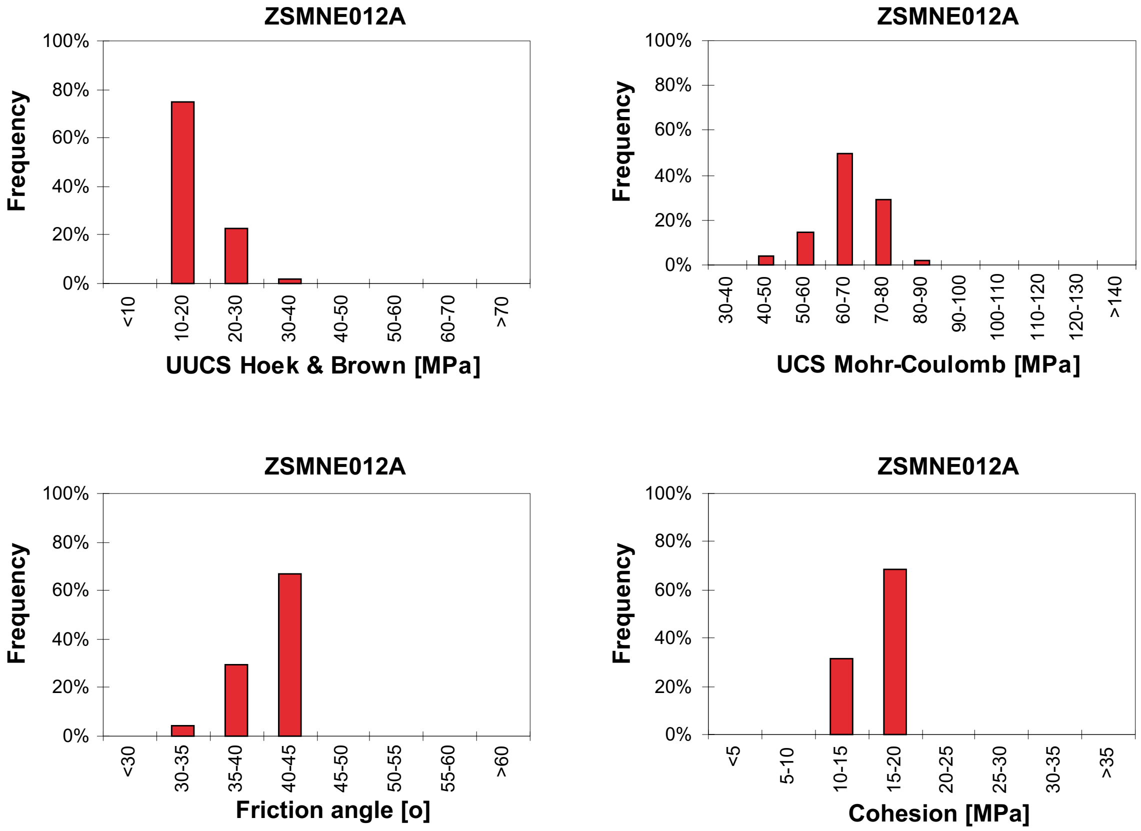

Figure A1-20. *Zone ZSMNE012A: Histograms showing the results of derived mechanical properties.*

A2.4 Histograms for Zone ZSMNE024A

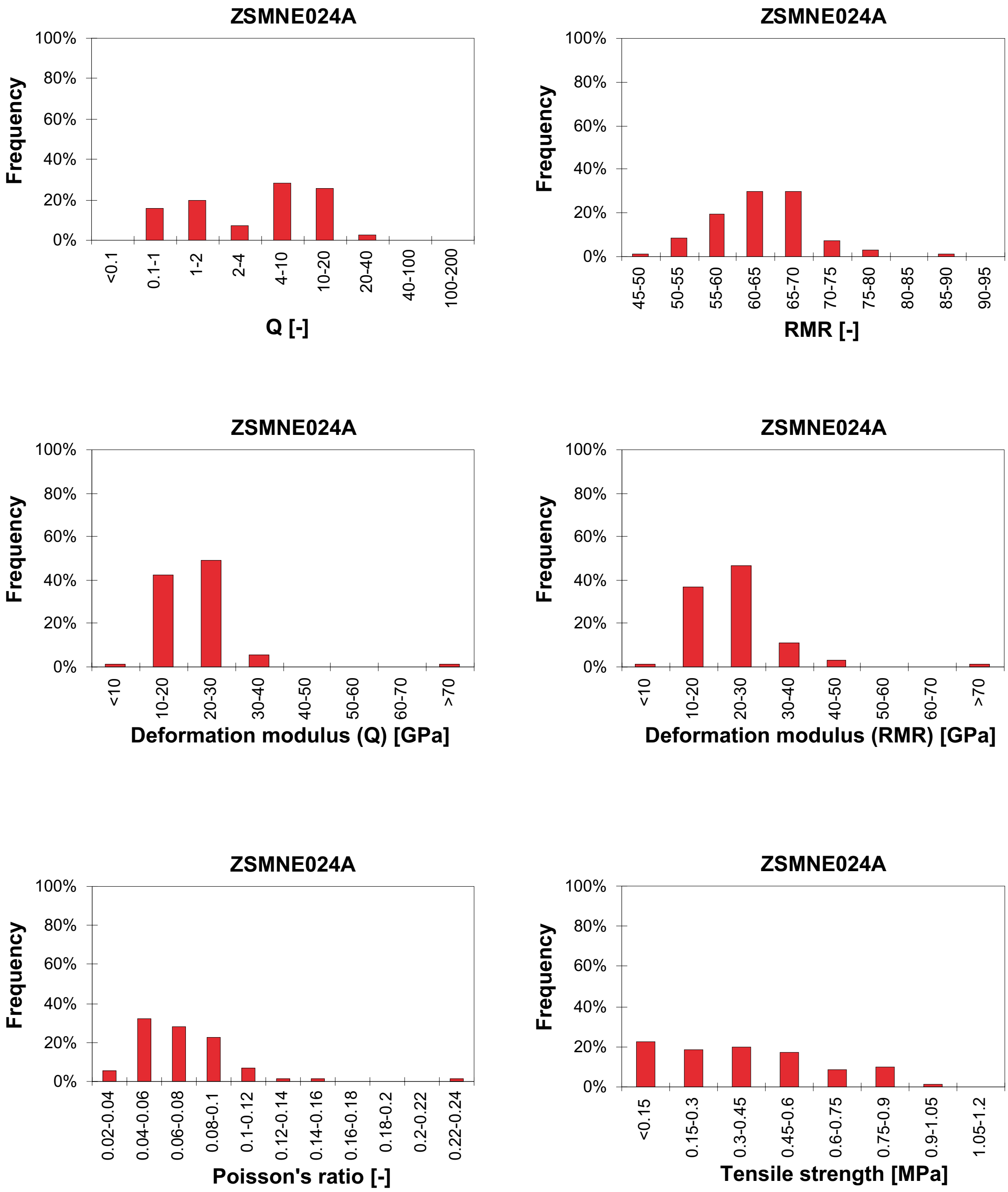

Figure A1-21. *Zone ZSMNE024A: Histograms showing the results of RMR and Q and derived mechanical properties.*

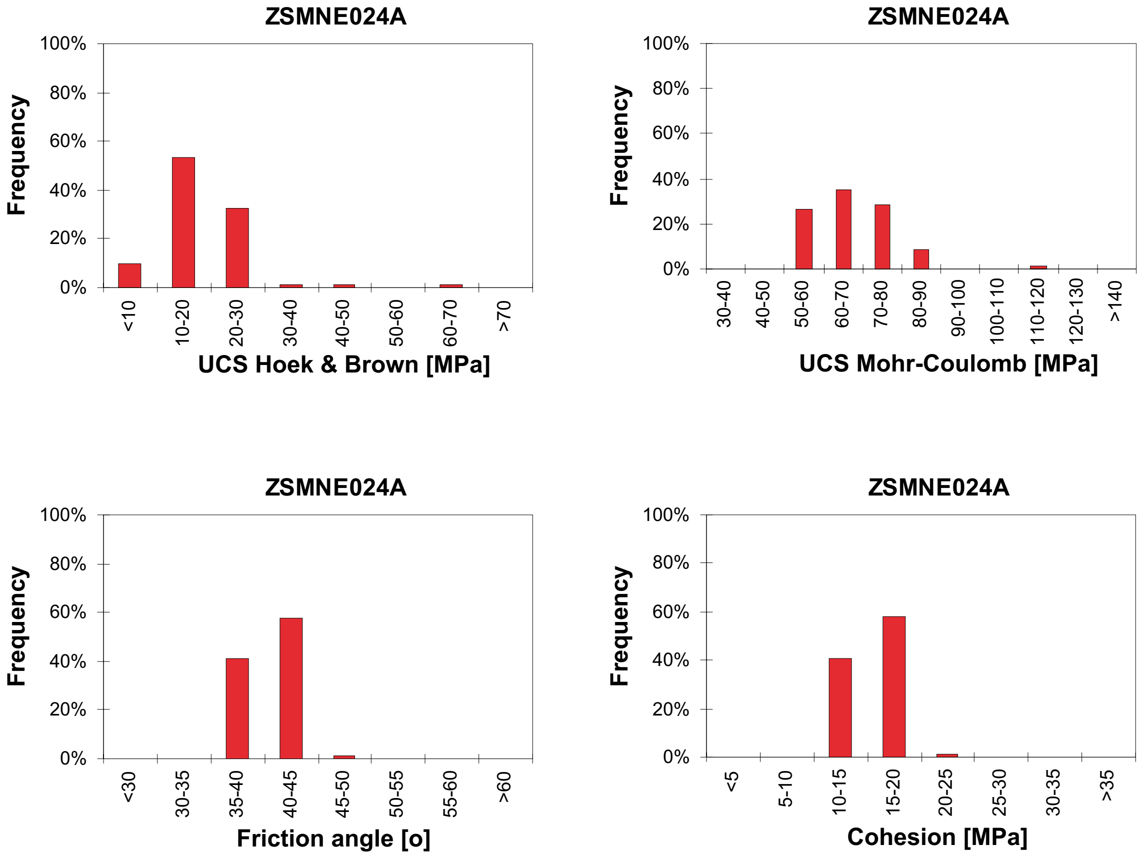

Figure A1-22. *Zone ZSMNE024A: Histograms showing the results of derived mechanical properties.*

A2.5 Histograms for Zone ZSMNE031A

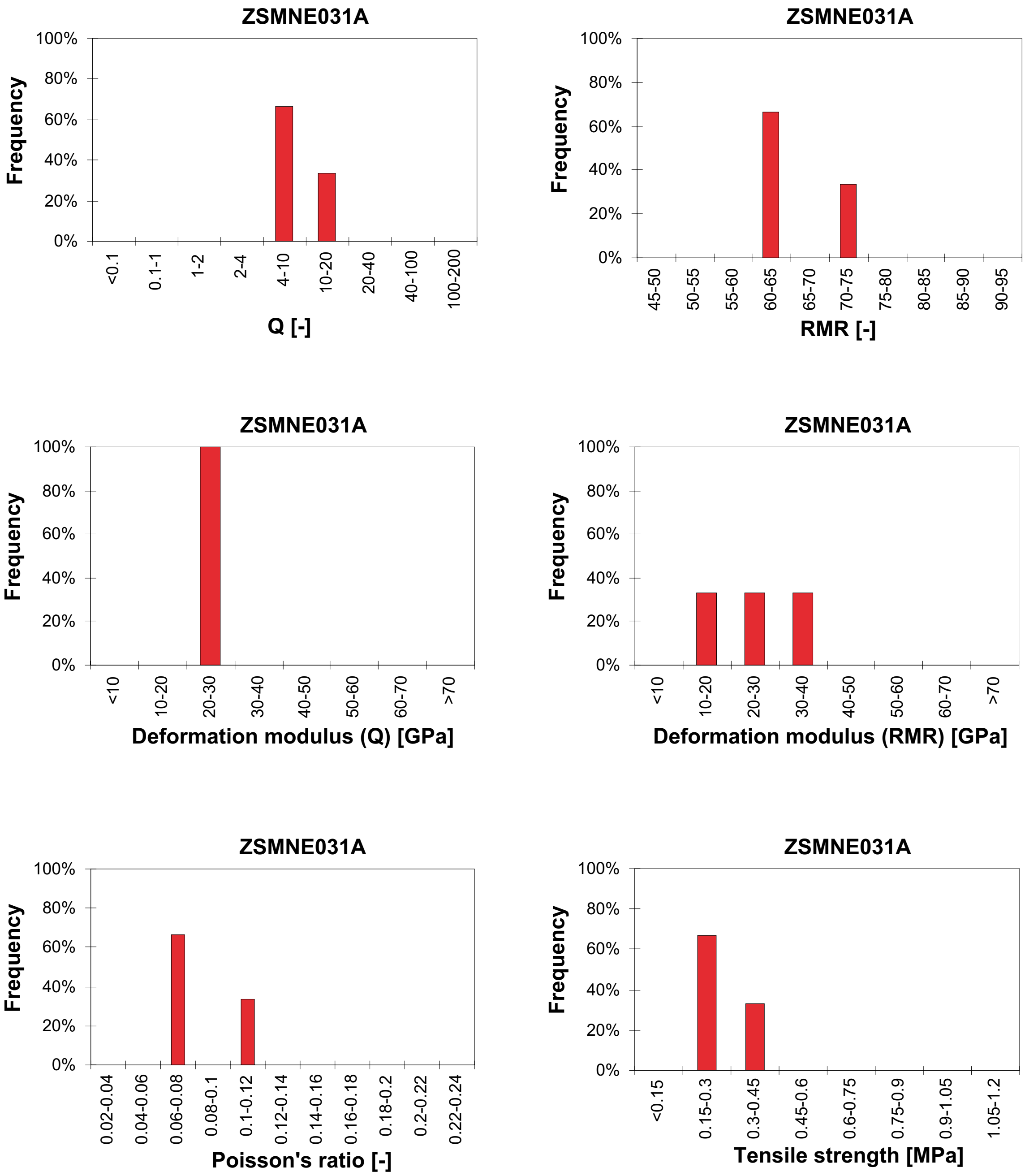

Figure A1-23. *Zone ZSMNE031A: Histograms showing the results of RMR and Q and derived mechanical properties.*

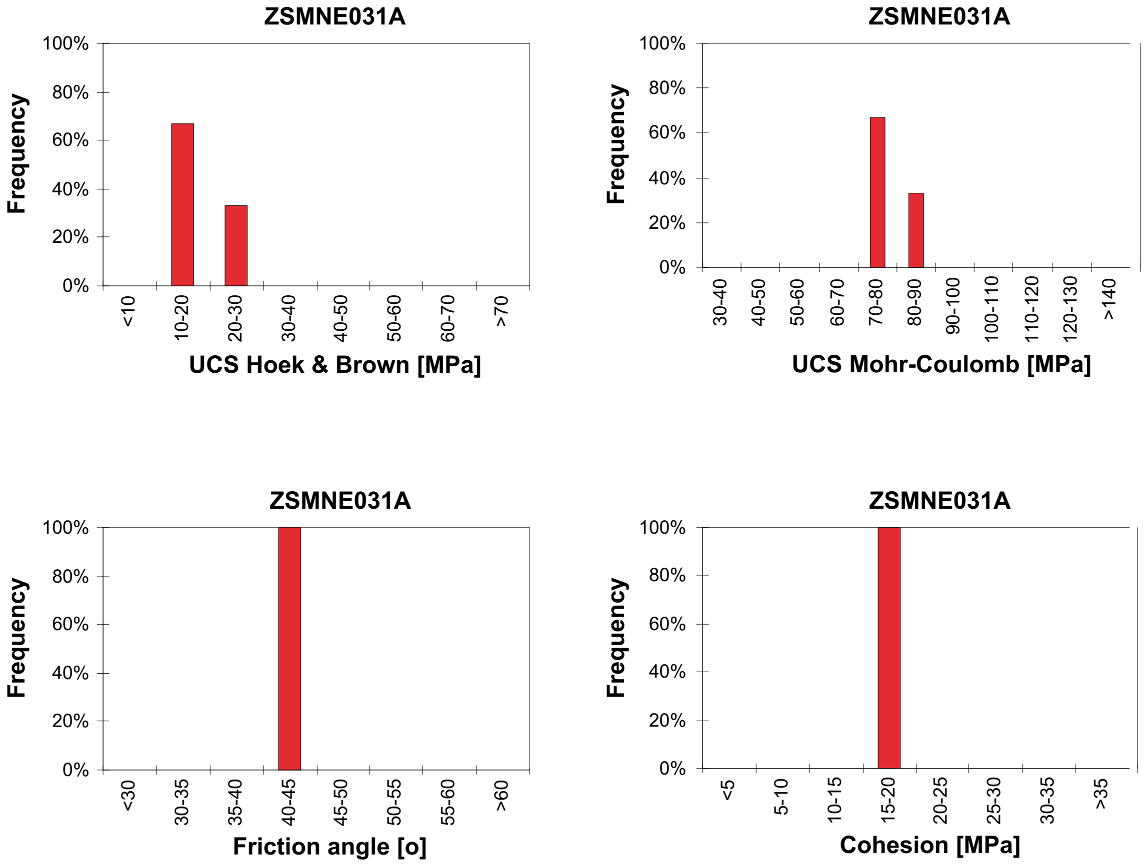

Figure A1-24. *Zone ZSMNE031A: Histograms showing the results of derived mechanical properties.*

A2.6 Zone ZSMNW932A

Only preliminary information was available about this zone.

A2.7 Zone ZSMNE004A

This Zone should intercept borehole KAV04, but clear signs of its presence were not observed by the geologist. Since no intersection with the boreholes is available, no rock mass properties could be determined.