R-05-83

Rock Mechanics Model – Summary of the primary data

Preliminary site description Forsmark area – version 1.2

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December 2005

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ISSN 1402-3091
SKB Rapport R-05-83

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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 authors and do not necessarily coincide with those of the client.

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Abstract

The present report summarises the laboratory results performed on samples of intact rock and natural fractures collected at Forsmark in relation to the Preliminary Site Descriptive Modelling, version 1.2.

Uniaxial, triaxial and indirect tensile tests on intact rock and; tilt, normal and shear tests on natural fractures were performed on samples from boreholes KFM01A, KFM02A, KFM03A and KFM04A. The samples were mainly taken from the rock types: granite to granodiorite and tonalite to granodiorite. The uniaxial compressive strength of the granite and granodiorite is higher (225 MPa) than that of the tonalite (156 MPa) (SP results). The uniaxial compressive strength obtained at HUT gives on average 5% higher strength than that obtained at the SP Laboratory. The cohesion and friction angle of 28 MPa and 60° for the granite to granodiorite, respectively, and 30 MPa and 47° for the tonalite to granodiorite, respectively. The crack initiation stress of the intact rock was also determined.

The values of the Young's modulus obtained range between 70 and 76 GPa on average for all rock types. The Poisson's ratio in uniaxial conditions, on the other hand, is on average 0.24 for the granite to granodiorite and 0.27 for the tonalite to granodiorite.

The mechanical properties of the rock samples taken from some of the boreholes might indicate a decrease of strength for depth larger than about 600 m due to microcracking induced by the release of high stresses during drilling. Further studies on the depth dependency of the mechanical properties of the intact rock should be carried out.

Natural fractures were also tested with the same technique by two laboratories, SP and NGI. Tilt tests show that the average JRC_0 of the fractures is on average around 6 while the basic friction angle is around 30°. The average peak cohesion and friction angle of all the samples tested in direct shear by the SP Laboratory was 34° and 0.6 MPa, respectively. The SP results were chosen to represent the properties of the fractures at Forsmark mainly because they were the most numerous and agreed well with the tilt test results. From the loading tests, the normal and shear stiffness of the fractures could also be obtained.

Sammanfattning

Denna rapport sammanfattar de laboratorieresultat på intakt berg och naturliga sprickor som samlats in i Forsmark i samband med den Platsbeskrivande modellen, version 1.2.

Enaxiella, triaxiella tryck-, och indirekta drag-hållfasthetstester genomfördes på prover från borrhål KFM01A, KFM02A, KFM03A och KFM04A. Bergarterna som provtagits var granit till granodiorit och tonalit till granodiorite. Den enaxiella tryckhållfastheten för graniten är i genomsnitt högre (225 MPa) än den för tonaliten (156 MPa). Samma typ av test genomfördes av HUT och resulterade i en 5 % högre hållfasthet för graniten jämfört med den som SP fick fram. Kohesionen och friktionsvinkeln för det intakta berget kunde också bestämmas och är 28 MPa respektive 60° för graniten, medan den är 30 MPa respektive 47° för tonaliten. Även ”crack initiation” spänningen bestämdes.

Den genomsnittliga Young-modulen för samtliga bergarter varierar mellan 70 och 76 GPa och det genomsnittliga Poissontalet varierar från 0.24 för graniten till 0.27 för tonaliten.

De mekaniska egenskaperna hos intakt berg verkar minska med djupet under ca 600 m i några av borrhålen. Detta kan bero på sprickbildning orsakad av en stor spänningsavlastning vid borrkärneupptagningen. Ytterligare studier av testresultatens djupberoende bör genomföras.

Naturliga sprickor testades för normal och sjuvbelastning med samma teknik men i olika laboratorier, SP och NGI. Tilttesterna returnerade en genomsnittlig JRC_0 på 6 och en bas-friktionsvinkel på 30°. De direkta sjuvtesterna gjorda av SP Laboratoriet visade en max-kohesion och max-friktionsvinkel på 34° respektive 0,6 MPa. SP-resultaten valdes för att representera sprickegenskaperna i Forsmark tack vare dess stora datamängd och överensstämmelsen med tilttesterna. Från testerna kunde den normala och sjuv-styvheten hos sprickorna också bestämmas.

Contents

1 Introduction

The present report shows the summary of the data used as base for the Rock Mechanics Descriptive Model for Forsmark version 1.2. The available primary data consist on test results of intact rock and natural rock fractures. The data analysed were those saved in SICADA by July 12th, 2004. After this date, normal and shear loading test results of natural fractures were also delivered. The data were obtained from borehole KFM01A, KFM02A, KFM03A and KFM04A. The tests were conducted on:

- Intact rock: uniaxial, triaxial and indirect tensile tests.
- Natural rock fractures: tilt and direct shear tests.

These data are illustrated here by means of tables and graphs. Old laboratory tests from the Forsmark Power Plant and the SFR Repository were also compared with the new laboratory data for the correspondent rock types /SKB 2004/.

The results are presented in this report to be used by different end-users:

a) Empirical Approach.

b) Theoretical Approach.

c) Site Descriptive Modelling.

d) Design and Safety Assessments.

The users can obtain specific information on Coulomb's and Hoek & Brown's Criterion parameters for the intact rock and for the Coulomb's parameters for the rock fractures. Barton-Bandis's Criterion from the tilt tests conducted on natural fractures can also be found.

The appendices show details on the frequency distributions of the parameters of the intact rock (Appendix 1) and the results from the tilt and direct shear tests (Appendix 2).

2 Intact rock

In this chapter, the results of the uniaxial compressive strength tests on intact rock samples are summarised independently and together with the results of the triaxial compressive strength tests. The rock types represented are: i) granite to granodiorite; ii) granodiorite; iii) tonalite to granodiorite.

Results from testing on the intact rock samples are also presented in Appendix 1.

Table 2-1. New laboratory tests carried out for the Forsmark Site Descriptive Model version 1.2.

Laboratory test	KFM01A	KFM02A	KFM03A	KFM04A
Uniaxial compressive tests	21	15	17	15
Triaxial tests	19	12	16	12
Indirect tensile tests	40	30	40	33
Shear tests on fractures	33 (7 samples)	21 (7 samples)	24 (8 samples)	18 (6 samples)
Tilt tests on fractures	41	40	35	26
P-wave velocity on core samples	34	79	68	37

2.1 Uniaxial compressive strength

The laboratory results of uniaxial compressive strength UCS on samples from borehole KFM01A, KFM02A, KFM03A and KFM04A were carried out at the SP Laboratory (Swedish National Testing and Research Institute) /Jacobsson 2004a–d/. They are sorted per rock type and the mean value and the standard deviation are determined (Table 2-2). The statistical description is completed with the minimum, maximum and most frequently occurring values.

In some cases, the records for each sample also refer to the presence of sealed fractures that could have affected the test behaviour. Sealed fractures occur in four samples of granite and tonalite. Statistics for these samples are given separately and show that their uniaxial strength is between the uniaxial strength of the granite and that of the tonalite. The sealed fractures in the boreholes represent about half of all the mapped fractures (on average 140 fractures every 100 m of borehole).

In Figure 2-1 and Figure 2-2, the frequency distributions of the samples from SFR /SKB 2004/ and the results in the present report can be compared. Only four tests were performed on tonalite, so the frequency distribution is uncertain for this rock type. It can be noticed that the SFR data refers to the rock types “gneissic granite” and “gneiss” that were not tested in the latest laboratory campaign for Forsmark SDM version 1.2.

/Eloranta 2004a/ carried out uniaxial compression tests at the HUT Laboratory (Helsinki University of Technology). The average uniaxial compressive strength of five samples of granite to metagranodiorite collected from borehole KFM01A (496–498 m depth) resulted to be 239 MPa, thus, a value about 5% higher than the mean value predicted at the SP Laboratory.

Table 2-2. Summary of the results of Uniaxial Compressive Strength tests (UCS) performed on intact rock samples from boreholes KFM01A, KFM02A, KFM03A and KFM04A.

Rock type	Number of samples	Minimum UCS (MPa)	Mean UCS (MPa)	Frequent UCS (MPa)	Maximum UCS (MPa)	UCS's Standard deviation (MPa)
Granite to granodiorite, metamorphic, medium-grained	52	166	225	223	289	22
Granodiorite, metamorphic*	4	222	236	236	249	12
Tonalite to granodiorite, metamorphic**	8	140	156	155	176	13
All intact samples	64	140	217	221	289	31
Only samples with sealed fractures	4	145	173	179	188	20

* These samples were collected along borehole KFM04A (161–164 m depth).
** These samples were collected along borehole KFM03A (278–310 m depth).

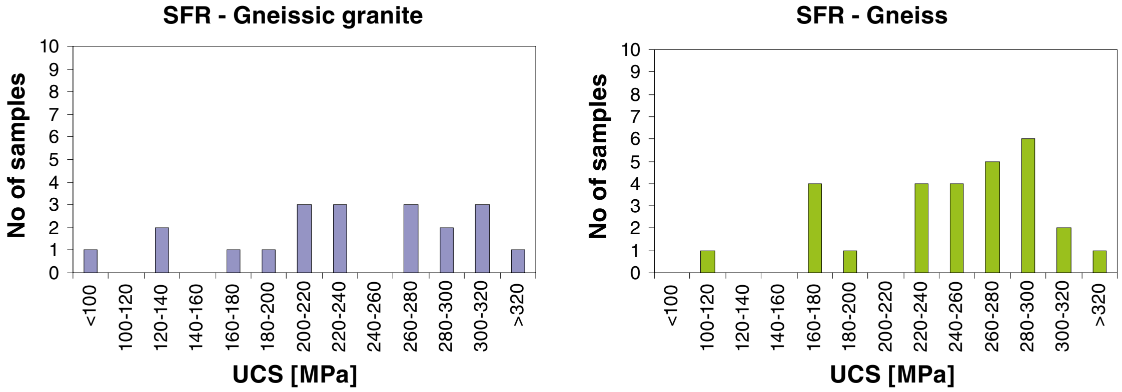

Figure 2-1. Frequency distributions of the Uniaxial Compressive Strength of rock types similar to granite and tonalite available from SRF.

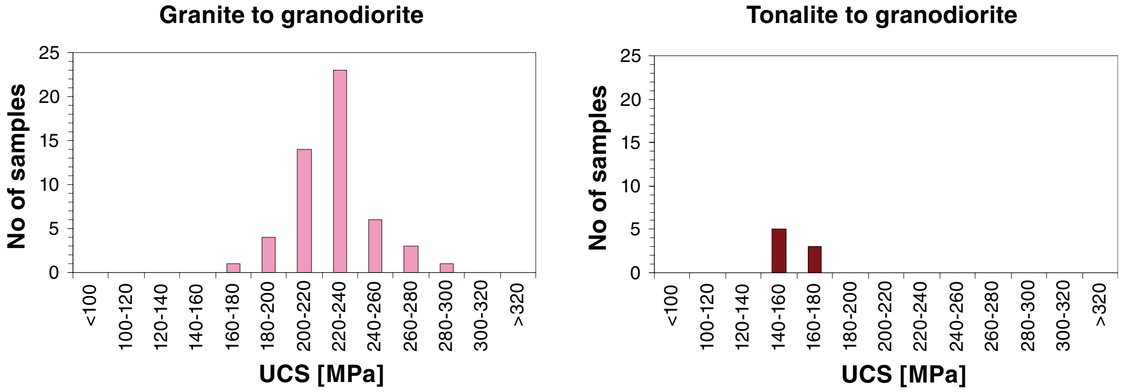

Figure 2-2. Frequency distributions of the Uniaxial Compressive Strength of similar rock types available for Forsmark SDM version 1.2.

2.1.1 Depth dependency

The high level of stress at Forsmark might imply that some of the borehole samples taken at depth can have experienced microcracking due to stress release. Figure 2-3 shows the variation of the uniaxial compressive strength of the intact rock samples with depth. Based on the UCS values, it can be observed that the only samples that could have been affected by microcracking were taken at about 813 m depth. For these samples, the average uniaxial strength is 197 MPa compared to the uniaxial strength of the rest of the samples in granite to granodiorite that is 228 MPa. The difference is, thus, about 14%.

In Figure 2-4, the maximum and minimum P-wave velocity measured in the laboratory by /Tunbridge and Chryssanthakis 2003, Chryssanthakis and Tunbridge 2004a–c/ is plotted along the cores of the boreholes at Forsmark. Borehole KFM01A, and in some extent KFM02A, shows some decrease of velocity with depth under 500 and 700 m, respectively. The remnant two cores do not exhibit the same marked decrease, and might seem to be less affected by the stress relief of the in-situ stresses applied by the drilling.

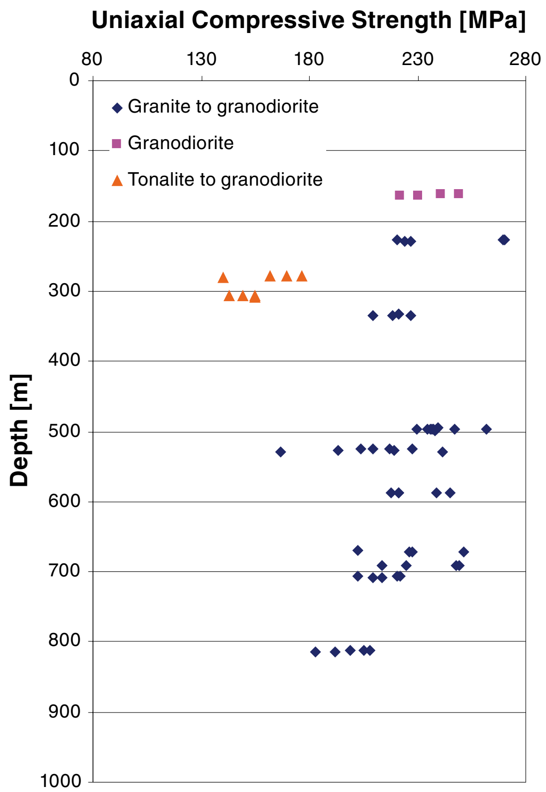

Figure 2-3. Variation of the uniaxial compressive strength (UCS) of the intact rock with depth for the data from Forsmark SDM version 1.2 (KFM01A, KFM02A, KFM03A and KFM04). Except for the large difference between granite and granodiorite on one side and tonalite on the other, the tests do not show significant variation of strength with depth for samples above 700 m.

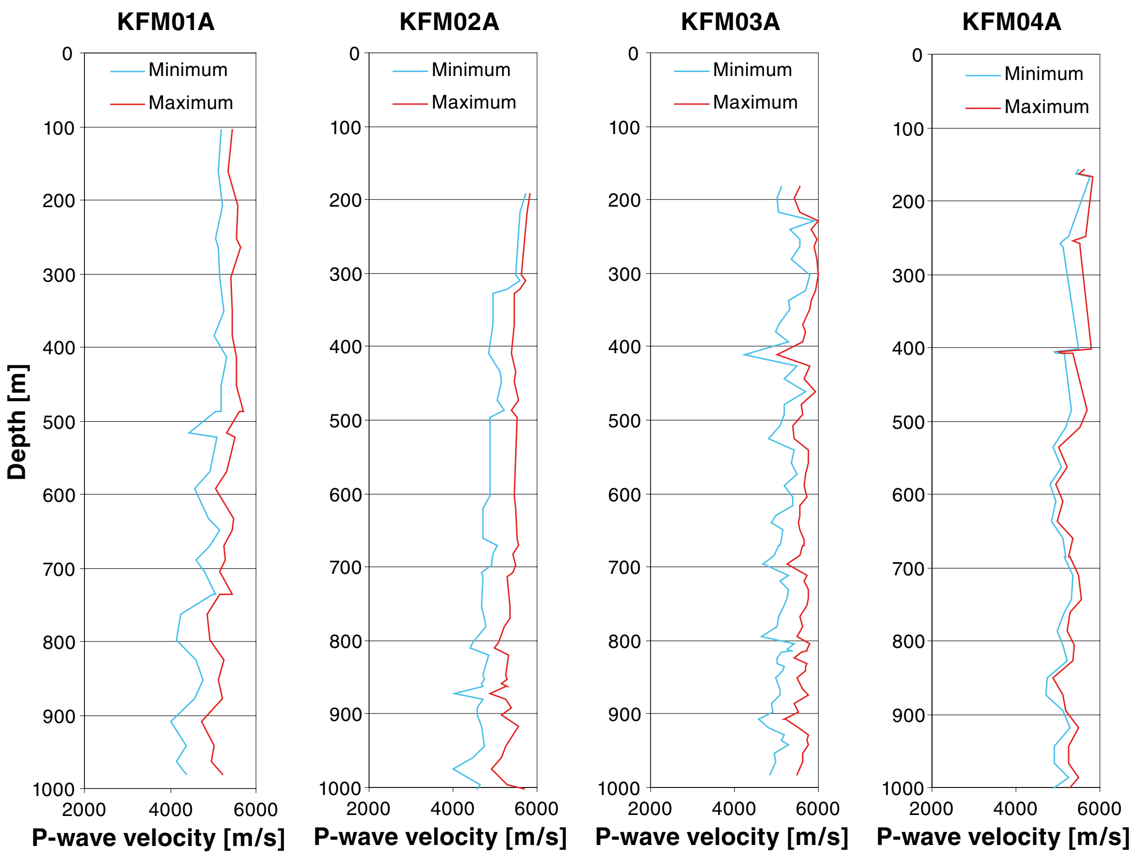

Figure 2-4. *P-wave velocity along the cores from borehole KFM01A, KFM02A, KFM03A and KFM034. The difference between the maximum and minimum recorded velocity indicate some anisotropy of the intact rock along the cores. Moreover, the decrease with depth might indicate damage of the cores due to stress-path during the relief of the in-situ stresses (particularly along KFM01A).*

2.1.2 Crack initiation stress

From the plots of the lateral strain during uniaxial loading, a point can be identified after which extensional strains start to develop in the samples /Stacey 1981/. This point coincides with the onset load of dilation and formation of micro-cracks in the rock sample. The correspondent normal stress is called “crack initiation stress” σ_{ci} and can be used for spalling, microcracking and core disking analyses /e.g. Martin 2004/.

The onset of dilation was identified for the samples of granite to granodiorite and tonalite to granodiorite (Table 2-3). On average, the crack initiation stress is about 53% of the uniaxial compressive strength for the two tested rock types. The frequency distribution of the crack initiation stress is shown in Figure 2-5, left for the granite to granodiorite and right for the tonalite to granodiorite.

Table 2-3. The crack initiation stress from uniaxial compressive tests performed on intact rock samples from boreholes KFM01A, KFM02A, KFM03A and KFM04A.

	Granite to granodiorite		Tonalite to granodiorite	
	Mean/Standard deviation	Truncation interaval: Min and Max	Mean/Standard deviation	Truncation interaval: Min and Max
Crack initiation stress, σ_{ci}	120/20 MPa	85–190 MPa	82/9 MPa	70–95 MPa

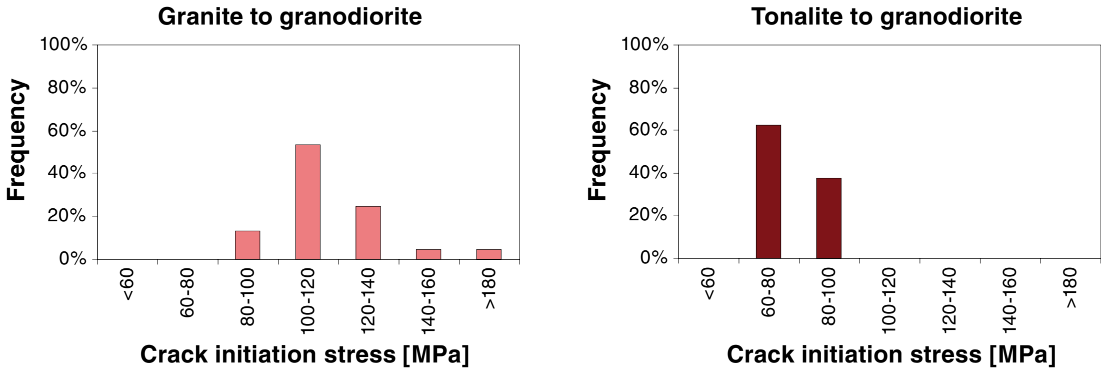

Figure 2-5. *Crack initiation stress for the granite to granodiorite (left) and for the tonalite to granodiorite (right) from the uniaxial compression test of samples from borehole KFM01A, KFM02A, KFM03A and KFM04A.*

2.2 Triaxial strength

Triaxial tests were carried out on samples from four boreholes /Jacobsson 2004e–h/. For each main rock type (granite to granodiorite, granodiorite, tonalite to granodiorite), the triaxial results were analysed together with the correspondent results of the uniaxial compressive tests. The laboratory results on intact rock samples were interpolated with the Hoek and Brown's Failure Criterion /Hoek et al. 2002/:

$$\sigma'_1 = \sigma'_3 + UCS_T \left(m_i \frac{\sigma'_3}{UCS_T} + 1 \right)^{0.5} \tag{1}$$

where σ'_1 and σ'_3 are the maximum and minimum principal stress and m_i is a strength parameter typical for each rock type. UCS_T is obtained by matching the uniaxial and triaxial test results and thus slightly differs from UCS values in Section 2.1.

When analysing the laboratory results, the intact rock parameters in Table 2-4 are calculated. Although obtained in a slightly different way, the results of the UCS are in rather good agreement with the values in obtained on uniaxial tests only (Table 2-2).

The Coulomb's linear approximations of the Hoek and Brown's Criterion were also calculated for a certain stress interval (0 to 15 MPa, Table 2-5). These linear approximations are shown in Figure 2-6 and Figure 2-7 for the granite to granodiorite and for the tonalite to granodiorite, respectively. The Hoek and Brown's Criterion also provides an estimation of the tensile strength of the intact rock that can be compared with the laboratory results in Section 2.3.

Five samples of metagranodiorite were also tested in triaxial compression conditions at the HUT Laboratory /Eloranta 2004b/. These results were not available at the time of compilation of the summary of the primary data presented in the present report, thus are not included in the statistics. However, a qualitative comparison of HUT results with those obtained by the SP Laboratory shows a good agreement (Figure 2-6).

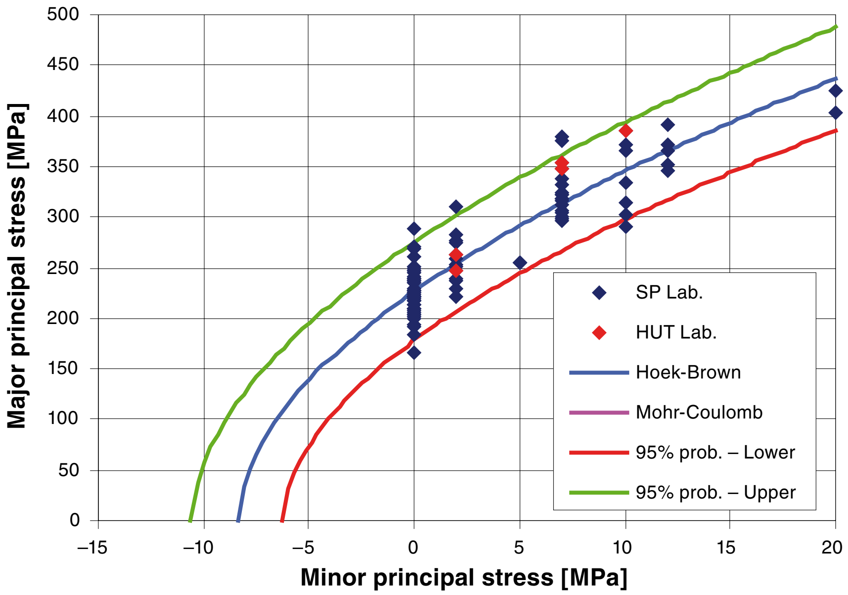

Figure 2-6. *Hoek and Brown's and Coulomb's failure envelopes for the samples of granite to granodiorite from the uniaxial and triaxial tests from Forsmark SDM version 1.2 (KFM01A, KFM02A, KFM03A and KFM04A).*

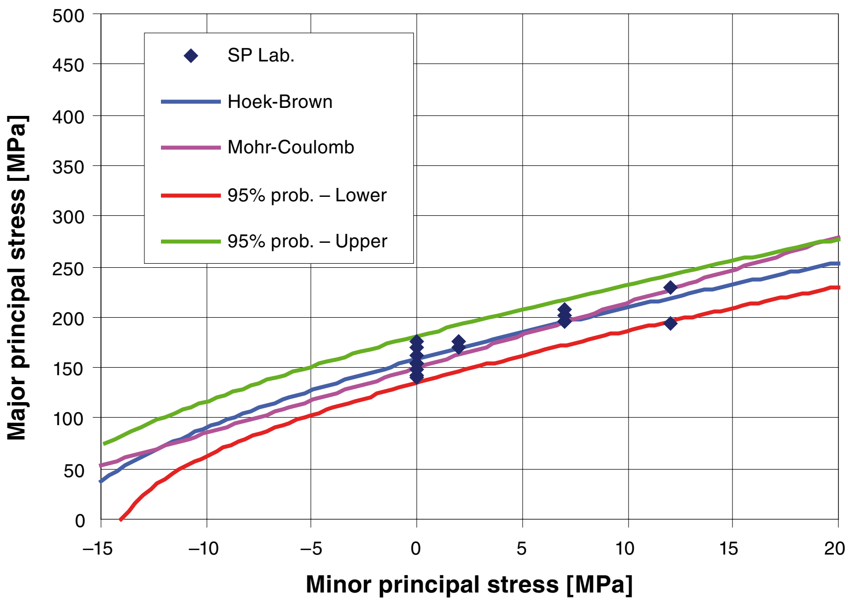

Figure 2-7. *Hoek and Brown's and Coulomb's failure envelopes for the samples of tonalite to granodiorite from the uniaxial and triaxial tests from Forsmark SDM version 1.2 (KFM03A).*

Table 2-4. Parameters for the Hoek and Brown's Criterion based on the results of uniaxial and triaxial tests performed on intact rock sampled from boreholes KFM01A, KFM02A, KFM03A and KFM04A.

Rock type	Number of samples	Lower envelope 95% probability		Average		Upper envelope 95% probability	
		USC (MPa)	mi	UCS (MPa)	mi	UCS (MPa)	mi
Granite to granodiorite, metamorphic, medium-grained	99	178	28.6	227	27.0	275	26.0
Granodiorite, metamorphic	7[1)]	185	31.6	230	30.6	275	29.9
Tonalite to granodiorite, metamorphic	16[2)]	135	9.6	158	9.4	181	9.2
All samples	122	139	27.1	218	24.3	298	23.0

[1)] Samples from KFM04A.
[2)] Samples from KFM03A.

Table 2-5. Parameters for the Coulomb's Criterion based on the results of uniaxial and triaxial tests performed on intact rock sampled from boreholes KFM01A, KFM02A, KFM03A and KFM04A.

Rock type	Number of samples	Lower envelope 95% probability		Average		Upper envelope 95% probability	
		C (MPa)	Fi (°)	C (MPa)	Fi (°)	C (MPa)	Fi (°)
Granite to granodiorite, metamorphic, medium-grained	99	22.5	59.4	28.1	60.0	33.7	60.4
Granodiorite, metamorphic	7	22.6	60.5	27.3	61.2	32.1	61.7
Tonalite to granodiorite, metamorphic	16	25.2	46.7	29.5	47.0	33.8	47.3
All samples	122	18.7	57.7	28.1	58.9	37.9	59.6

These values of cohesion and friction angle are determined for a confinement stress between 0 and 15 MPa.

2.3 Tensile strength

Indirect tensile tests were conducted on 143 core samples in direction parallel and perpendicular to the foliation at the SP Laboratory (borehole KFM01A, KFM02A, KFM03A and KFM04A) /Jacobsson 2004i–l/.

Table 2-6 contains the statistics of the test results for each of the main rock types. The values in this table show that the loading direction with respect to foliation does not affect much the results: the difference is largest for the granite to granodiorite (about 8%), and least for the granodiorite (0%). It can also be observed that the granite has the lowest tensile strength of all the tested rock types. In Figure 2-8, the frequency distribution of the tensile strength is shown for the granite and tonalite. The difference between the mean values of the tensile strength of the granite (average 13.5 MPa) and of the tonalite (average 15.6 MPa) is evident. These two values do not coincide with the tensile strength estimated by the Hoek and Brown's Criteria shown in Figure 2-6 and Figure 2-7 also because the fitting is optimised for the field of compressive stresses between 0 and 15 MPa.

Figure 2-9 shows the variation of the tensile strength with depth for the three tested rock types. It can be noticed that the tensile strength of the granodiorite (average 18 MPa) is larger than for the other rock types. Moreover, not very clear trends with depth can be observed in the data.

Also the HUT Laboratory /Eloranta 2004c/ performed independent testing of the tensile strength of 10 fully-saturated samples of medium-grained metagranodiorite and granite. These tests resulted in an average tensile strength of 15.3 MPa, ranging between 14 and 16 MPa. A difference of about 2.5% on the average was observed between the tests carried out perpendicularly and parallelly to the foliation. On average, the difference between the results at SP and HUT Laboratories is about 18%.

Table 2-6. Summary of the results of indirect tensile tests performed on intact rock samples from boreholes KFM01A, KFM02A, KFM03A and KFM04A.

Rock type	Orientation with respect to foliation	Number of samples	Minimum TS (MPa)	Mean TS (MPa)	Frequent TS (MPa)	Maximum TS (MPa)	TS's Standard deviation (MPa)
Granite to granodiorite, metamorphic, medium-grained	parallel	60	10	13	13	17	2
	perpend.	52	10	14	14	18	2
Granodiorite, metamorphic	parallel	5	17	18	17	19	1
	perpend.	6	17	18	18	20	1
Tonalite to granodiorite, metamorphic	parallel	10	15	16	16	17	1
	perpend.	10	14	15	15	18	1
All samples	–	143	10	14	14	20	2

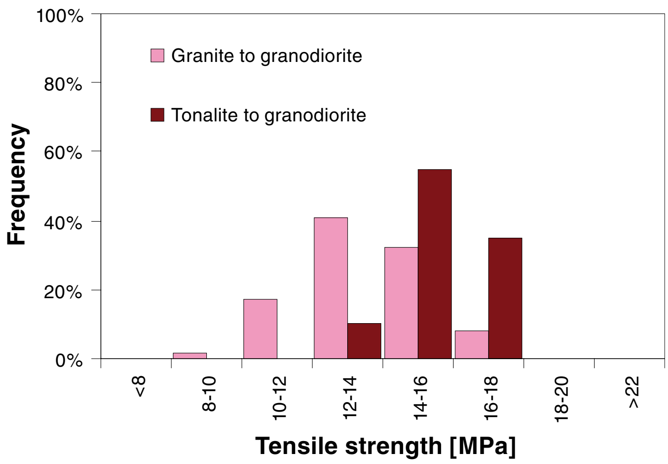

***Figure 2-8.** Frequency distribution of the indirect tensile strength TS for all the tests on intact rock samples from boreholes KFM01A, KFM02A, KFM03A and KFM04A (all orientations with respect to the foliation).*

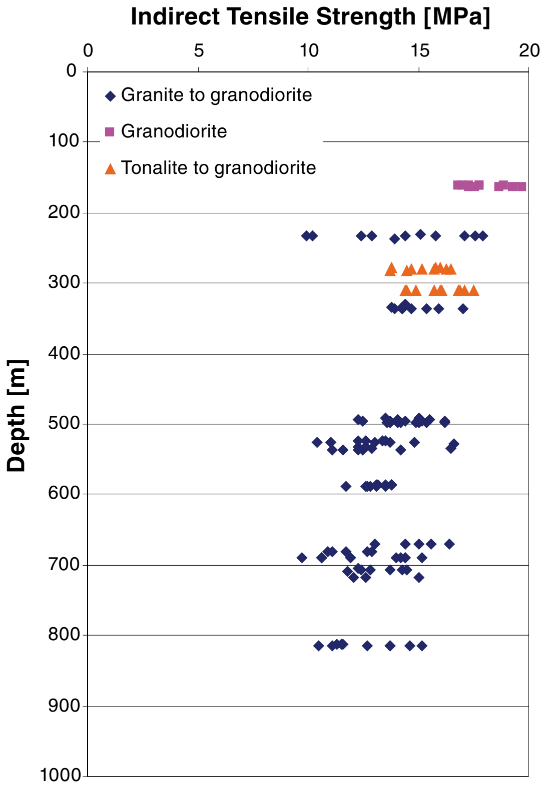

Figure 2-9. *Variation of the indirect tensile strength TS of the intact rock with depth for the data from Forsmark SDM version 1.2 (boreholes KFM01A, KFM02A, KFM03A and KFM04A). For the same rock type, the tests do not show significant variation of strength with depth.*

2.4 Young's modulus

The uniaxial and triaxial compressive tests, other than the strength, also provide the deformability of the intact rock samples. The deformability is quantified by means of the elastic parameters Young's modulus and Poisson's ratio. Due to the fact the loading conditions considered are different and for reasons of engineering practice, two sets of Young's modulus and Poisson's ratio are presented, one for uniaxial and one for triaxial loading conditions, respectively.

2.4.1 Uniaxial loading

The Young's modulus obtained from uniaxial loading is often used in practice for the ease of determination. /Jacobsson 2004a–d/ provided the values obtained for the core samples taken from borehole KFM01A, KFM02A, KFM03A and KFM04A. Table 2-7, the statistics of the Young's modulus of the intact rock samples of granite to granodiorite, granodiorite and tonalite to granodiorite are summarised. It is interesting to notice that, for the samples containing sealed fractures, the Young's modulus of the samples is slightly higher (on average about 7%) than for the intact rock samples. In general, the intact samples have high Young's modulus almost independently on the rock type considering that the differences between rock types are contained within 6%.

The comparison between the new test results and the data available from SFR show almost the same average Young's modulus (Figure 2-10). However, the ranges obtained for the SFR data are wider (60 to 93 GPa) than that obtained for the granite to granodiorite (69 to 82 GPa) for Forsmark SDM version 1.2.

Figure 2-11 show the variation of the Young's modulus from uniaxial compression tests with depth. Except for the samples at 813 m depth, all the other results seem to be almost unaffected by depth. The Young's modulus at around 226 m is about 78 GPa, while that at 708 m is about 75 GPa.

The results at HUT /Eloranta 2004a/ on granite to granodiorite (metagranodiorite) gave an average Young's modulus of 75 GPa. This result, obtained based on six samples, is in agreement with the results in Table 2-7.

Table 2-7. Summary of the results of Young's modulus E from uniaxial compressive tests performed on intact rock samples from borehole KFM01A, KFM02A, KFM03A and KFM04A.

Rock type	Number of samples	Minimum E (GPa)	Mean E (GPa)	Frequent E (GPa)	Maximum E (GPa)	E's Standard deviation (GPa)
Granite to granodiorite, metamorphic, medium-grained	52	69	76	76	82	3
Granodiorite, metamorphic	4	73	77	77	81	3
Tonalite to granodiorite, metamorphic	8	69	72	71	78	3
All intact samples	64	69	75	75	82	3
Only samples with sealed fractures	4	76	80	80	83	3

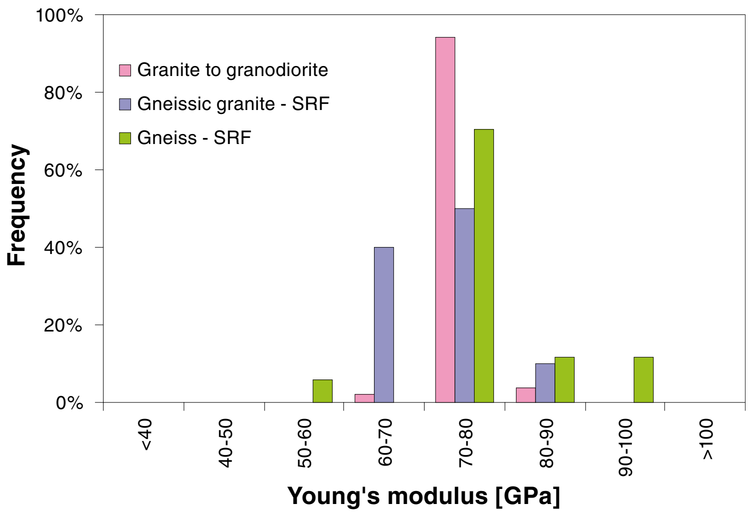

Figure 2-10. *Comparison of the frequency distributions of the Young's modulus E from uniaxial tests on similar rock types from Forsmark SDM version 1.2 and SRF.*

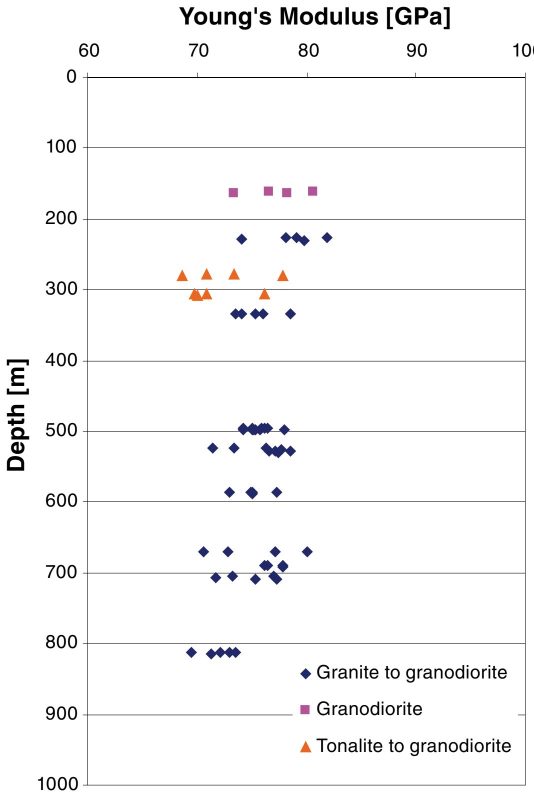

***Figure 2-11.** Variation of the Young's modulus of the intact rock with depth for the data from Forsmark SDM version 1.2 (uniaxial compression tests – boreholes KFM01A, KFM02A, KFM03A and KFM04A).*

2.4.2 Triaxial loading

The Young's modulus could also be determined from the results of triaxial loading tests by /Jacobsson 2004e–h/. This Young's modulus was obtained for confinement stresses between 2 and 20 MPa. The Young's modulus in triaxial conditions compares well with the Young's modulus from uniaxial tests since the difference is less than 3%. The two sets of parameters could then be considered to represent the same physical property of the intact rock. In Figure 2-12, the frequency distributions of the uniaxial and triaxial Young's modulus are plotted together and appear to almost coincide.

The variation of the triaxial Young's modulus with depth is even less evident than for the uniaxial Young's modulus in Figure 2-11. The effect of the confinement stress in triaxial condition probably compensates for the degradation of the modulus due to the unloading stress-path during coring. Figure 2-13 shows the plot of the triaxial Young's modulus with depth for the samples from Forsmark SDM version 1.2.

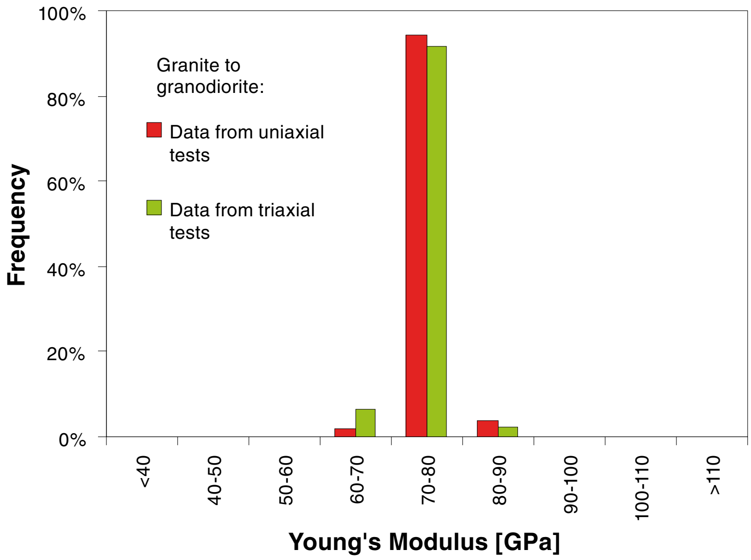

Figure 2-12. *Comparison of the frequency distributions of the Young's modulus from uniaxial and triaxial tests for Forsmark SDM version 1.2.*

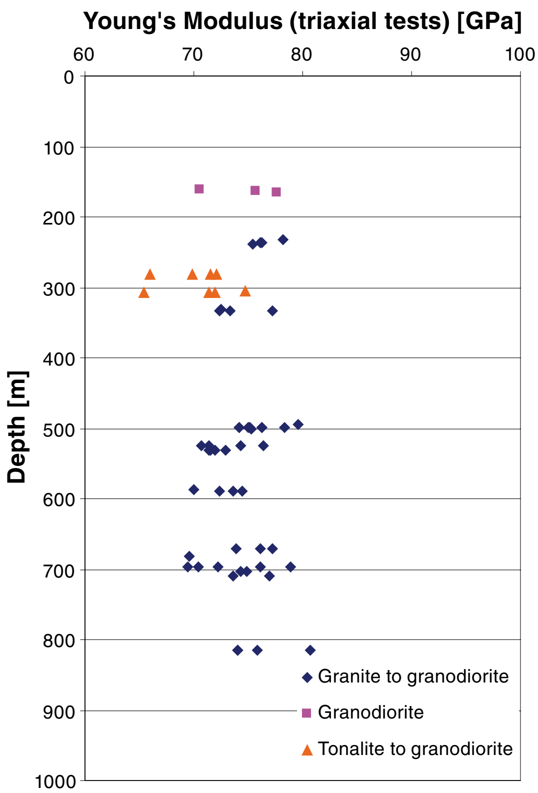

Figure 2-13. *Variation of the Young's modulus of the intact rock with depth for the data from Forsmark SDM version 1.2 (triaxial compression tests – boreholes KFM01A, KFM02A, KFM03A and KFM04). The tests do not show significant variation of stiffness with depth and with rock type. The confining pressure varies from sample to sample and between 2 and 20 MPa.*

Table 2-8. Summary of the results of deformation modulus Et from triaxial compressive tests performed on intact rock samples from borehole KFM01A, KFM02A, KFM03A and KFM04A. The confining pressure varies from sample to sample and between 2 and 20 MPa.

Rock type	Number of samples	Minimum Et (GPa)	Mean Et (GPa)	Frequent Et (GPa)	Maximum Et (GPa)	Et's Standard deviation (GPa)
Granite to granodiorite, metamorphic, medium-grained	47	69	74	74	81	3
Granodiorite, metamorphic	3	71	75	76	78	4
Tonalite to granodiorite, metamorphic	8	65	70	71	75	3
All intact samples	59	65	74	74	81	3

2.5 Poisson's ratio

As for the Young's modulus, also the Poisson's ratio of the intact rock can be obtained from uniaxial and triaxial tests.

2.5.1 Uniaxial loading

The summary values of the Poisson's ratio are shown in Table 2-9 as obtained from uniaxial compressive tests on intact rock samples /Jacobsson 2004a–d/. The tonalite exhibits a Poisson's ratio higher than the granite to granodiorite and the samples containing sealed fractures. The last two groups of samples approximately have the same Poisson's ratio. The experimental data of Poisson's ratio for samples collected at a certain depth are very scattered as shown in Figure 2-14. However, the mean values for each depth do not seem to sensibly change with depth.

Comparing the results as in Figure 2-14, the values of the Poisson's ratio of the granite to granodiorite seems to resemble those of the gneiss and gneissic granite tested for the construction of the SRF Repository.

The Poisson's ratio for the granite to granodiorite (metagranodiorite) obtained at HUT /Eloranta 2004a/ does not agree with the results obtained by SP. In fact, the values by HUT range between 0.28 and 0.30 with an average value of 0.29. This large difference cannot be explained only by variation of the intact rock properties within the same rock type.

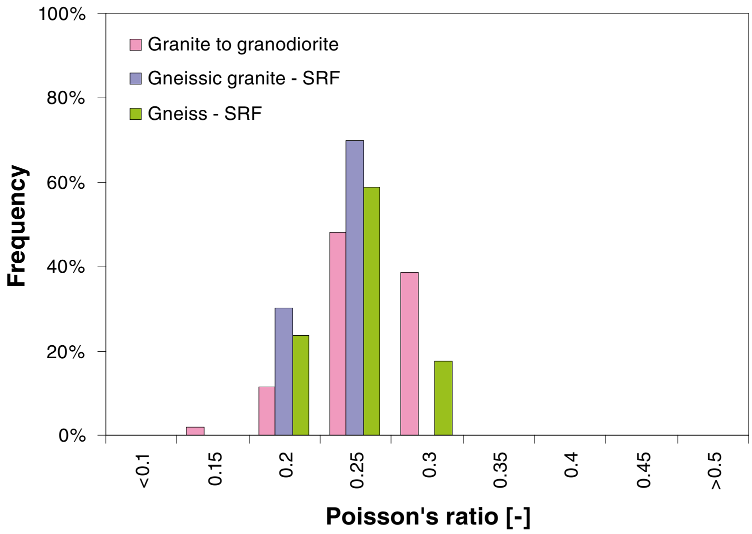

Figure 2-14. *Comparison of the frequency distributions of the Poisson's ratiov from all uniaxial tests on intact samples for Forsmark SDM version 1.2 and SRF.*

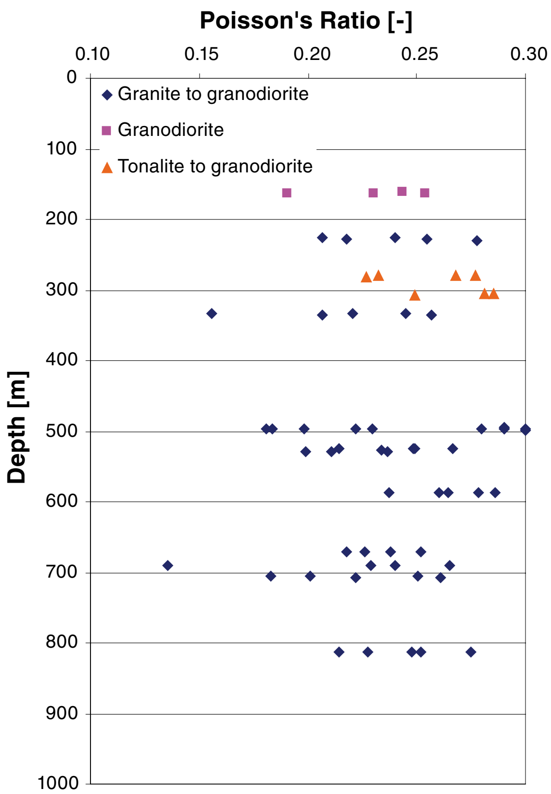

Figure 2-15. *Variation of the Poisson's ratio of the intact rock with depth for the data from Forsmark PFM version 1.2 (uniaxial compression tests – boreholes KFM01A, KFM02A, KFM03A and KFM04A).*

Table 2-9. Summary of the results of Poisson's ratio ν from uniaxial compressive tests performed on intact rock sampled from borehole KFM01A–KFM04A. The confining pressure varies from sample to sample and between 2 and 20 MPa.

Rock type	Number of samples	Minimum ν (–)	Mean ν (–)	Frequent ν (–)	Maximum ν (–)	ν's Standard deviation (–)
Granite to granodiorite, metamorphic, medium-grained	52	0.14	0.24	0.24	0.30	0.04
Granodiorite, metamorphic	4	0.19	0.23	0.24	0.25	0.03
Tonalite to granodiorite, metamorphic	8	0.23	0.27	0.27	0.34	0.04
All intact samples	64	0.14	0.24	0.24	0.34	0.04
Only samples with sealed fractures	4	0.18	0.24	0.23	0.31	0.06

2.5.2 Triaxial loading

The values of the Poisson's ratio obtained by /Jacobsson 2004e–h/ by means of triaxial compressive tests are summarised in Table 2-10. On average, all rock types show a Poisson's ration around 0.20. Differently than for the Young's modulus, the Poisson's ratio from triaxial tests is much lower than that from uniaxial tests, and the difference is as large as 20%. This is the effect of the confinement pressure that in triaxial conditions varied between 2 and 20 MPa. The distribution of the Poisson's ratio from triaxial test has a peak for the lower values. However, the two distributions have almost the same scatter between 0.14 and 0.34.

The results by /Jacobsson 2004e–h/ were also plotted against depth. Other than the scatter, Figure 2-17 shows that mean value do not seem to be markedly affected by depth.

Table 2-10. Summary of the results of Poisson's ratio νt from triaxial compressive tests performed on intact rock sampled from borehole KFM01A–KFM04A. The confining pressure varies from sample to sample and between 2 and 20 MPa.

Rock type	Number of samples	Minimum νt (–)	Mean νt (–)	Frequent νt (–)	Maximum νt (–)	νt's Standard deviation (–)
Granite to granodiorite, metamorphic, medium-grained	47	0.15	0.20	0.19	0.31	0.04
Granodiorite, metamorphic	3	0.18	0.18	0.18	0.19	0.01
Tonalite to granodiorite, metamorphic	8	0.18	0.20	0.20	0.23	0.02
All intact samples	59	0.15	0.20	0.19	0.31	0.03

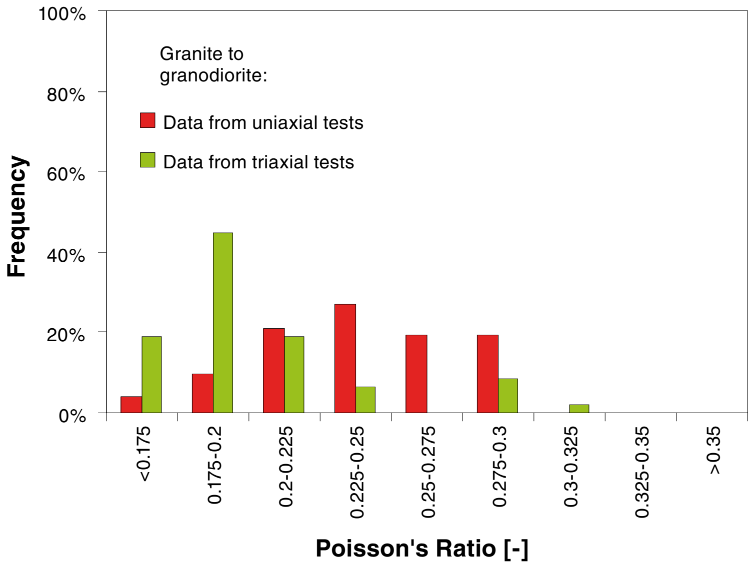

Figure 2-16. *Comparison of the frequency distributions of the Poisson's ratio from uniaxial and triaxial tests for Forsmark PFM version 1.2.*

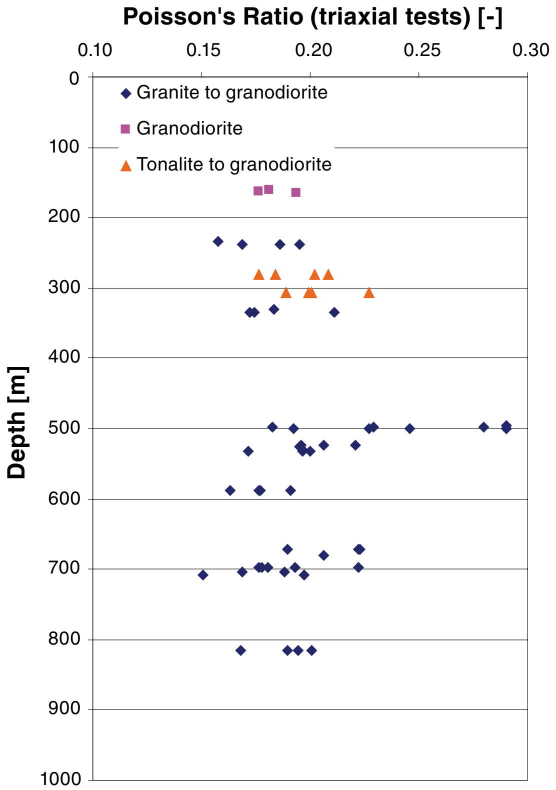

Figure 2-17. *Variation of the Poisson's ratio of the intact rock with depth for the data from Forsmark PFM version 1.2 (triaxial compression tests – boreholes KFM01A, KFM02A, KFM03A and KFM04A). The confining pressure varies from sample to sample and between 2 and 20 MPa.*

3 Natural rock fractures

The strength and deformability of the natural rock fractures was determined in two ways:

1) By means of tilt tests where shearing is induced by sliding due to the self-weight of the upper block when the fracture is progressively tilted;
2) By means of direct shear tests where shearing is induced by actuators that apply a load perpendicular and parallel to the fracture plane.

Tilt tests were performed on samples from borehole KFM01A, KFM02A, KFM03A and KFM04A. Direct shear tests were performed by two different laboratories on fractures from borehole KFM01A (NGI Norwegian Geological Institute Laboratory) and KFM01A, KFM02A, KFM03A and KFM04A (SP Laboratory). In the following sections, a summary of the fracture strength results is provided.

Results from testing of the natural fractures are also reported in Appendix 2.

3.1 Tilt tests

Tilt tests were carried out on 142 samples from borehole KFM01A, KFM02A, KFM03A /Chryssanthakis 2003a–c/ and KFM04A /Chryssanthakis and Tunbridge 2004d/. The tilt tests are designed to suit the fracture parameter determination according to /Barton and Bandis 1990/. The shear strength of the fracture is a function of the normal stress σ_n as:

$$\tau = \sigma_n \tan\left[\Phi_b + JRC \log\left(\frac{JCS}{\sigma_n}\right)\right] \qquad (2)$$

JRC is Joint Roughness Coefficient that quantifies roughness, JCS is Joint Wall Compression Strength of the rock surfaces, and Φ_b is basic friction angle on dry saw-cat surfaces, respectively. The residual friction angle Φ_r is used instead of Φ_b if the strength of wet surfaces is concerned. /Barton and Bandis, 1990/ also suggest truncating the strength envelope as follows: τ/σ should always be smaller than 70° and, in this case, the envelope should go through the origin ($\sigma_n = \tau = 0$ MPa), in other words the cohesion is zero.

The parameters of the Barton and Bandis's criterion are summarised in Table 3-1 for each borehole and for all the fractures. In Table 3-2, the samples are grouped into fracture sets according to the DFN model of the Site (see also Appendix 2). It can be observed that, independently on the fracture orientation and borehole, the fracture parameters do not noticeably change. Some of the tested samples were mapped as "sealed fractures" in BOREMAP maybe because of some mismatch in the reported sample depth.

The variation of the basic and residual friction angle, JRC_0 and JCS_0 with depth are reported in Appendix 2. The data are so scattered that no trends with depth can be recognised. However, the different fracture sets seem to behave the same way.

When a certain level of stresses is considered, the relation in Equation (2) can be linearly approximated so that friction angle and cohesion of the Coulomb's Strength Criterion can be determined as reported in Table 3-5.

Table 3-1. Summary of the results of tilt tests performed on rock fractures sampled from borehole KFM01A, KFM02A, KFM03A and KFM04A.

Borehole	Number of samples	Basic friction angle (°)	JRC0 (100 mm)	JCS0 (100 mm)	Residual friction angle (°)
KFM01A	41	28.9 (2.1)	6.0 (1.6)	102.1 (25.7)	24.6 (3.0)
KFM02A	40	31.2 (2.0)	5.7 (1.6)	79.5 (19.8)	24.6 (3.0)
KFM03A	35	32.0 (1.2)	5.7 (1.5)	70.5 (17.8)	26.8 (2.2)
KFM04A	26	31.4 (1.1)	5.8 (1.2)	79.9 (22.7)	28.0 (2.2)
All fractures	142	30.8 (2.1)	5.8 (1.5)	83.9 (24.8)	26.3 (2.9)

The average values are indicated. The standard deviation is set between brackets.

Table 3-2. Summary of the results of tilt tests performed on rock fractures grouped in different fracture sets and from borehole KFM01A, KFM02A, KFM03A and KFM04A.

Fracture set	Number of samples	Basic friction angle (°)	JRC0 (100 mm)	JCS0 (100 mm)	Residual friction angle (°)
EW	7	29.0 (2.2)	7.0 (2.0)	99.9 (27.7)	23.9 (2.1)
NW	10	31.9 (1.3)	5.9 (1.9)	77.4 (14.0)	27.4 (2.1)
NE	10	30.1 (2.0)	5.7 (1.8)	112.0 (34.4)	26.4 (3.2)
NS	14	31.5 (2.7)	6.2 (1.7)	82.2 (21.8)	26.3 (2.5)
SubH	48	30.7 (1.7)	5.4 (1.2)	80.6 (22.5)	26.5 (2.7)
Random	35	30.7 (2.7)	5.9 (1.7)	83.9 (21.8)	26.2 (2.5)
Sealed	17	30.9 (1.7)	6.0 (1.2)	75.1 (22.5)	26.6 (2.7)

The average values are indicated. The standard deviation is set between brackets.

3.2 Direct shear tests

Two different laboratories were asked to perform normal loading and shearing tests on natural fractures from borehole KFM01A. More samples were collected from borehole KFM02A, KFM03A and KFM04A and tested at the SP Laboratory. The testing results are shown in the following sections.

3.2.1 NGI Laboratory results

At the NGI Laboratory /Chryssanthakis 2004d/, five samples of natural fracture in fine-grained granodiorite were tested in a shear machine under normal stresses of 0.5, 5 and 20 MPa (Figure 3-1). In dry conditions, the average peak and residual friction angle of the samples were 37° and 32°, respectively. The average cohesion of the samples was 1.2 and 0.7 MPa in peak and residual conditions, respectively. Before shearing, the samples were also normally loaded to determine the normal stiffness.

The secant normal stiffness determined by analysing the NGI results is high and on average 415 MPa/mm. The secant shear stiffness could also be computed based on the NGI results and resulted to be 26 MPa/mm when all samples and stress levels were considered.

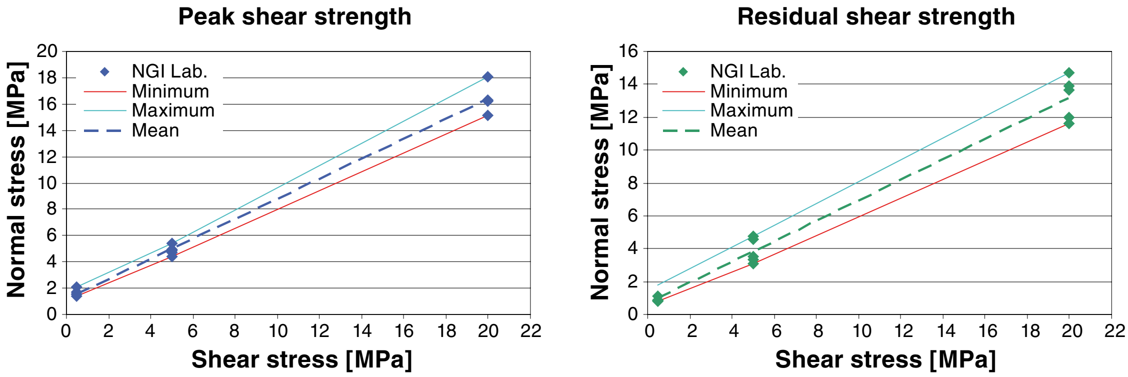

Figure 3-1. *Peak (left) and residual (right) shear strength according to the Coulomb's Criterion for the fracture samples from borehole KFM01A (NGI Laboratory results).*

3.2.2 SP Laboratory results

/Jacobsson 2004/ carried out shear testing on 27 natural fractures taken from the cores of borehole KFM01A, KFM02A, KFM03A and KFM04A. The displacement curves were also measured during normal loading and shearing so that the normal and shear stiffness of the samples could be determined. The fractures were not grouped according to fracture sets at the Site because of some problems in matching the reported fracture depth with the BOREMAP records in SICADA.

Deformability

The secant normal stiffness of the fracture samples for normal stress between 0.5 and 10 MPa was evaluated for the second loading cycle. The shear stiffness was determined as the secant stiffness between 0 MPa and half of the peak shear stress. Table 3-3 shows the summary statistics of the normal and shear stiffness obtained from the tests.

Table 3-3. Minimum, mean and maximum normal and shear stiffness for all the tested fracture samples from borehole KFM01A, KFM02A, KFM03A and KFM04A (SP Laboratory results).

	Minimum		Mean		Maximum		Standard deviation	
	Normal stiffness (MPa/mm)	Shear stiffness (MPa/mm)	Normal stiffness (MPa/mm)	Shear stiffness (MPa/mm)	Normal stiffness (MPa/mm)	Shear stiffness (MPa/mm)	Normal stiffness (MPa/mm)	Shear stiffness (MPa/mm)
All samples	68.0	11.2	128.4	38.8	288.4	55.1	51.6	10.8

Strength

The strength envelopes of the natural fractures were rather linear so that they suited the fitting with the Coulomb's Criterion. Table 3-4 summarises the experimental results in terms of minimum, mean and maximum cohesion and friction angles. Furthermore, peak and residual conditions could be considered.

Table 3-4. Minimum, mean and maximum envelopes of the peak and residual friction angle and cohesion of the Coulomb's Criterion. All tests on samples from borehole KFM01A, KFM02A, KFM03A and KFM04A are shown (SP Laboratory results).

	Minimum		Mean		Maximum	
	Friction angle φ' (°)	Cohesion c' (MPa)	Friction angle φ' (°)	Cohesion c' (MPa)	Friction angle φ' (°)	Cohesion c' (MPa)
Peak envelope	27.3	0.00	34.0	0.67	39.1	1.10
Residual envelope	21.8	0.28	30.8	0.49	38.3	0.71

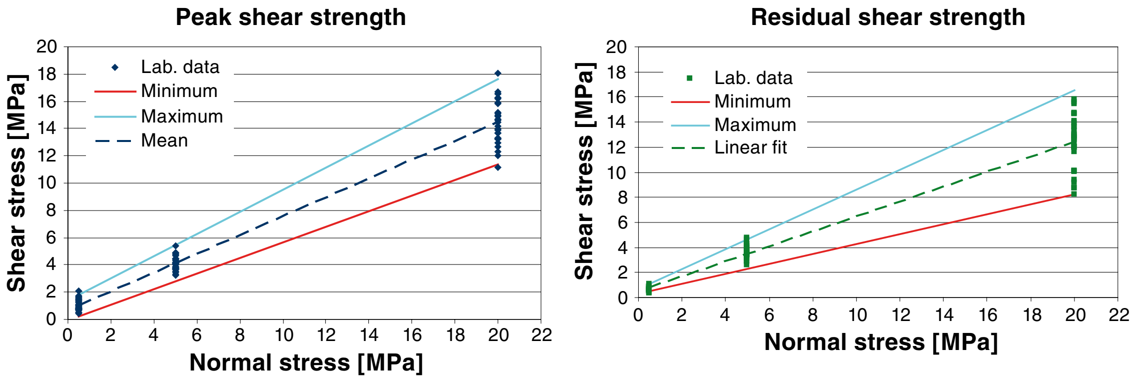

Figure 3-2. *Peak (left) and residual (right) shear strength according to the Coulomb's Criterion for all fracture samples from borehole KFM01A, KFM02A, KFM03A and KFM04A (SP Laboratory results).*

3.3 Comparison of the laboratory results

The statistical parameters obtained from the three different sets of tests on natural fractures are compared in Table 3-5. The different testing techniques and the number of tested samples for each set of results justify the slight spread of the results. However, it was decided to give more weight to the largest set of results of direct shear tests (e.g. the test results obtained at the SP Laboratory).

The presence of correlation between the peak cohesion and friction angle of the natural fractures was checked for the different sets of laboratory results. In Figure 3-3, all the analyzed results are shown. They show no correlation between the peak friction angle and the peak cohesion for the samples from Forsmark.

The basic friction angle (Section 3.1), which is the frictional strength of rock saw-cut surfaces, can be used to determine the dilation angle and quantify the frictional effect of the asperities of the fracture walls for a certain normal stress. The difference between the peak friction angle and the basic friction angle can be used as a measure of the dilation angle in peak strength conditions and for a particular level of normal stress.

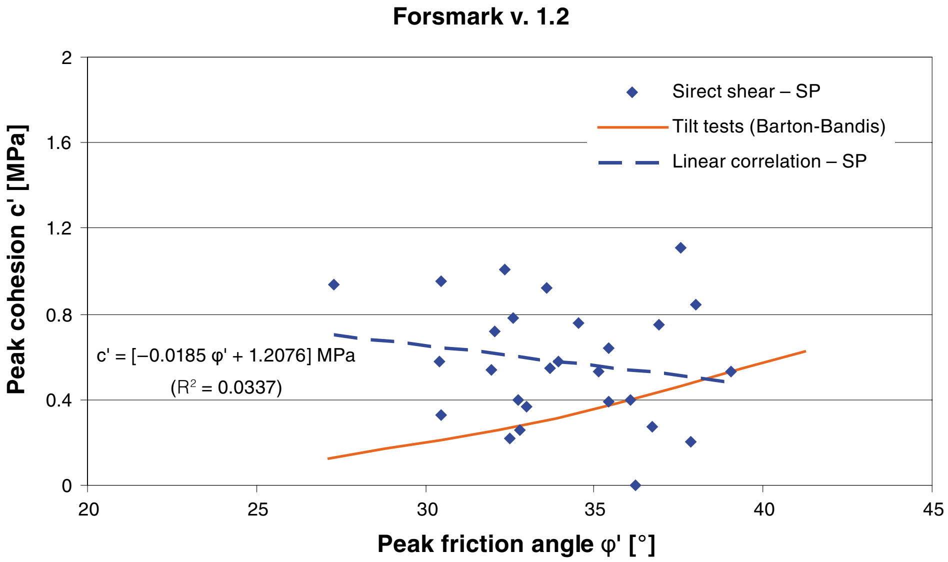

Figure 3-3. *Correlation between the peak friction angle and cohesion obtained with different testing techniques.*

Table 3-5. Comparison of the mean and standard deviation of the peak cohesion and friction angle obtained from different testing techniques and laboratories.

Laboratory test results	Number of samples	Mean peak friction angle (°)	Standard deviation peak friction angle (°)	Mean peak cohesion (MPa)	Standard deviation peak cohesion (MPa)
Direct shear test – SP Laboratory KFM01A, KFM02A, KFM03A and KFM04A	27	34	3	0.6	0.3
Direct shear test – NGI Laboratory KFM01A	5	37	1	1.2	0.2
Tilt test * KFM01A, KFM02A, KFM03A and KFM04A	125 (17 sealed neglected)	34	4	0.3	0.1

* The values reported here are obtained from the Barton-Bandis’ Criterion for normal stresses between 0.5 and 20 MPa.

4 Conclusions

This report contains the summary of the Rock Mechanics laboratory tests used as base for the Site Descriptive Model for Forsmark version 1.2. The tests consist of uniaxial and triaxial compression and indirect tensile tests on intact rock and tilt, normal and shear tests on natural fractures. Samples were taken from boreholes KFM01A, KFM02A, KFM03A and KFM04A. Three rock types were tested: granite to granodiorite, granodiorite (only few samples), and tonalite to granodiorite. The tests were carried out by different laboratories, so that some comparison of the results could be carried out.

The tests on the intact rock showed that the strength of the granite and granodiorite is very high compared to that of the tonalite. The uniaxial compressive strength of the granite to granodiorite, the most dominant rock type in the analysed boreholes, is on average 225 MPa while that of the tonalite is 156 MPa. Some samples tested in uniaxial conditions contained sealed fractures that affected the strength. However, even these samples with sealed fractures exhibited a uniaxial compressive strength (on average 173 MPa) larger than the tonalite.

The triaxial compressive tests, combined with the uniaxial tests, returned the strength envelopes of the intact rock of the three rock types. The Hoek and Brown's parameters were determined, together with the simpler Coulomb's parameters (cohesion and friction angle). In summary, the granite to granodiorite presented an average cohesion and friction angle of 28 MPa and 60°, respectively, while the same parameters for the tonalite were 30 MPa and 47°, respectively. The granodiorite presented properties very similar to the granite.

From the compression tests, also the crack initiation stress, or stress at which "dilation" phenomena start to occur in the samples of the intact rock, was determined. In this report, only the values determined by uniaxial compression were considered. However, the definition of crack initiation stress applies in triaxial conditions too.

The Young's modulus of the intact rock could be determined from the two test procedures. The values obtained seem to be in good agreement and range between 70 and 76 GPa on average for all rock types. The Poisson's ratio, on the other hand, is much affected by the confinement in the triaxial tests. While the granite shows an average Poisson's ratio of 0.24 and the tonalite an average of 0.27 in uniaxial conditions, respectively, the two rock types present an average Poisson's ratio of 0.20 in triaxial conditions.

The results from uniaxial tests obtained at the HUT give a uniaxial strength on average 5% higher than for the SP Laboratory results. The Young's moduli obtained from the two laboratories are almost coincident. The triaxial strength of the intact rock in the two sets of results is in good agreement.

The indirect tensile strength of the intact rock was also determined parallel and perpendicular to the rock foliation. The tonalite seems to have a higher strength (about 15–16 MPa) than the granite to granodiorite (13–14 MPa). The granodiorite alone exhibits the highest average value of 18 MPa. The mean values and standard deviations of the results for all the tested rock types do not show any directional properties (of the tensile strength anisotropy).

The mechanical properties of the rock samples taken from some of the boreholes might indicate a decrease of strength for depth larger than about 600 m. This can be explained by the fact that the complex stress path the cores undergo during drilling in highly stressed rock might induce microfracturing. The P-wave velocity across the core, that indicate increased porosity and presence of cracks, clearly diminishes in borehole KFM01A. However, this trend is not as marked in the other three boreholes. The depth dependency of the mechanical properties of the intact rock should be investigated more in detail in the further Site Descriptive Models for Forsmark.

Natural fractures were also tested according to different techniques and by two laboratories. Tilt tests show that the average JRC_0 of the fractures is on average around 6 while the basic friction angle is around 30°. The joint wall strength of the fractures JCS_0 seems to be rather high (around 80 MPa).

From the normal loading tests, the normal stiffness of the fractures can be obtained. However, the stiffness obtained from the NGI Laboratory is much higher than that obtained by the SP Laboratory. NGI results show an average of about 415 MPa/mm, while SP results present an average normal stiffness of 128 MPa/mm. These difference, even tough the natural variability of the experimental results, might indicate that there are slightly different accuracy and/or testing procedures at the two laboratories.

The direct shear also returned the strength of the natural fractures. The average peak cohesion and friction angle of all the samples tested by the SP Laboratory was 34° and 0.6 MPa, respectively, while the same parameters determined from the NGI shear results were slightly higher and equal to 37° and 1.2 MPa. When re-analysing the tilt tests in terms of peak cohesion and friction angle, the values of 34° and 0.3 MPa were respectively obtained. Among these three sets of results, the SP results were chosen to represent the properties of the fractures at Forsmark mainly because they were the most numerous and agreed well with the tilt tests.

From the shear tests, also the shear stiffness at half the peak shear strength could be determined. Average values of 39 MPa/mm and 26 MPa/mm were respectively obtained from the SP and NGI Laboratory, respectively.

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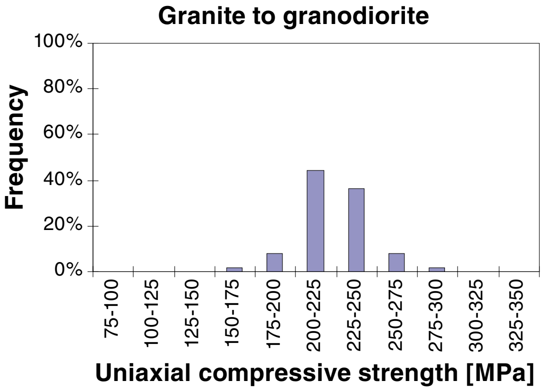
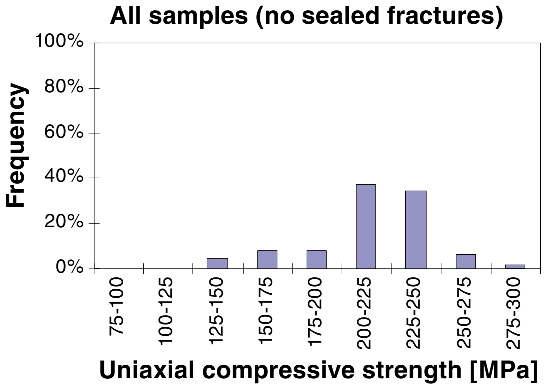
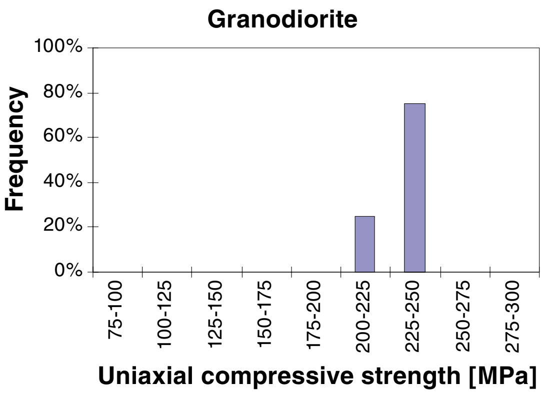
Appendix 1

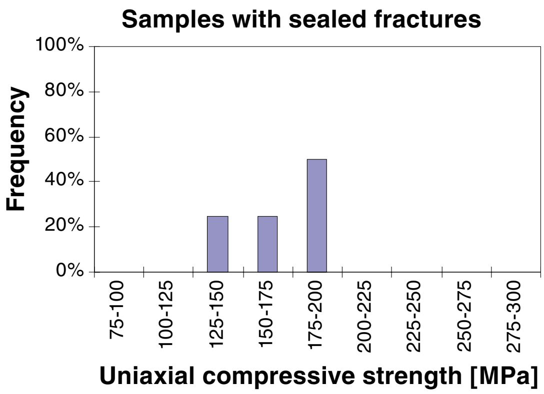
Intact rock

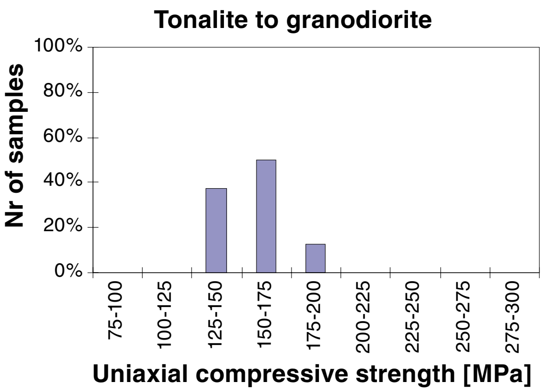
Uniaxial compressive strength (borehole KFM01A, KFM02A, KFM03A and KFM04A)



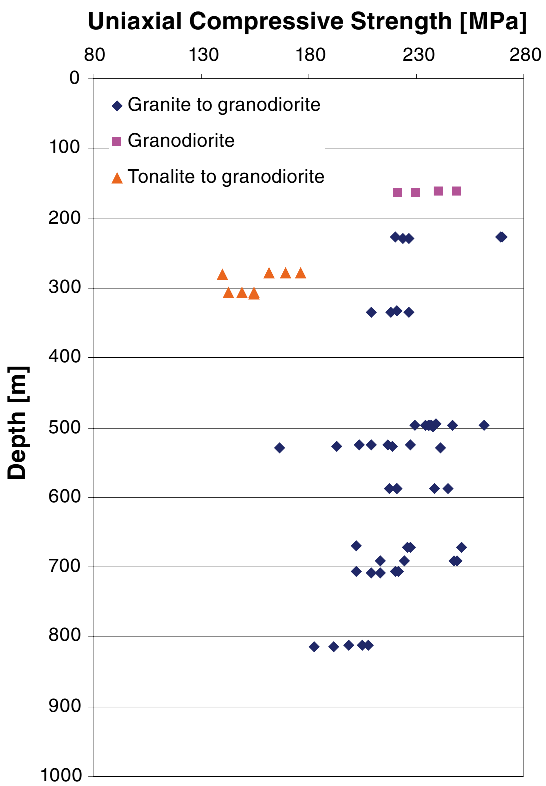


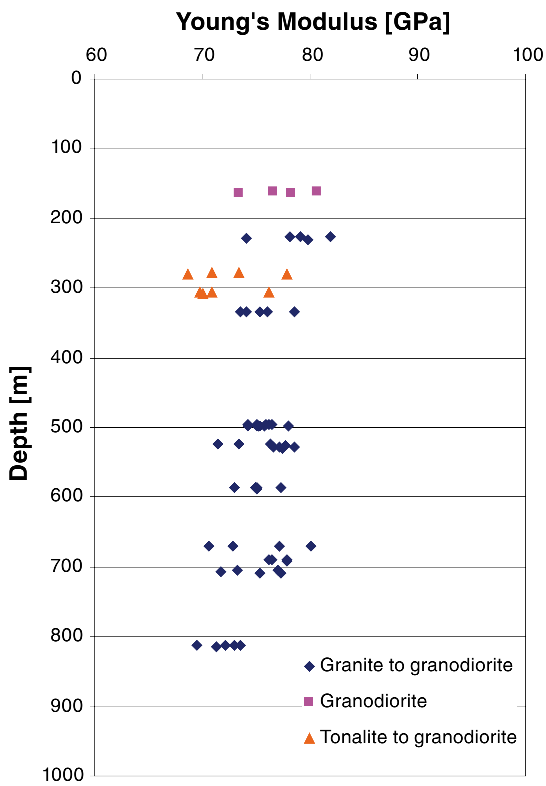


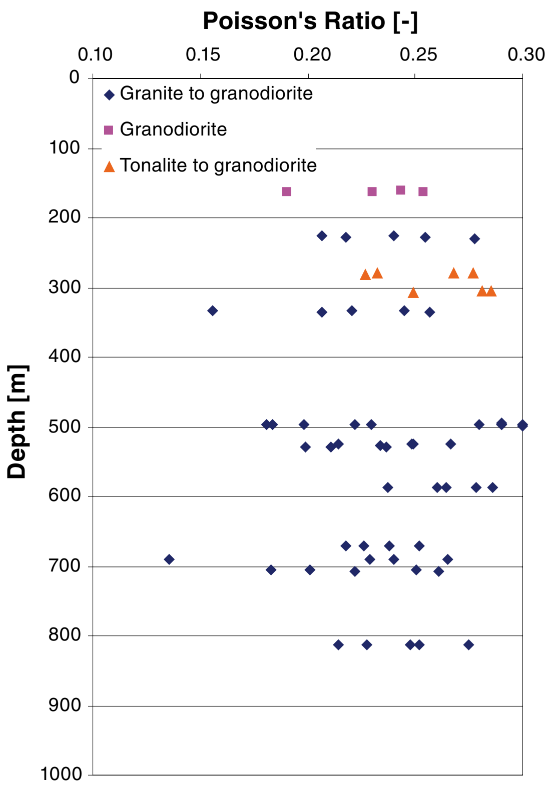




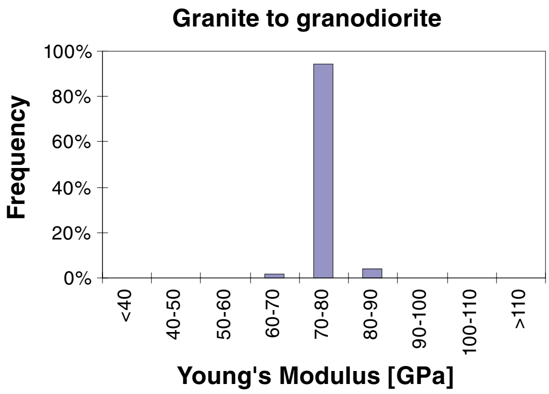
Variation of the parameters from uniaxial compression tests with depth

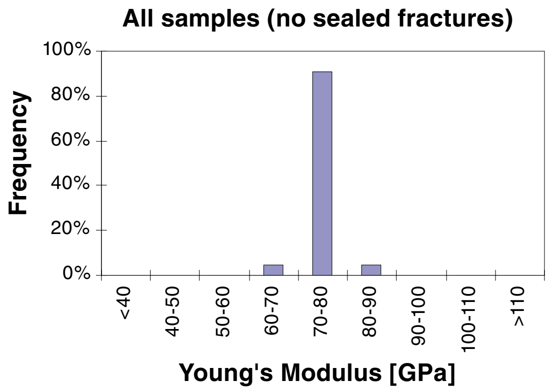


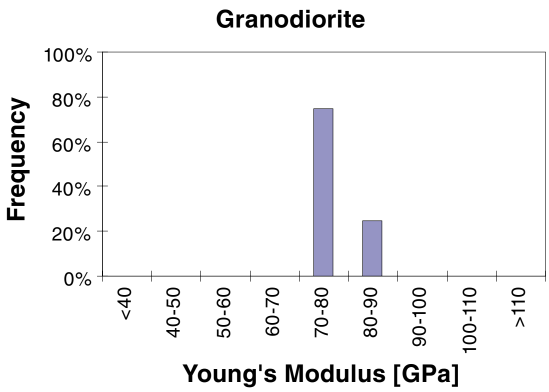


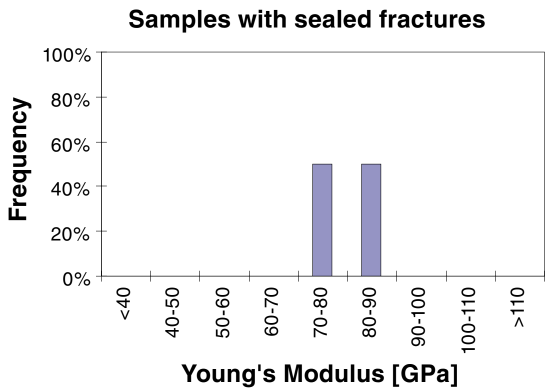


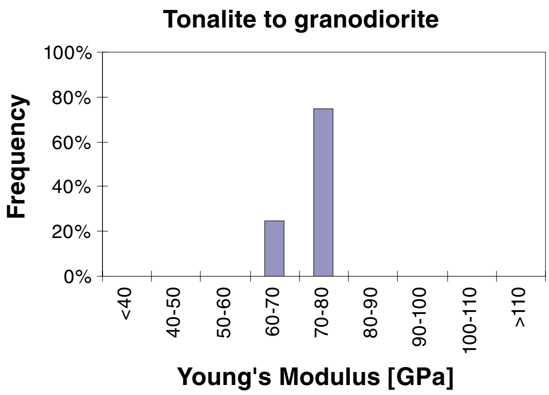
Young's modulus from uniaxial tests



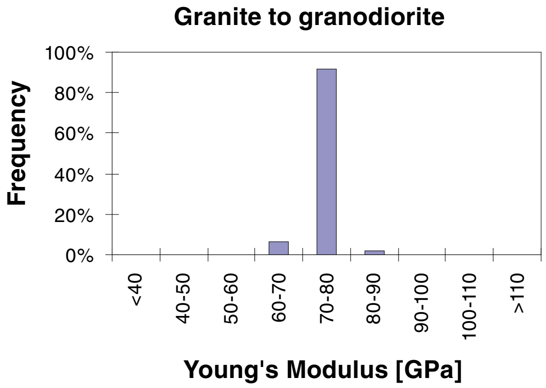


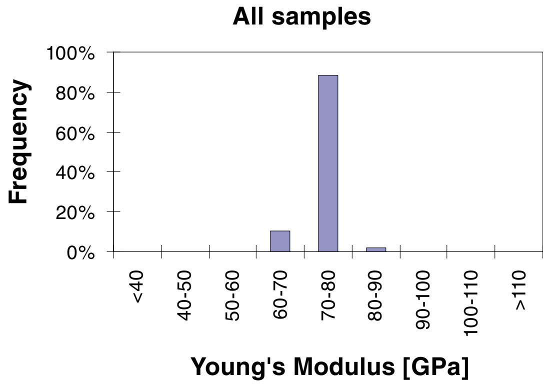


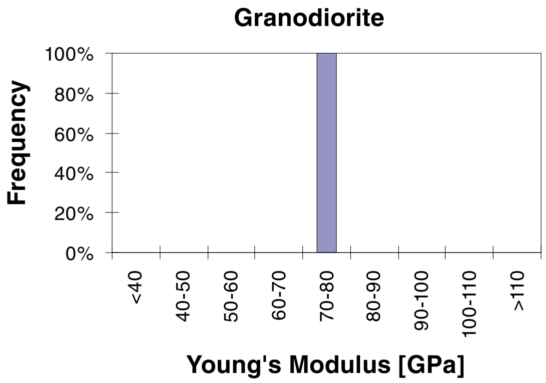


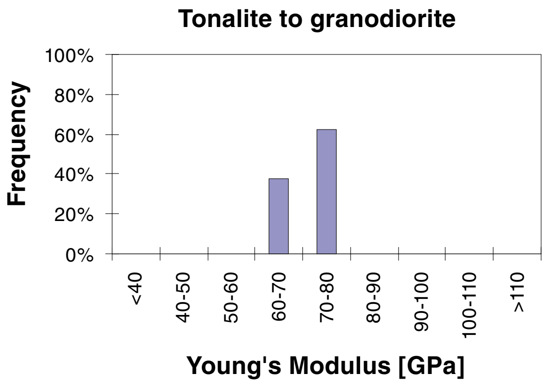


Young's modulus from triaxial tests

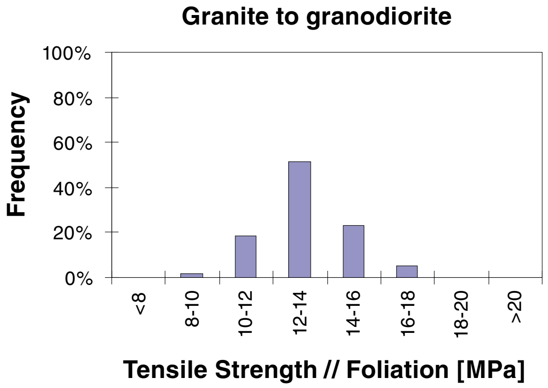


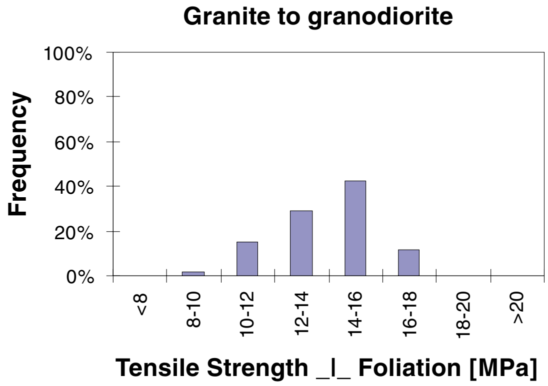


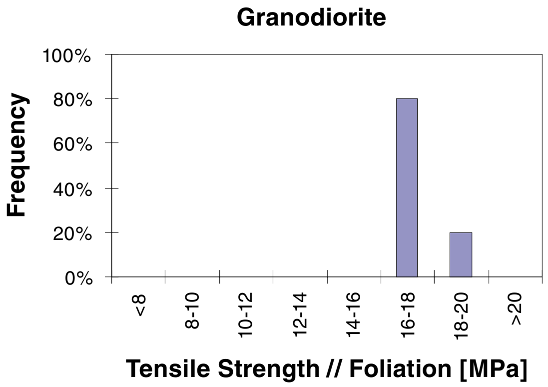


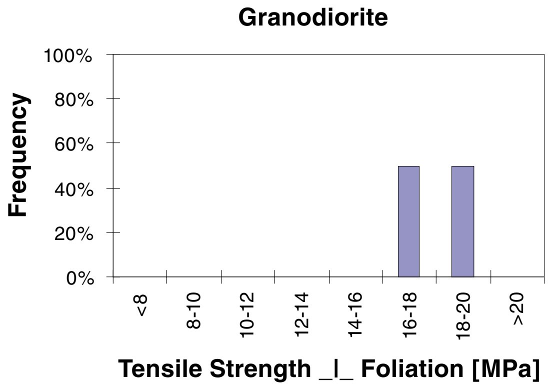


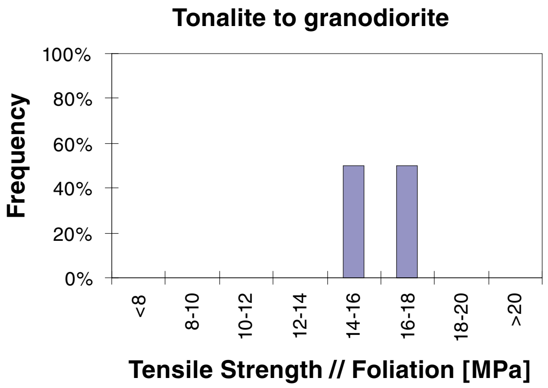
Indirect tensile strength

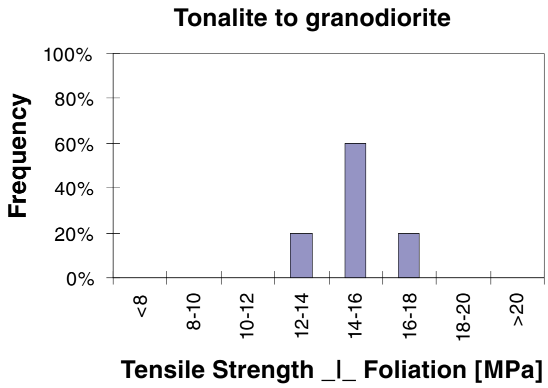




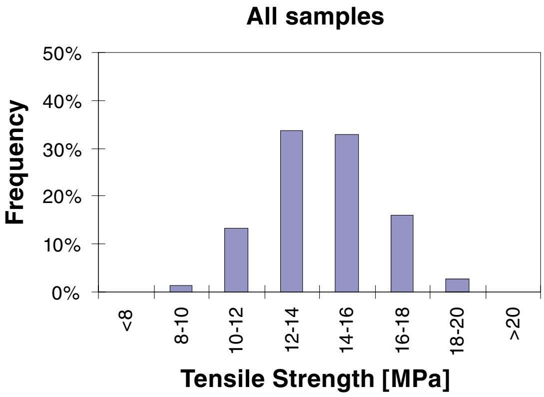




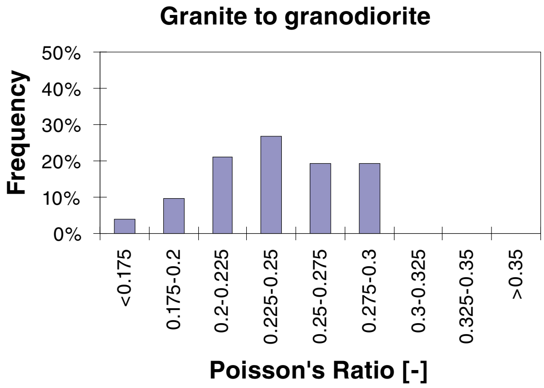


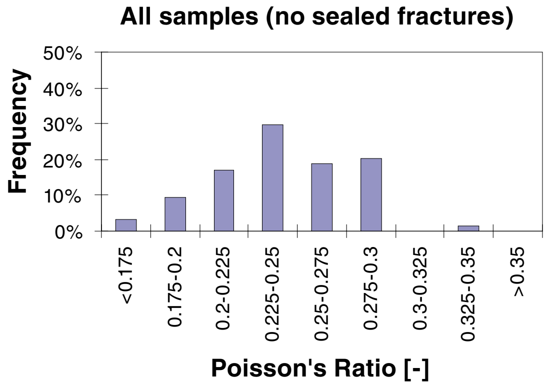


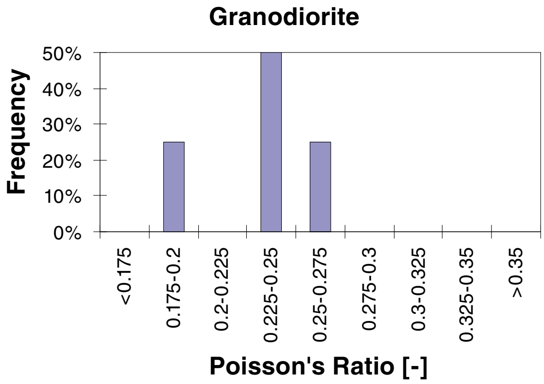
Poisson's ratio from uniaxial tests

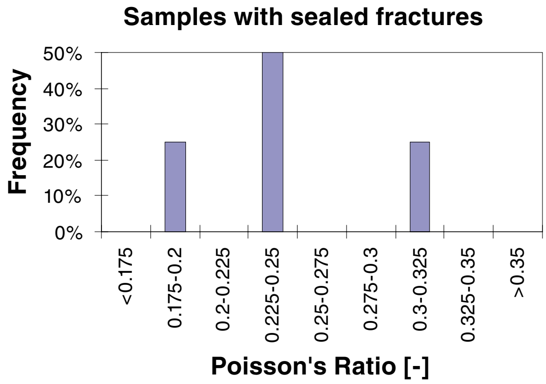


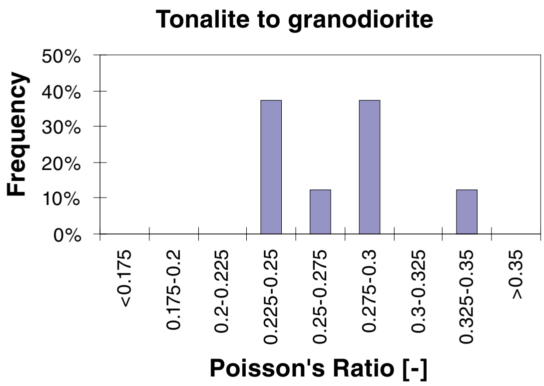
Poisson's ratio from triaxial tests







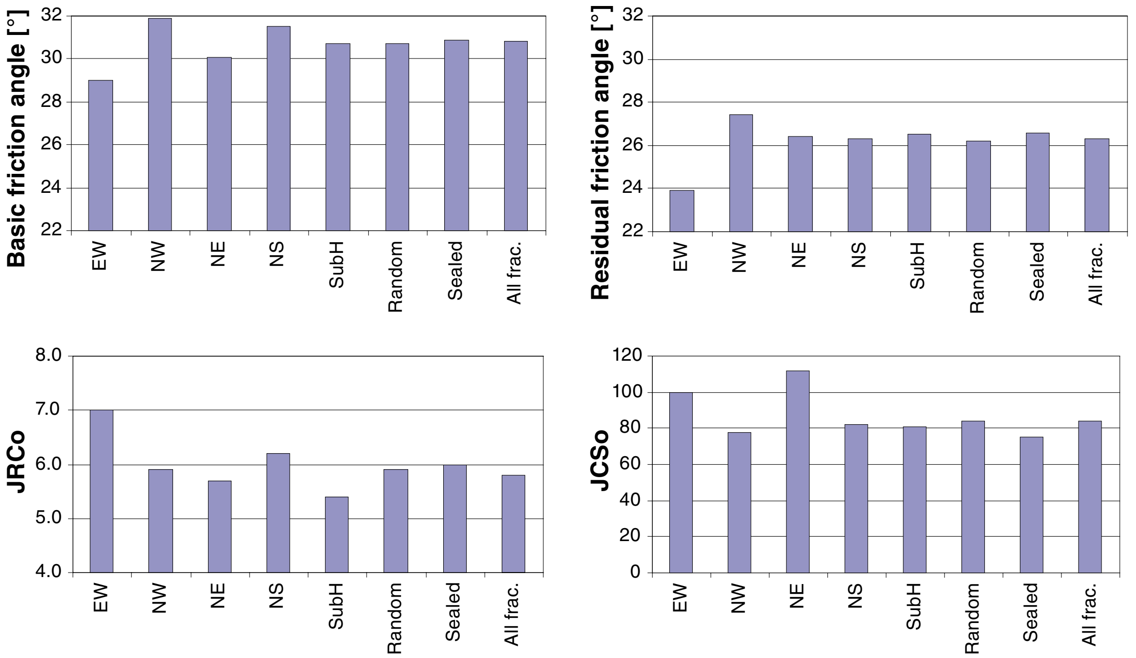




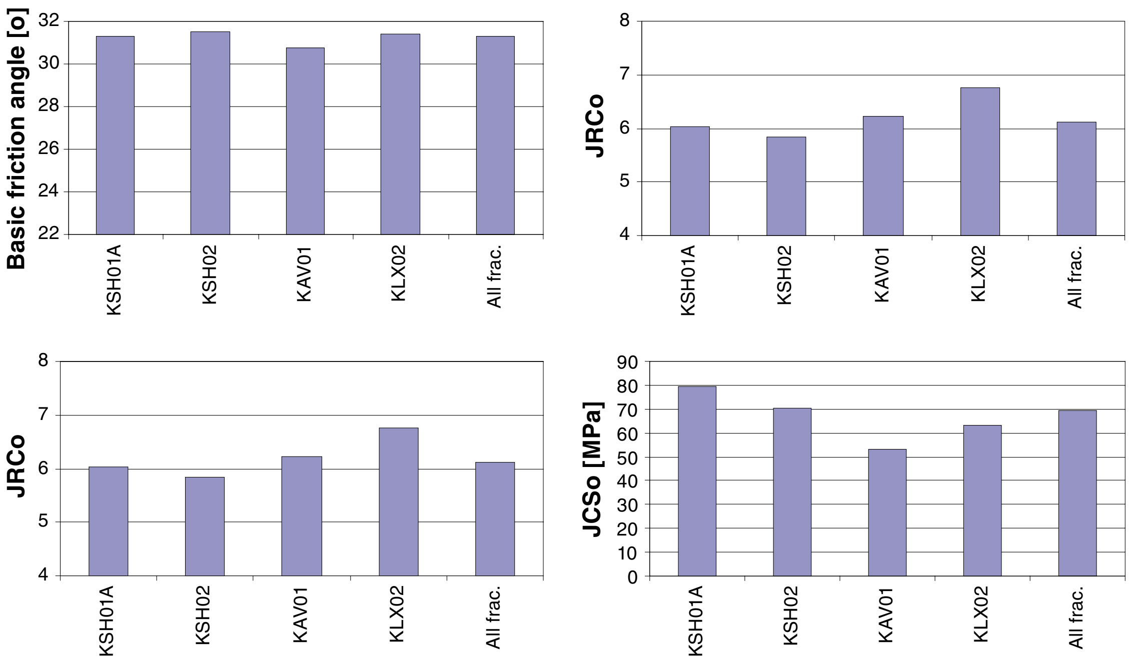
Appendix 2

Natural fractures

Tilt tests – Barton-Bandis' parameters for each fracture set and borehole

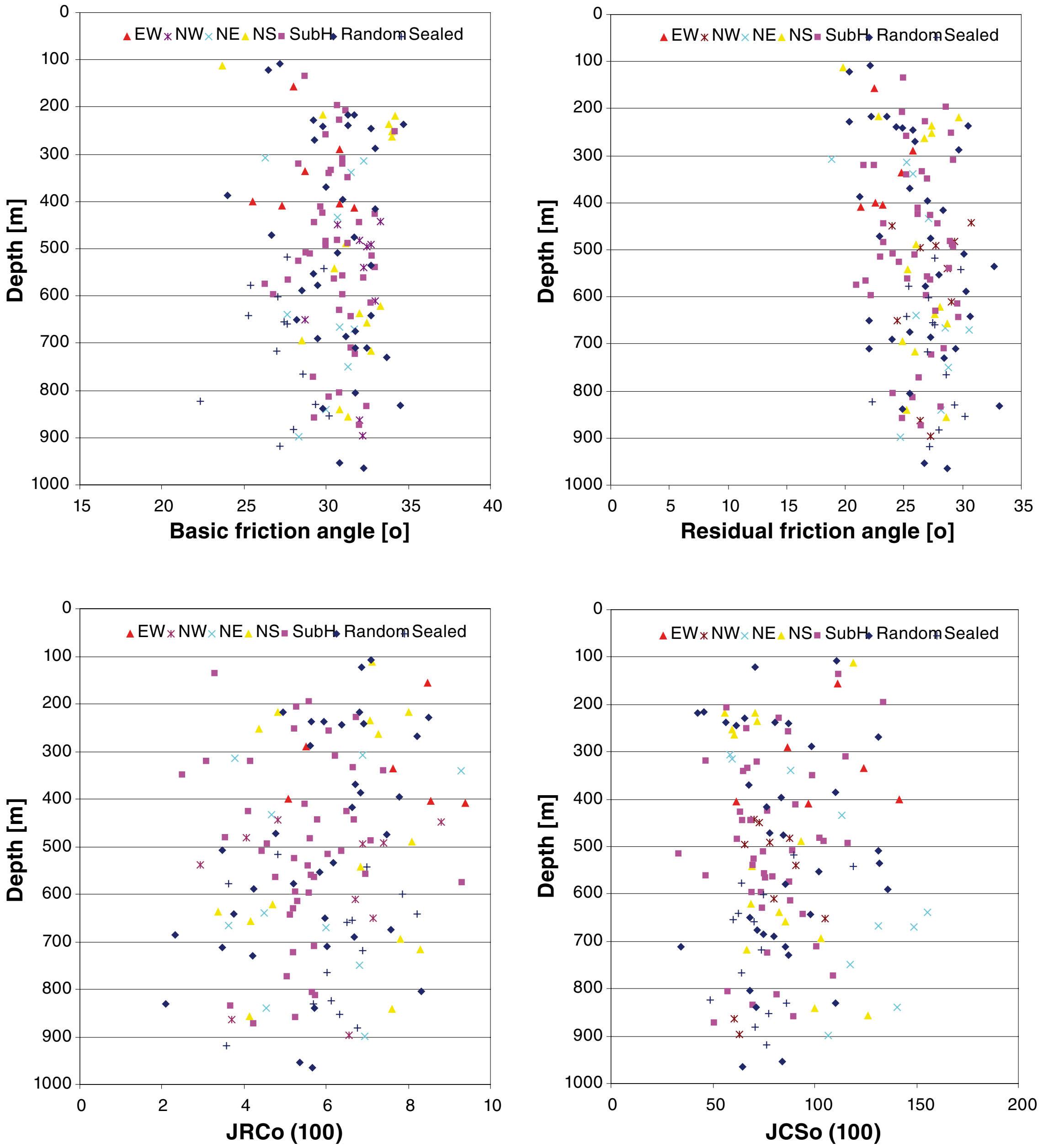


Peak and residual shear strength, joint roughness coefficient JRCo and Joint Compression Strength JCSo for all fracture samples from borehole KFM01A–KFM04A. The fractures are grouped into fracture sets.



Peak and residual shear strength, joint roughness coefficient JRCo and Joint Compression Strength JCSo for all fracture samples from borehole KFM01A–KFM04A. The fractures are grouped per borehole of origin.

Tilt tests – Variation with depth of the Barton-Bandis' parameters for each borehole



Basic and residual friction angles, joint roughness coefficient JRCo and Joint Compression Strength JCSo from tilt tests for the fracture samples from borehole KFM01A–KFM04A. The fractures are grouped per fracture sets.

SP Laboratory – Coulomb's parameters and stiffness from normal load and direct shear tests

Test sample	Cohesion c' (MPa)	Peak friction angle φ' (°)	Normal stiffness Kn (MPa/mm)	Shear stiffness Ks (MPa/mm)
KFM01A-117-01	0.22	32.52	68.0	36.8
KFM01A-117-03	0.20	37.86	75.2	45.1
KFM01A-117-05	0.55	33.68	113.4	28.4
KFM01A-117-07	1.01	32.33	91.3	47.0
KFM01A-117-11	0.00	36.24	106.9	50.4
KFM01A-117-12	0.37	33.02	96.0	26.1
KFM02A-117-01	0.72	32.06	88.6	33.3
KFM02A-117-02	0.95	30.46	80.6	28.3
KFM02A-117-03	0.26	32.82	163.4	43.6
KFM02A-117-04	0.94	27.28	87.9	28.1
KFM02A-117-05	0.54	31.94	103.4	38.4
KFM02A-117-06	0.84	38.02	288.4	43.8
KFM02A-117-07	0.58	33.92	79.9	26.6
KFM03A-117-01	0.27	36.70	206.7	52.1
KFM03A-117-02	0.64	35.44	153.7	41.0
KFM03A-117-03	0.53	35.12	196.3	41.3
KFM03A-117-05	0.40	36.09	96.0	53.3
KFM03A-117-06	0.75	36.93	110.6	32.6
KFM03A-117-07	0.92	33.58	181.0	55.1
KFM03A-117-08	0.40	32.75	123.5	27.8
KFM03A-117-09	0.39	35.41	167.8	44.7
KFM04A-117-01	0.76	34.51	122.1	43.0
KFM04A-117-02	0.78	32.61	184.0	51.7
KFM04A-117-03	0.33	30.45	79.1	11.2
KFM04A-117-04	0.58	30.44	142.4	27.0
KFM04A-117-06	0.53	39.07	158.5	42.4
KFM04A-117-08	1.11	37.58	103.2	48.2

Mechanical properties of fractures evaluated from laboratory tests (borehole KFM01A, KFM02A, KFM03A and KFM04A).