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Äspö Hard Rock Laboratory

TRUE Block Scale experiment

Input data for discrete feature network modelling of the TRUE Block Scale site

Part 1 - Structural analysis of fracture traces in boreholes KA2563A and KA3510A and in the TBM tunnel

Jan Hermansson
Sven Follin
Lingli Wei

Golder Associates

October 1997

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

Äspö Hard Rock Laboratory

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Author	Date
Hermansson, Follin, Wei	
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Keywords: DFN, fractures, statistics, TRUE Block Scale

CONTENTS

1. INTRODUCTION

1.1 BACKGROUND

The rock volume of the TRUE Block Scale experiment is currently investigated by means of structural, hydraulic and geophysical measurements in several boreholes. These measurements constitute an important input to the conceptual and quantitative DFN modeling of the TRUE Block Scale experiment.

1.2 OBJECTIVES

The objective of this note is to evaluate the structural measurements made in the boreholes KA2563A and KA3510A and conclude whether there is statistical or geological evidence to separate the observed fracture traces into sets with possibly different geometric (and hydraulic) properties. The measurements discussed in this report consist mainly of BIPS images of the fracture interceptions with KA2563A and KA3510A (Stråhle, 1996). To some extent the analysis also treat data from the TBM tunnel (Follin and Hermanson, 1996).

1.3 SCOPE OF WORK

The work consists of three parts: orientation analysis, size analysis and intensity analysis.

- The orientation analysis defines fracture sets from field data using an adaptive , probabilistic pattern recognition algorithm.

- The size analysis estimates fracture size distributions for each defined fracture set based on observations of fracture trace lengths on tunnel walls.

- The intensity analysis quantifies the areal intensity of fracturing based on borehole data. The intensity in the structural analysis is based only on existing fractures.

2. ORIENTATION

Knowledge on the rock mass fracturing within and close to the TRUE Block Scale site is currently based on the observations made in the three boreholes, KA2563A, KA3510A and KA2511A and in the last 200 m of the TBM tunnel. At the time of the performed analysis, only drill cores from KA2563A and KA3510A where suitable for an orientation analysis of the fracturing as the database for KA2511A does not contain any information on fracture orientations. The TBM data is considered to be of high quality as it covers a larger volume and is thus less affected by an orientation bias and also contain information on fracture trace length which is necessary for size estimations. However, the TBM data set is a small sample, less than 300 fractures and should therefore be used with caution. For the purpose of an analysis of orientation, clustering of the fractures in the site, drill core data from KA2563A and KA3510A are preferred.

An orientation analysis is performed with the purpose of finding statistical or geological evidence to separate the observed orientations of fractures into sets with possibly different properties. The guiding parameter for such a separation can be orientation alone, or a combination of orientation and other geological and physical properties. Figure 1 shows the stereo plot of the poles to the fracture planes observed in KA2563A and KA3510A. The orientation bias have been geometrically corrected using the Terzaghi correction (Terzaghi, 1965). This technique balances the orientation bias such that fractures at acute angles to the borehole axis are enhanced in number according to a weighting factor that is inversely proportional to the probability of intersecting those fractures with the borehole. To avoid that fracture normals with acute angles close to 90° completely dominates the corrected set, the weighting factor has to be constrained to a maximum number of around 10 according to studies by Yow (1987). For this study, a correction factor of 5 have been used in all analyses, based on previous experience from La Pointe *et al.* (1995) and Dershowitz *et al.* (1996).

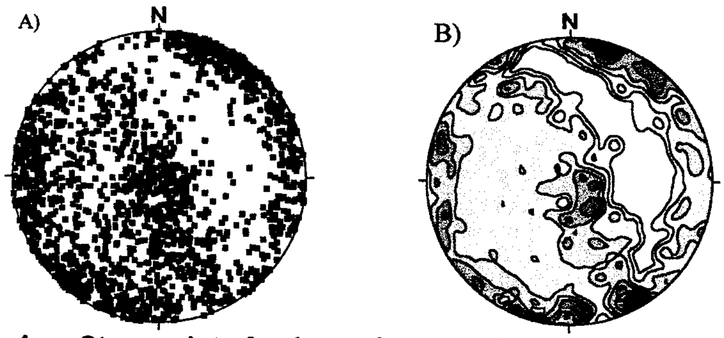

Figure 1 **Stereo plot of poles to fracture planes observed in KA2563A and KA3510A. A shows poles of fractures whereas B shows Kamb contours of the same poles. Contouring is used as a guideline for an initial "guess" of clusters. Orientation correction have been employed according to Terzaghi (1965). Lower hemisphere projection**

In the orientation analysis, cluster parameters for fracture sets are defined by using an adaptive, probabilistic pattern recognition algorithm on the field data. Unlike conventional approaches to fracture sets definition, which define sets by contouring orientations on stereo plots, the FracMan Interactive Set Identification System, ISIS (Dershowitz *et al.* 1995), is as useful for overlapping sets as for clearly defined sets. The premise of the ISIS approach is that fractures may be grouped not only by orientation but also by trace length, termination and fillings etc. ISIS identifies fracture sets using initial input of the number of clusters and their center points, calculates the distribution of properties for the fractures assigned to each set, then reassigns fractures to sets according to probabilistic weights proportional to their similarity to other fractures in the set. The properties of the sets are then recalculated, and the process is repeated until the set assignment is optimized.

In a first attempt to find evidence for a separation into fracture sets, only orientation data from KA2563A and KA3510A have been used. The initial starting points for the pattern recognition algorithm are based on the orientation bias corrected stereo plots in Figure 1. ISIS then repeats and reassigns fractures until the set assignment is optimized. The statistical results shown in Figure 2 and in Table 1 reveals that there are three possible fracture sets, although not very well defined. Set 1 and 2 are steep, NE and NW trending respectively while Set 3 is subhorizontal. The K-S goodness-of-fit statistic for set 1 is poor, whereas set 2 and 3 are more statistically well defined. The set orientations fits very well with previous experiences from the HRL.

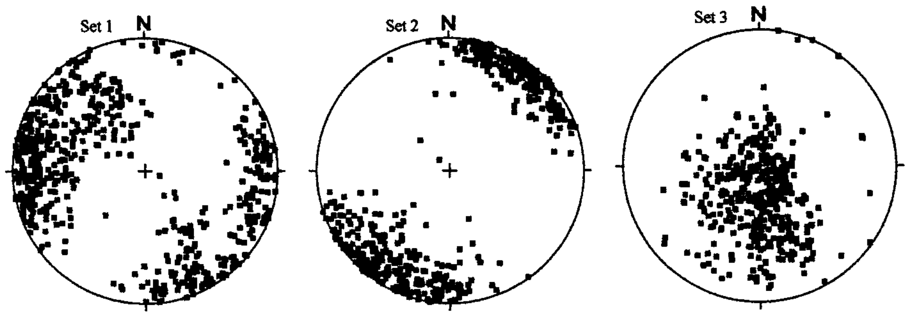

Figure 2 **"Best fit" statistical separation of fracture sets based on data from KA2563A and KA3510A. Lower hemisphere projection.**

The main reason for separating the observed fracture traces into sets is to conclude whether the important parameters, which control flow in the network, are set specific. Fracture size and fracture termination are two such parameters. As fracture trace length is missing in the borehole data due to censoring, information has to be found elsewhere in the vicinity of TRUE Block Scale site. The last section of the TBM tunnel is located on the northern rim of the site and contain information regarding trace length.

Table 1 **Statistical separation of fracture sets based on data from KA2563A and KA3510A (cf. Figure 2). The K-S statistic in column one represent the maximum absolute difference between a theoretical distribution and the observed distribution. This maximum absolute difference is always non-negative. Percent significance means the probability that the maximum absolute difference is actually greater than the calculated one, given the sample size.**

Fracture set 1		
Orientation (trend, plunge)	302.1	6.5
Fisher K	4.51	
Kolmogorov- Smirnov (K-S, %)	0.08	0.01
Number of fractures	781	
Fracture set 2		
Orientation (trend, plunge)	209.8	2
Fisher K	9.46	
Kolmogorov- Smirnov (K-S, %)	0.037	40.1
Number of fractures	583	
Fracture set 3		
Orientation (trend, plunge)	177.8	70.6
Fisher K	6.88	
Kolmogorov- Smirnov (K-S, %)	0.033	67.8
Number of fractures	478	

Figure 3 shows a stereo plot of the last section of the TBM tunnel where it is clear that the same three sets of fracturing dominate here as in the borehole data. As mentioned earlier, previous investigations at the Äspö HRL by Hermanson (1995) and Munier (1995) show that the three clusters of fractures similar to those found in the drill cores can be found throughout the HRL. Statistical fracture set separation of the fractures in the last section of the TBM tunnel using the same pattern recognition approach as in the boreholes show a great similarity to orientations of the previously separated sets. The sets in the TBM are somewhat more clustered (cf. Fisher K values in Table 2) than in the boreholes. This may be caused by the orientation bias correction method in the borehole data. The statistical output coincide with what could be called fracture set separation based on expert judgment, i.e. a separation of the contoured stereo plot into three sets simply by visual inspection and perhaps mixed with fracture mapping experience in the Äspö bed rock. It seems that fracture set 3 in both the TBM and in the borehole data have the best correlation with a Fisher model of all sets. Set 1 in the borehole data is poorly defined in comparison to the tighter, more defined cluster in the TBM data. It is difficult to say whether this is a local variation or just an artifact by the bias correction method. At this stage it only seems obvious that we have two steep sets and one subhorizontal. The distributional data should be interpreted and used with care.

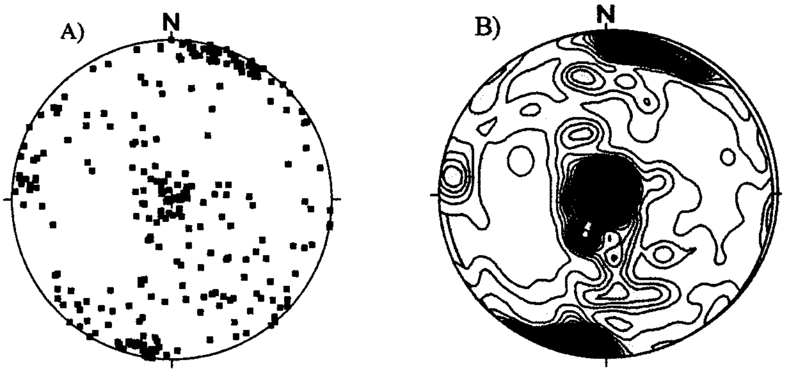

Figure 3 **Stereo plot of poles to fractures planes in the last 120 m of the TBM tunnel. B shows Kamb contours of the poles in A. Lower hemisphere projection.**

However, it should be noted that the statistics of the fracture set separation is not particularly successful and is probably one of many possible models. The reason for choosing this particular model is the obvious correlation with the geological expert judgment model. An alternative modeling approach to the one discussed above is to directly bootstrap the simulated fracture orientations from the field observations, i.e. without orientation analysis. A relevant reference which describes the bootstrapping technique is the analysis by Follin and Hermanson (1996).

Table 2 **Statistical separation of fracture sets (poles) based on data from the last 120 m of the TBM tunnel. The K-S statistic is explained in Table 1.**

Fracture set 1		
Orientation (trend, plunge)	117.9	12.9
Fisher K	5.64	
Kolmogorov- Smirnov (K-S, %)	0.16	38.5
Trace length statistics		
Mean	8.359375	
Sample Variance	27.85475	
Kurtosis	-0.56353	
Skewness	0.894438	
Minimum	2.1	
Maximum	20.3	
Count	77	
Fracture set 2		
Orientation (trend, plunge)	200.4	2
Fisher K	15.75	
Kolmogorov- Smirnov (K-S, %)	0.163	4.6
Tracelength statistics		
Mean	7.916901	
Sample Variance	22.19228	
Kurtosis	-0.14086	
Skewness	0.904207	
Minimum	1.8	
Maximum	20.5	
Count	305	
Fracture set 3		
Orientation (trend, plunge)	186.5	81.1
Fisher K	13.6	
Kolmogorov- Smirnov (K-S, %)	0.095	79.7
Trace length statistics		
Mean	8.873913	
Standard Deviation	116.1037	
Kurtosis	17.26704	
Skewness	3.76579	
Minimum	1.4	
Maximum	65.5	
Count	275	

3. SIZE

The general shape of a fracture in three dimensions is essentially unknown. We can observe traces and cuts on walls and outcrops but the complete shape of the fracture remains invisible. For conceptual purposes, fractures can be simplified as disks, and their sizes[1] can be estimated by looking at the trace length on outcrops and tunnel walls.

In this study, two different methods have been used for the size estimation. The first method, as published by La Pointe *et al.* (1993), uses the fact that for a particular fracture orientation, tunnel orientation and tunnel cross-section, the probability that a fracture trace could be mapped all the way around the tunnel surface is a function of fracture size. Size can thus be estimated by defining how large part of a tunnel surface a fracture intersects. The second method is similar to the first, but instead of measuring intersected part of tunnel surface, this method make use of the complete observed trace length distribution.

Throughout this estimate of the fracture size assumptions have been made not only of the fracture shape but also of the fracture size distribution. For time critical reasons only lognormal size distributions have been considered. Such an assumption have been advocated by other authors in previous investigations (La Pointe *et al.*, 1995; Dershowitz *et al.*, 1996; Priest 1993, Kulatilake 1984a). This assumption is valid for both size estimate techniques.

3.1 TRACE LENGTH DATA FROM THE TBM TUNNEL

There exist two different sets of data from the last section of the TBM tunnel. Traces on the tunnel walls have been mapped by site geologists through visual inspection just after blasting of a new section. The two data sets origin from the mapping technique of the geologists. The first data set consists of hand drawn maps of the traces in the tunnel. These maps have then been digitized at the site, and later converted by VBB Viak to 3D coordinates as reported in Appendix A by Follin and Hermanson (1996). These sketched traces are here referred to as the VBB Viak data set. The second data set origins from the estimation of the trace length performed by the same geologist simultaneously as he draws the trace map. This estimate is then recorded in SICADA, and is here referred to as the SICADA data set. Ideally they should be identical. However, estimating the length of an object by sketching is generally easier than estimating with numbers. This can be seen by looking at the mean trace lengths from these different data sets,

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[1] In FracMan, fracture size is expressed as the equivalent radius of a circular disk with the same area as the fracture, independent of shape.

- SICADA data set, mean trace length 5.5 m.
- VBB Viak data set, mean trace length 8.3 m

The TBM tunnel is circular and has fracture traces all around its perimeter. Unfortunately, when the original mapping was performed in the tunnels of the HRL, fracture traces less than one meter were excluded (not recorded). This trace truncation implies that fractures with a radius less than 0.5 m intersecting the tunnel can not be analyzed as traces are not measured. It also implies that traces of larger fractures, which are just intersecting a small part of the tunnel wall (< 1 m) are truncated.

3.2 SIZE ESTIMATE USING METHOD 1 (after La Pointe *et al.* 1993)

By means of exploration simulation and sampling with a 16 sided "TBM tunnel" in a stochastic network, intersection statistics on the tunnel walls have been compared to observed intersections in the real TBM tunnel. The three fracture sets have been analyzed separately with regard to their size distribution(s). The procedure used in the performed analysis is described by La Pointe *et al.* (1993) and in detail by Follin and Hermanson. (1996) and is shortly summarized below:

1. Intersections statistics from the field observations was produced using 16 panels on the walls of the TBM tunnel (i.e. resembling a 16 sided tunnel)
2. A DFN model was generated with parameters according to Table 3.
3. A 16 sided tunnel resembling the size and orientation of the TBM tunnel was inserted into each network realization of the DFN models.
4. For each trace the number of panels intersections were calculated.
5. A correlation analysis of the 16 panel intersection statistics between the simulations and the observations show in which mean size window there is best correlation of trace statistics.

The input data for this analysis is the VBB Viak data set. The analysis was subjected to the following rationale: Traces shorter than a meter was discarded from the analysis as the observations are subjected to such a truncation. However, a non-truncated size distribution was used in the stochastic network realizations, as truncation of traces does not necessarily imply that fractures of sizes less than 0.5 m in radius does not exist. The latter is certainly true, as can be observed in drill cores and on tunnel walls. But by using a non-truncated size distribution and only truncating the traces on the tunnel wall, we may enhance our possibility to recreate what has been observed also in the more fractured drill cores.

The analysis is based on calculating number of panels intersected by fractures and comparing the observed panel intersections with simulated panel intersections. There may be several weaknesses to such a method, such as correlation to a small observed sample with an uneven distribution, and lack of panel intersection statistics for fracture sets with an extremely acute angle to the tunnel axis. However, one may also argue that small samples are always subject to weak statistical significance.

Table 3 DFN network parameters used in the exploration simulations.

Spatial model	Enhanced Baecher
Orientation	According to previous findings for Set 1 - 3
Size distribution	Lognormal
Size	Mean = 1 - 12 m, Std. Dev = 1 - 5 m
No. of fractures/realization	10 000
No. of realizations	10 realizations for each combination

The simulations where carried out in two steps. In the first step a large number of possible fracture mean sizes where tested for each fracture set to establish a window of well correlated sizes. The results are presented in Figures 4 – 6. Acceptable mean size intervals are: 2 – 4 m for Set 1, 5-10 m for Set 2 and at least 4 – 7 m for Set 3. Secondly, a more detailed analysis was performed using these mean size intervals. The standard deviation was altered between 1 – 5 for each mean size, a number of realizations where run (10 for each combination), and the correlation analyses were repeated once more. The results from these latter analyses are shown in Figures 7 – 9 and in Table 4.

Table 4 Lognormal fracture size estimates of the three orientation sets.

Orientation	Lognormal size distribution
Set 1 (NE)	Mean 1-3 m , Standard deviation 1-2 m
Set 2 (NW)	Mean 5-9 m , Standard deviation 1-2 m
Set 3 (Subhorizontal)	Mean 4-7 m , Standard deviation 2-4 m

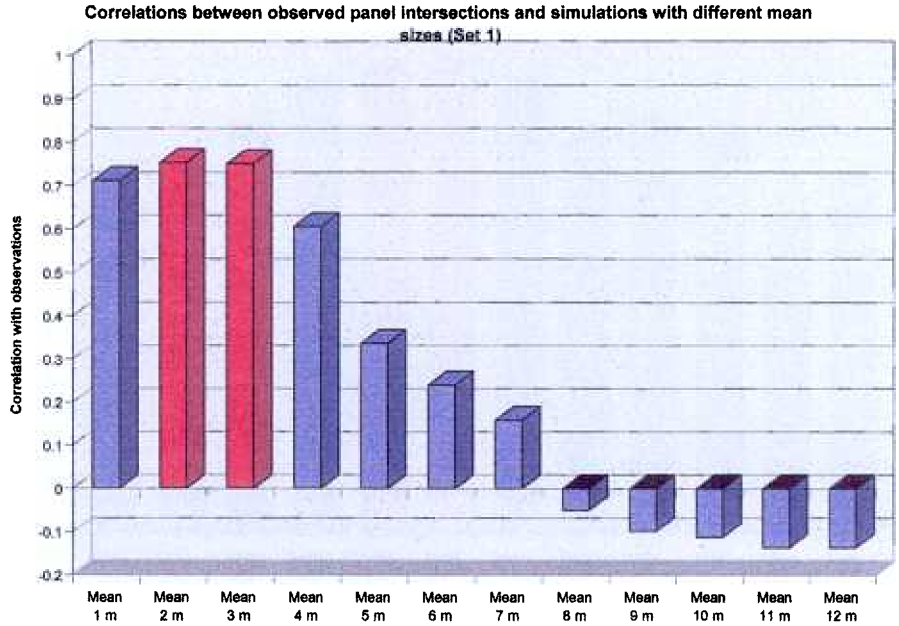

Figure 4 **A correlation analysis of the intersection statistics show that a mean size of 2 to 4 m with a standard deviation of 1 fits well with observed data. To optimize this estimation, new simulations with a varying standard deviation is performed over the identified "best" mean interval.**

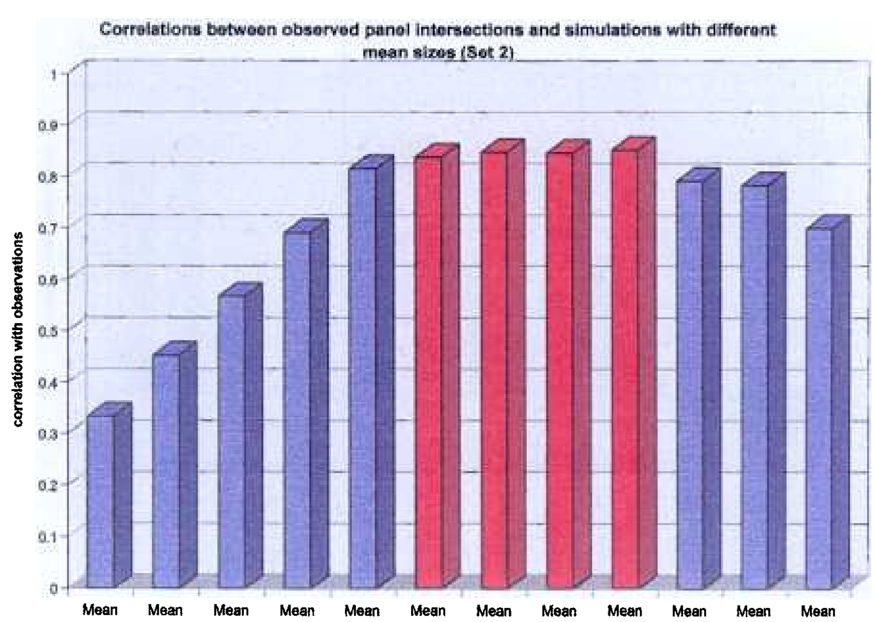

Figure 5 **Correlation analysis of the intersection statistics show that a mean size of 5 to 10 m and with a standard deviation of 1 fits best with observed data.**

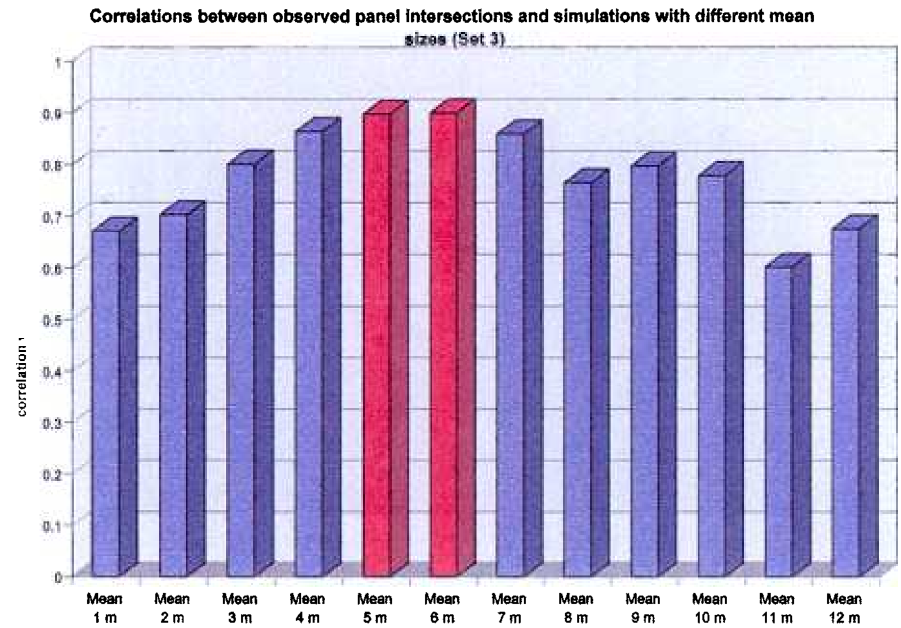

Figure 6 **Correlation analysis of the intersection statistics show that a mean size of 4 to 7 m with a standard deviation of 1 fits best with observed data.**

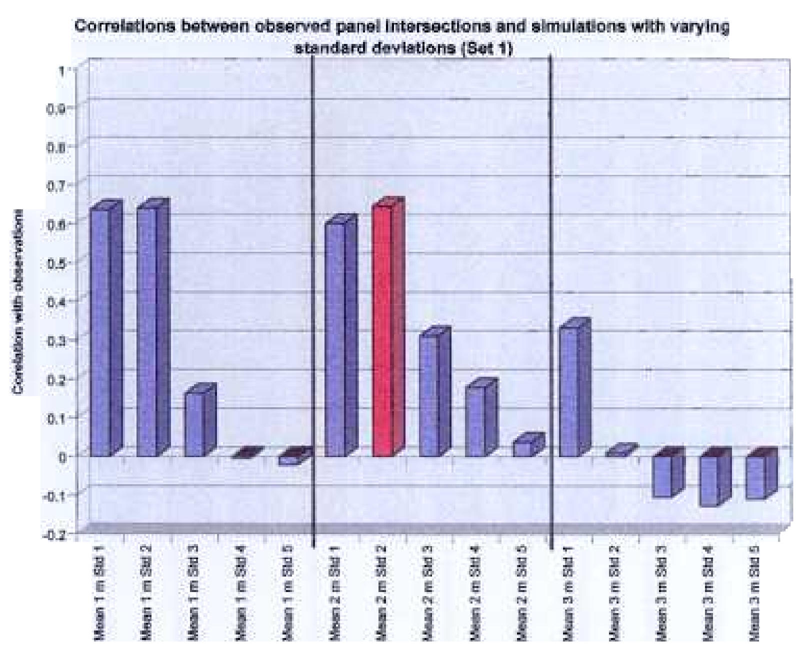

Figure 7 **Correlation between observed and simulated traces for orientation set 1 (NE-trending). To optimize the previous size analysis, a simulated size distribution in the estimated mean window is varied in standard deviation. The best fit estimation is observed for lognormally distributed fracture sizes of mean sizes 1-3 m with a standard deviation of 1-2 m.**

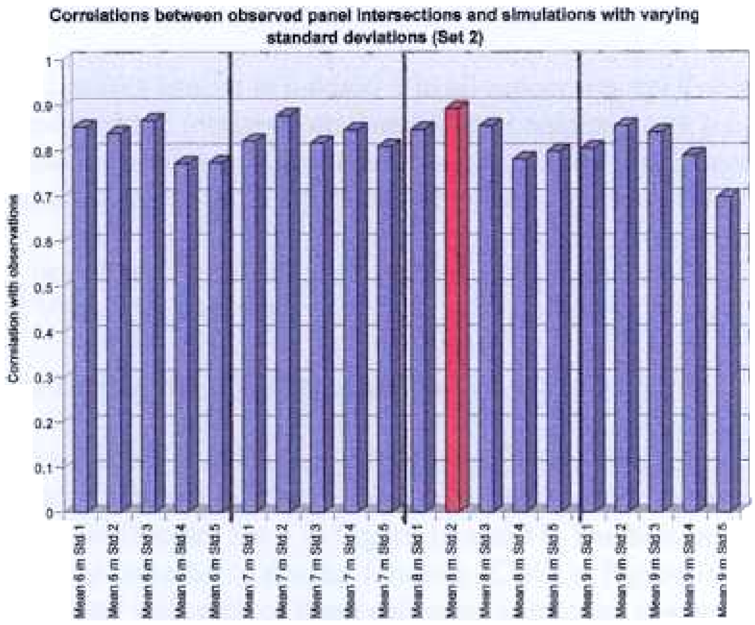

Figure 8 Set 2 (NW-trending) correlation between observed and simulated traces in the mean size interval 6 to 9 m. The standard deviation is varied between 1 and 5. The best fit estimation is observed for lognormally distributed fractures of mean sizes of 5 to 9 m m with a standard deviation of 2.

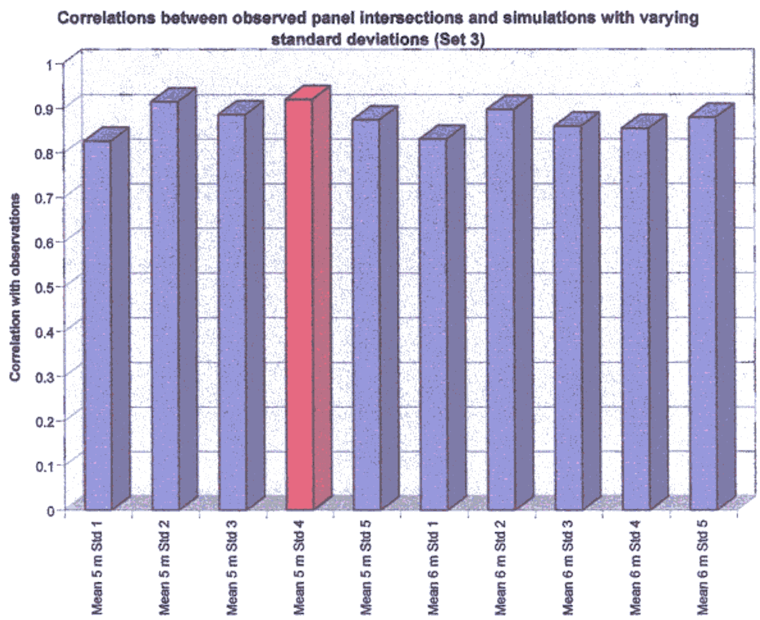

Figure 9 Set 3 (Subhorizontal). The correlation between observed and simulated traces in the mean size interval 5 to 6 m (lognormal distribution) reveal that one cannot make more exact statements than the first estimate of a best fit estimate of mean size 4 to 7 m. A variation in standard deviation makes little difference.

3.3 SIZE ESTIMATE USING METHOD 2

Method 2 works similar to method 1 in all aspects except that traces are not converted to panel intersections. Instead the complete trace length distribution is used to estimate size. The best fit size distribution is estimated by comparing trace length statistics from observations and simulations.

Both types of raw data has been used in this size analysis, i.e. SICADA data set and VBB Viak data set.

3.3.1 Method 2 using the SICADA data set

Simulations using a wide range of different possible lognormal fracture size distributions resulted in a range of possible mean sizes. Examples of results are shown for fracture Set 1 in Figure 10 and 11. The best estimates are plotted in the cumulative density function (CDF) in Figure 10. Figure 11 illustrates how well each of these estimates mimic the observed CDF for all different classes. Trend lines are inserted to show if the simulated traces tend to over or under-replicate traces. Ideally, the trend line should be located close to 0 (=little deviation) and have a slope of 0 (=no trend).

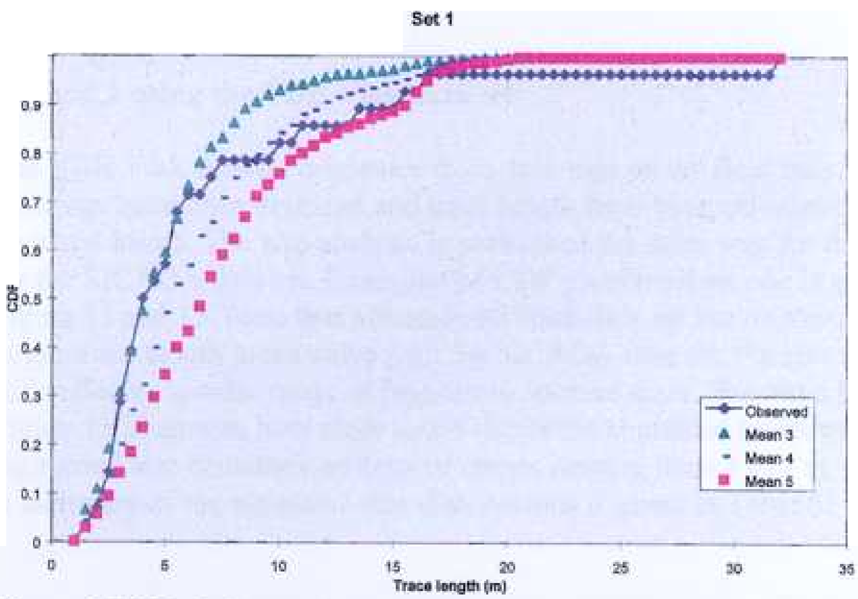

Figure 10 CDF of observed trace lengths (blue line) and of the best fit simulated trace lengths for Set 1. The analysis suggests that a lognormal fracture size distribution with mean values around 3 to 5 m produces traces that fits well with the observed trace lengths.

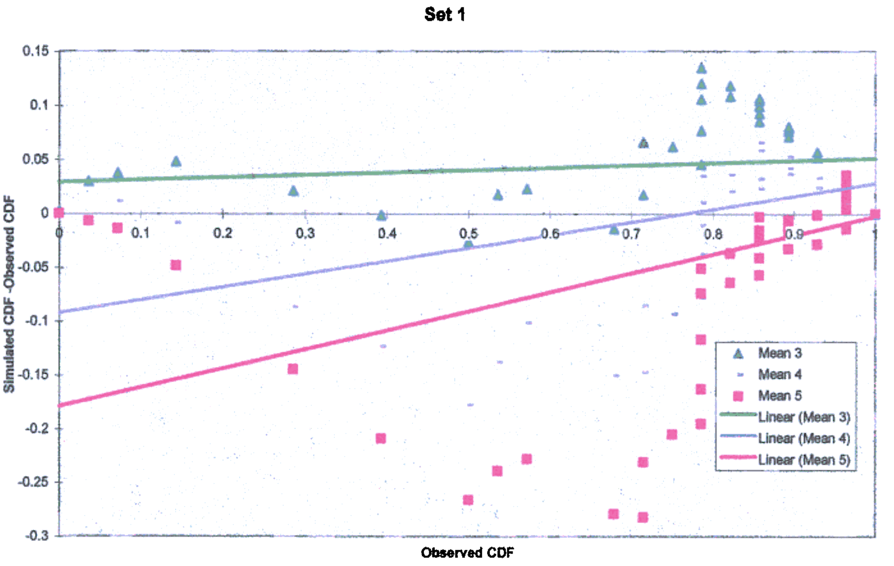

Figure 11 Observed CDF plotted against the difference between Simulated CDF and Observed CDF. This plot illustrates how well the simulated trace lengths mimic the observed. Trend lines show if the simulations tend to divert from the observed CDF.

A summary of the size analysis using raw data from the SICADA data set is given in Table 5.

3.3.2 Method 2 using the VBB Viak data set

The VBB Viak data set originates from drawings on the field map. These drawings have been digitized and trace length have been calculated from the digitized traces. The size analysis is performed the same way for this data as for the SICADA data set. Examples of CDF plots from set one is given in Figure 12 and 13. Note that although the Viak data set has on average a larger trace length mean value than the SICADA data set, the size analysis still reflects a similar range of lognormal fracture sizes. The trend lines in Figure 13 illustrates how close resemblance the simulated traces of the lognormal size distributions have of means ranging from 4 to 7 m.
A summary of the estimated size distributions is given in Table 5.

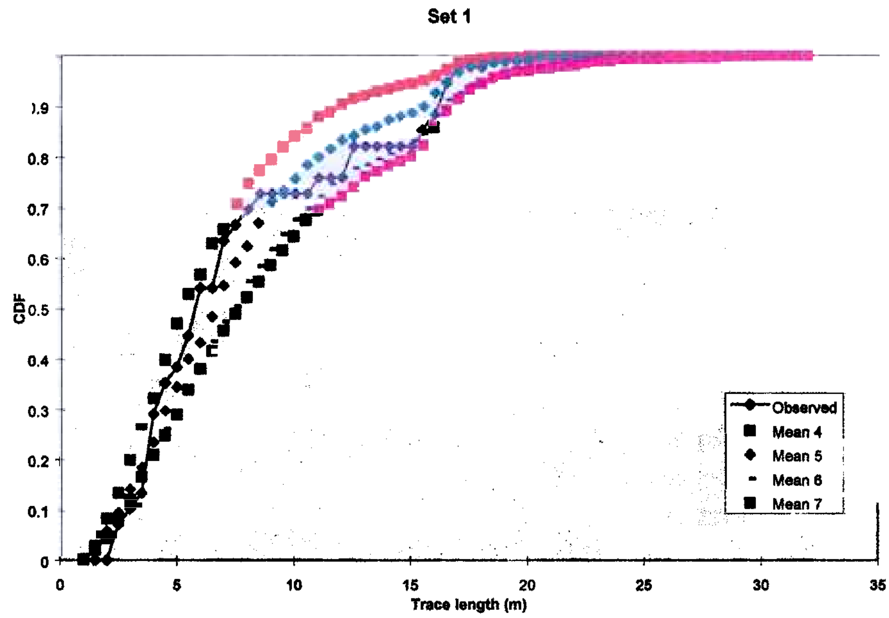

Figure 12 CDF of observed and simulated traces using the VBB Viak data set. The best lognormal size distribution estimates range from mean 5 to 7 m.

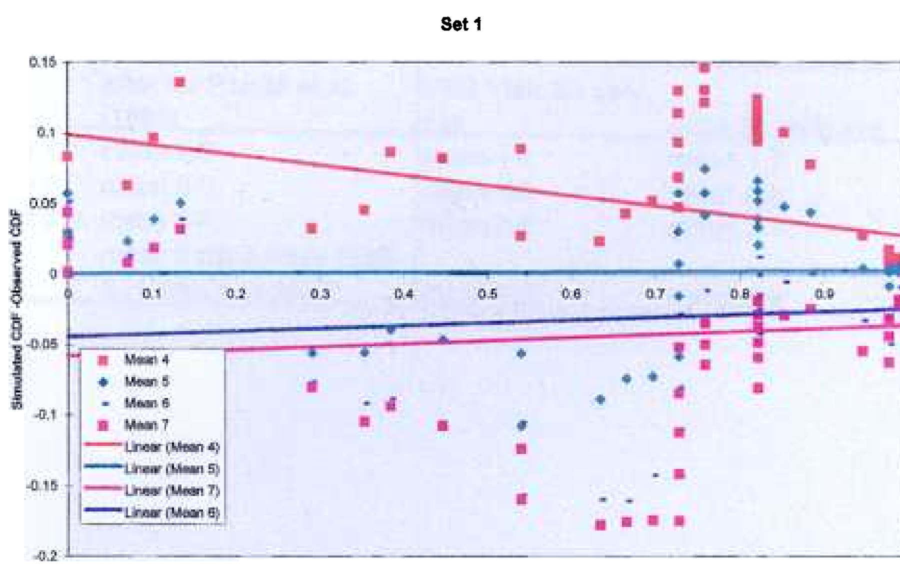

Figure 13 Observed CDF plotted against the difference between Simulated CDF and Observed CDF. Results show little difference between observed traces and traces from simulated lognormal mean size distributions with means ranging from 4 to 7 m.

3.4 SUMMARY OF SIZE ESTIMATES

Method 1, after La Pointe *et al.* (1993), is based on a discretisation of the tunnel in panels, in this case subhorizontal as the TBM tunnel. When calculating how many panels each trace intersects it is clear that the orientation of the trace relative to the panel influence the result. In particular, one expects that the subhorizontal set would be the most biased set as traces tend to intersect few of the subparallel panels. Looking at results from both methods the difference between estimates of different orientation sets is not large, although the range of possible "good" estimates for size is generally larger using method 1. Rather, what can be emphasized is that the difference in size between different orientations is not significant. Although the variability between different methods and data sets is large, it is clear that fracture size alone is not reason enough to generate DFN models with different fracture orientation sets. However, if one couples fracture orientation sets with other parameters such as transmissivity, aperture etc, there may be significant difference. Also, it is worth noting that P_{32} is dependent on orientation, and not on size.

Table 5 Estimates of fracture size r (m) using two methods and two different data sets.

	Method 1	Method 2	
	after La Pointe et al. (1993)	VBB Viak 3D data set	SICADA data set
Set 1	mean 2-3	mean 4-7	mean 3-5
Set 2	mean 5-9	mean 4-6	mean 4-6
Set 3	mean 4-7	mean 3-5	mean 2-4
All	mean 6 std 3 (from Follin & Hermanson 1997)	mean 4-5	mean 3-5

4. FRACTURE INTENSITY

The fracture intensity, denoted as P_{10} or λ, is a measure of "linear intensity", i.e., measured along a borehole or scanline. It depends on the orientation of the borehole. For simulations with FracMan/MAFIC, it is much better to use intensity measure P_{32}, i.e., the conductive fracture area per unit volume of rock. This intensity measure is scale-invariant, i.e., it is independent of model size, fracture sizes, and borehole lengths and orientations. The determination of P_{32} from P_{10}, is accomplished by using the following procedure in FracMan (FracWorks):

1. assume an initial guess of P_{32} and generate a fracture network using the bootstrapping technique or the given fracture orientation and size distributions,
2. sample the network using a borehole with the same orientation as, e.g., KA2563A, and calculate P_{10} (initial) for the initial P_{32},
3. calculate the "true" P_{32} corresponding to the "true" P_{10}, i.e., the observed fracture intensity in KA2563A as:

$$P_{32}\,(\text{true}) = P_{10}\,(\text{true}) \times P_{32}\,(\text{initial}) / P_{10}\,(\text{initial})$$

4. use the calculated P_{32} (true) to generate another fracture network, and check by means of sampling whether the simulated P_{10} equals the observed value, and
5. repeat the procedure by modifying the initial P_{32} to assess the robustness of the derived P_{32}.

Table 6 summarizes the results for the data derived in the previous sections of this report:

Table 6 Fracture intensity of the TRUE Block Scale volume based on the data gathered in KA2563A and in the TBM tunnel.

Parameter	Set 1	Set 2	Set 3	Σ 1-3	Bootstrapping
No. of fractures, -	360	455	344		1159
BH Length, m	362	362	362		362
Mean Size, m	4	4	4		6
Std. dev. Size, m	2	2	2		3
P_{10}, m^{-1}	0.994	1.256	0.950	3.20	3.20
P_{32}, m^2/m^3	2.84	2.525	1.265	6.63	5.72
P_{32}/P_{10}, -	2.86	2.01	1.33	2.07	1.79

Finally, 10 realizations with the bootstrapping technique yield that the ratio of the P_{32} to P_{10} along KA2563A is between 1.6 to 2.0. Hence, if the observed P_{10} in the borehole is 3.2 m^{-1}, the derived P_{32} will be between 5.1 and 6.4 m^2/m^3.

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